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International VLBI Service for Geodesy and Astrometry 2017+2018 Biennial Report

Kyla L. Armstrong, Karen D. Baver, and Dirk Behrend

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Foreword

Since its creation in 1999, the International VLBI Service for Geodesy and Astrometry (IVS) has documented its progress and current status in the form of annual or biennial reports. The first sixteen years were recorded in the form of annual reports, while starting with the years 2015+2016 the rhythm was changed to two years. Hence, the 2017+2018 Biennial Report constitutes the second installment of the two-yearly reporting scheme, documenting the work of the IVS components for the calendar years 2017 and 2018.

As a testament to its usefulness, the general structure of the reporting has remained stable over the years: the individual components of the IVS contributed short reports describing their numerous activities, progress, and future plans. Without the continued input from the VLBI groups of the international geodetic and astrometric community, this publication could not be compiled and the IVS itself would not be able to flourish. So, once again many thanks to all IVS components who contributed to this Biennial Report.

The IVS has decided to go green. For that, like with the IVS Newsletter and the General Meeting Proceedings, this Biennial Report will only be available electronically—there will be no printed version distributed. The contents of this report appear on the IVS Web site at

`https://ivscc.gsfc.nasa.gov/publications/br2017+2018`

The contents of the report are organized as follows:

- The initial section holds a special report. At its 40th meeting, the IVS Directing Board approved the Final Report of the Working Group on Galactic Aberration (WG8) and WG8 was officially closed. The Final Report is reproduced here.
- The next seven sections hold the reports from the Coordinators (including the Chair) and the reports from the IVS Permanent Components: Network Stations, Operation Centers, Correlators, Data Centers, Analysis Centers, and Technology Development Centers.
- The final section provides reference information about IVS. Following the current (September 23, 2011) version of the IVS Terms of Reference, a reference table is provided with links to the IVS Member and Affiliated organizations, the IVS Associate Members, and the IVS permanent components.

Given that the Biennial Report in its online location is in the immediate vicinity of information concerning the IVS organization, the editors felt that it is not indicated to reproduce this information in the report itself. Hence, we would like to ask our readers to make use of the online tools to look up the most recent lists of IVS components, its member organizations as well as affiliated organizations, and Directing Board Members. Useful links are compiled in the closing section of this report.

During the report period, the IVS consisted of

- 32 Network Stations, acquiring high performance VLBI data,
- 3 Operation Centers, coordinating the activities of a network of Network Stations,
- 7 Correlators, processing the acquired data, providing feedback to the stations and providing processed data to analysts,
- 5 Data Centers, distributing products to users, providing storage and archiving functions,

- 28 Analysis Centers, analyzing the data and producing the results and products,
- 7 Technology Development Centers, developing new VLBI technology, and
- 1 Coordinating Center, coordinating daily and long-term activities.

There were altogether

- 83 Permanent Components, representing 41 institutions in 21 countries, and
- about 300 Associate Members.

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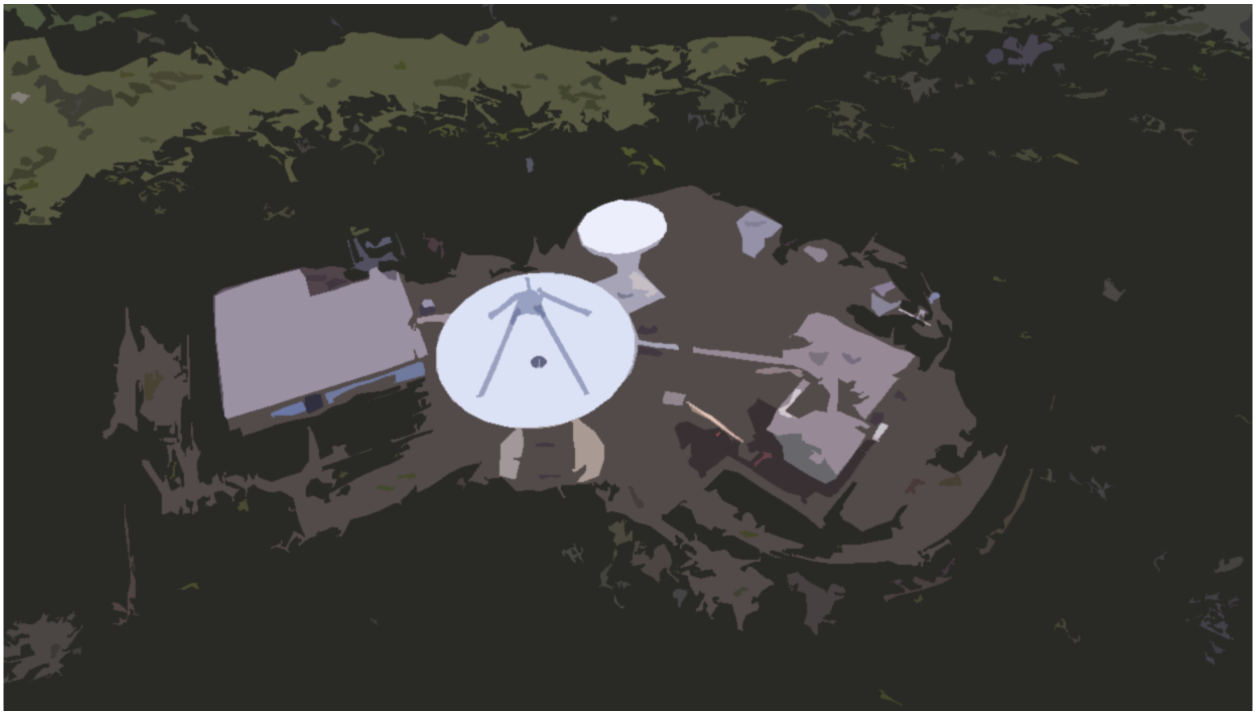
SPECIAL REPORTS



Final Report of the IVS Working Group 8 (WG8) on Galactic Aberration

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Executive Summary

The recommended value of the aberration constant A_G = 5.8 ± 0.3 µas/yr is based on a solution using VLBI geodetic data from 1979 until May 2018. This is the value used for the ICRF3 solution. It is close to the weighted mean of estimates of the aberration component in the direction of the galactic center from geodetic VLBI solutions performed by working group members that used data until 2016. The aberration vector estimates for most of these solutions had components not directed toward the galactic center that were at most 25% of the estimated aberration vector amplitudes. The working group also considered estimates of the aberration constant derived from estimates of the rotation speed of the solar system about the Galactic center and the distance to the Galactic center that were derived by galactic astrometry measurements of parallax and proper motion of galactic masers. The weighted mean of these estimates based on several recent galactic astronomy investigations was A_G = 4.9 ± 0.2 µas/yr. A possible recommendation would be to average the weighted means of the geodetic and galactic astronomy estimates. However, the WG recommends a geodetic value for analysis of geodetic VLBI data in order to be self-consistent with geodetic VLBI applications, specifically for the generation of the ICRF3 solution.

1. Introduction

The IVS Working Group on Galactic Aberration (WG8) was established by the IVS Directing Board at its meeting in November 2015. The purpose of the group was to investigate the issues related to incorporating the effect of galactic aberration in IVS analysis. Based on these studies, the WG was tasked to formulate a recommendation for an aberration correction model to be applied in IVS data analysis and to be provided to the ICRF3 working group.

Secular aberration drift is caused by the acceleration of the Solar System barycenter. It is mainly due to the rotation of the barycenter about the center of the Milky Way galaxy. This motion induces an apparent proper motion of extragalactic objects observed by VLBI. It was predicted theoretically to have a dipolar structure with an amplitude of 4-6 µas/yr (see e.g., Fanselow 1983, Bastian 1995, Kovalevsky 2003, Kopeikin & Makarov 2006, Gwinn 1997, Sovers 1998, Mignard 2002).

The effect of aberration is to cause apparent source positions to change over time. Several studies in recent years, which we discuss in Section 3, have shown that aberration can be estimated from VLBI geodetic data. The VLBI estimates of the aberration amplitude are in the range 5-7 µas/yr. These estimates are close to independently determined estimates of 4.8-5.5 µas/yr that can be derived from recent astrometric measurements of proper motions and parallaxes of masers in the Milky Way galaxy. Although the effect of aberration is small, it is not negligible in terms of future micro-arcsecond astrometry. The systematic drift due to an aberration drift of 5 µas/yr would lead to a dipole systematic error of 100 µas after 20 years. One of the effects of applying an aberration model is to change the source positions for a given reference epoch. If the reference epoch of the aberration model is J2000, when the correction is defined to be zero, the aberration corrections to radio source positions at J2000 are as large as 40-50 µas depending on the source coordinates. This arises from the distribution of the median epochs of observation of the sources observed by VLBI over the last three decades. The correction increases as the temporal difference between the median epoch and the reference epoch increases.

2. Terms of Reference

In this section, we summarize the terms of reference and briefly discuss how they were addressed by the working group. The primary objective (ToR-1) of the WG was to develop a recommended aberration correction model to be applied in VLBI analysis. The results of this work are discussed in Section 3. The mandate of WG8 comprised the following objectives (from the charter of WG8):

ToR-1. Determine a value of the secular aberration drift constant to be applied in an *a priori* model of aberration

The application of an *a priori* model of aberration will most importantly account for the systematic error that is committed without the model. Clearly the dipole systematic due to aberration is significant compared to the CRF noise floor, which in the case of ICRF2 was 40 µas. We will see below that applying the correction causes a change of ±40-50 µas at the epoch J2000.

In Section 3.2 and 3.3, we discuss possible choices of the model aberration constant: 1) a VLBI determined value, 2) a value determined from recent parallax and proper motion measurements of galactic masers, 3) an average of the two techniques. Then in Section 3.4, we consider the effects of applying aberration on estimates of EOP and source positions from VLBI analysis.

ToR-2. Investigate the significance of the non-galactic center components of the VLBI estimated aberration acceleration vector

The aberration vector estimates from most of the VLBI WG member solutions have components not directed toward the galactic center, which are at most 25% of the aberration amplitude. The WG investigated whether this could be due to how VLBI analysis is performed. Among the issues investigated were 1) dependence of aberration estimates on experiment sessions included in solutions, 2) dependence on sources included, and 3) dependence on solution parametrizations.

ToR-3. Consider the redefinition of the ICRS to account for aberration

The ICRF realizes the ICRS by the positions of a set of defining sources that are assumed to have no measurable proper motion. An underlying issue is that applying apparent proper motion corrections due to aberration in VLBI analysis could require a redefinition of the ICRS. The ICRS is defined not by the positions of defining sources only, but by its origin (barycenter) properties. ICRS is considered to be a quasi-inertial reference frame. It is known that this concept allows non-zero acceleration of the origin. However, for an inertial reference frame any acceleration of its origin is not allowed. For this reason, ICRS redefinition is not urgent. In any case, a redefinition of ICRS is not something that the IVS can do as it would have to be done by the IAU.

The working group found that it was not necessary to redefine the ICRS. We can simply apply an aberration proper motion correction in VLBI analysis by a procedure that is similar to that followed in VLBI analysis to account for other effects like precession or annual aberration. (See Section 3). For non-VLBI applications requiring source positions at an epoch other than J2000, one would need to apply the galactic aberration model proper motions with reference epoch J2000 to the source positions given in a catalog generated with the model.

It is true that applying an aberration proper motion model opens the door to all causes of proper motion. Estimation of the apparent linear proper motions of all sources in a TRF/CRF solution yields a large range of linear proper motions (as large as several hundred µas/yr), many of which are much larger than proper motion due to galactic aberration. In addition, source position time series solutions indicate that apparent proper motion for many sources is nonlinear and not well described by a linear model. Source structure variation is the most likely explanation for the observed apparent proper motion. Correction of source structure effects is a complicated process involving generating time series of source maps and performing consistent registration of the maps in a series.

ToR-3 indicated that the WG would investigate how to optimally handle these other apparent proper motion estimates in the generation of an ICRF. However, it is beyond the scope of the WG investigation to determine the likely source structure corrections that would be needed. In contrast, galactic aberration proper motion is a systematic effect that can be expressed via an analytic model.

3. Results

3. 1 Aberration proper motion

A change in the source direction due to aberration in a time interval $(t - t_0)$ can be expressed as

$$\Delta \boldsymbol{s} = \boldsymbol{s} - \boldsymbol{s_0} = \frac{\boldsymbol{s_0} \times (\Delta \boldsymbol{v} \times \boldsymbol{s_0})}{c} = \frac{[\Delta v - (\boldsymbol{s_0} \cdot \Delta \boldsymbol{v})\boldsymbol{s_0}]}{c}$$

where the change in velocity $\boldsymbol{\Delta v} \equiv \boldsymbol{A}\,(t - t_0)$. $\boldsymbol{A}$ is the acceleration of the observer, t is the observing epoch and $\boldsymbol{s_0}$ is the source position direction at the reference epoch t_0.

The components of the aberration proper motion

$$\boldsymbol{\mu} = \frac{\boldsymbol{s_0} \times (\boldsymbol{A} \times \boldsymbol{s_0})}{c}$$

for a source at right ascension and declination (α, δ) are

$$\Delta\mu_\alpha cos\delta = \frac{1}{c}(-A_1 sin\alpha + A_2 cos\alpha) \quad (1)$$

$$\Delta\mu_\delta = \frac{1}{c}(-A_1 cos\alpha\ sin\delta - A_2 sin\alpha\ sin\delta + A_3 cos\delta),$$

where the A_i are the geocentric components of the acceleration vector.

If $\boldsymbol{A}$ is due only to galactic acceleration, then $\boldsymbol{A} = \boldsymbol{A}_G$ points toward the galactic center (α_G = 266.4°, δ_G = -28.9°) and has components,

$$\boldsymbol{A}_G = |A_G|[cos\delta_G cos\alpha_G, cos\delta_G sin\alpha_G, sin\delta_G\ ].$$

The contribution of aberration to geometric delay is determined from

$$\frac{\partial\tau}{\partial\boldsymbol{A}} = \frac{\partial\tau}{\partial\boldsymbol{s}} \cdot \frac{\partial\boldsymbol{s}}{\partial\boldsymbol{A}} = \frac{\partial\tau}{\partial\boldsymbol{s}} \cdot \frac{\partial\boldsymbol{\mu}}{\partial\boldsymbol{A}} \cdot (t - t_0)$$

where the derivative with respect to each component A_i is the sum of the contributions from the proper motion in declination and right ascension given in (1) above. This expression is used in Calc/Solve to compute the delay contribution for a given value of the acceleration vector. Alternatively, these partial derivatives can be used to estimate the acceleration vector in a Calc/Solve solution.

3.2.1 Geodetic VLBI aberration estimation

Over the last several years, members of our working group made several solutions for the acceleration vector $\boldsymbol{A}$ using Calc/Solve and VieVS. Table 1 shows the estimates and uncertainties of the galactic center component A_G, the magnitude $|\boldsymbol{A}|$ of the vector, and the direction of the vector that was estimated for each solution. We usually inflate Calc/Solve parameter estimate uncertainties by a factor of 1.5, which was derived in decimation studies (for example, Fey et al., 2015). To be consistent, the uncertainties of all the amplitudes in the table were all scaled up by this factor.

The global Calc/Solve solutions estimated the components of $\boldsymbol{A}$ as additional global parameters using the userpartial feature of Calc/Solve (Xu et al., 2012 and 2017 and MacMillan, 2014 and 2016). For the Calc/Solve 'time series' solutions (Titov et al., 2011 and Titov and Lambert, 2013), $\boldsymbol{A}$ was estimated in three steps: 1) estimate source position time series in Calc/Solve solutions, 2) estimate source apparent proper motions from these time series, and 3) estimate $\boldsymbol{A}$ from these proper motions. Figure 1 shows the aberration proper motions based on the estimate of $\boldsymbol{A}$ from Titov and Lambert (2013).

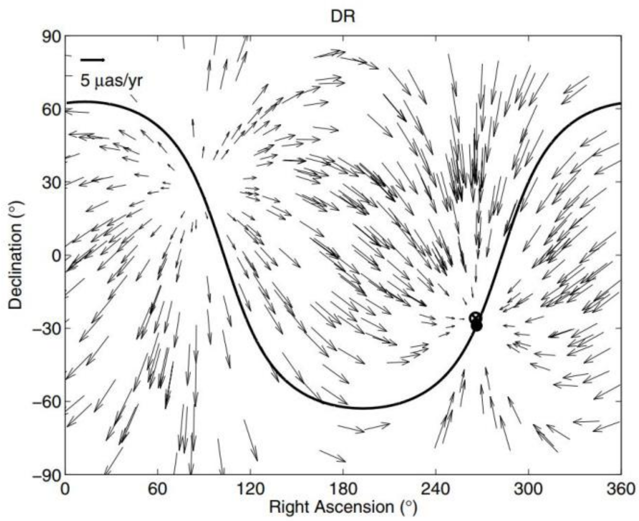

Figure 1. Aberration proper motion with aberration amplitude of 6.4 µas/yr from Titov and Lambert (2013). The Galactic center is indicated by the open circle.

Using the expression for Δs above, the aberration delay is

$$\Delta\tau = -\frac{B \cdot \Delta\boldsymbol{s}}{c} = -\frac{\boldsymbol{B} \cdot \mathbf{A}\Delta t}{c^2} - \frac{F\,\Delta t\boldsymbol{B} \cdot \boldsymbol{s}}{c}$$

$$F \equiv \frac{-(\boldsymbol{A} \cdot \boldsymbol{s})}{c}$$

where $\boldsymbol{B}$ is the a priori baseline vector, $\boldsymbol{s}$ is the unit source direction vector, and $\Delta t = (t - t_0)$. The first term contains a contribution to the proper motion of sources. The second term is the contribution to the reference frame scale since F is a scaling factor of the baseline vector. For the 'scale' solution (Titov and Krásná, 2018), a global scale factor parameter F was estimated for each source using only this second term and $\boldsymbol{A}$ was then derived from the estimated scale factor parameters for all sources using the expression above for F. In the Calc/Solve global solutions, no such separation was made and $\boldsymbol{A}$ was estimated essentially from the proper motions of all the sources. Titov and Krásná found that the effect of secular aberration drift on the scale factor of the terrestrial reference frame was significant (as large as ± 0.2 ppb over the period 1979-2016). An advantage of their method is that it allows one to estimate $\boldsymbol{A}$ from different subsets of all sources and thereby remove poorly determined sources from the estimation. For example, one can require that only sources with at least some given number of observations are used to determine $\boldsymbol{A}$. The scale solution in Table 1 required a minimum of 50 observations to include a source.

Most of the VLBI estimates of $\boldsymbol{A}$ have relatively small components (less than 25% of $|\boldsymbol{A}|$) not in the Galactic center direction. An exception is the first solution of Xu et al. (2011), where the component of the acceleration $\boldsymbol{A}$ perpendicular to the Galactic plane was 46% of $|\boldsymbol{A}|$. They suggested several hypothetical mechanisms that could explain this estimate, for example, a companion star orbiting the Sun. The second solution of Xu et al. made in 2017 has significantly smaller components not in the direction of the Galactic center. Further investigation of possible physical means for producing non-galactic center components could provide a bound for the VLBI estimates of these components. For the recommended model, we will just consider the Galactic center component $\boldsymbol{A}_G$ of the estimated aberration acceleration vector.

Table 1. Estimates of the aberration vector from geodetic VLBI solutions

		A_G µas/yr	σ	$\|A\|$ µas/yr	σ	RA deg	σ	DEC Deg	σ	
Titov et al. (2011)	1990-2010	6.3	1.4	6.4	1.5	263	11	-20	12	C/S, time series
Titov&Lambert (2013)	1979-2013	6.4	1.1	6.4	1.1	266	7	-26	7	C/S, time series
Xu (2013)	1980-2011	5.2	0.5	5.8	0.5	243	4	-11	4	C/S, global
Xu (2017)	1980-2016	6.0	0.3	6.1	0.3	271	2	-21	3	C/S, global
MacMillan (2014)	1979-2014	5.3	0.4	5.6	0.4	267	4	-11	6	C/S, global
MacMillan (2017)	1979-2016	5.7	0.3	5.8	0.3	273	3	-22	5	C/S, global
Titov&Krásná (2018)	1979-2016	6.0	0.3	6.1	0.3	260	2	-18	4	VieVS, global
Titov&Krásná(2018)	1993-2016	5.4	0.6	5.4	0.6	273	4	-27	8	VieVS, global
Titov&Krásná (2018)	1979-2016	5.1	0.3	5.2	0.3	281	3	-35	3	VieVS, global/scale
MacMillan (2018)	1979-2018	5.8	0.3	5.8	0.3	270	3	-21	5	C/S, global, ICRF3

Excluding the ICRF3 solution: weighted mean = 5.6±0.13 µas/yr, weighted rms = 0.4 µas/yr, Galactic center: RA = 266.4 deg, DEC = -28.9 deg

3.2.2 Galactic astrometry aberration estimates

Aberration can also be derived from recent (2009-2017) stellar astronomy measurements (e.g., Reid et al., 2014, Rastorguev et al. 2016, Brunthaler et al., 2011). These measurements are trigonometric parallaxes and proper motions of masers in high-mass star-forming regions in the Milky Way galaxy. These measurements were made using the Very Long Baseline Array

(VLBA), the European VLBI network (EVN), and the Japanese VLBI Exploration of Radio Astronomy Project (VERA). The most recent investigation noted here Rastorguev (2017) used a maser sample of 136 sources. Using these parallax and proper motion measurements, different investigators have derived models of the galaxy. Among the parameters of these models are the radial distance R (kpc) to the galactic center and circular rotation speed V (km/s) of the solar system barycenter. Based on the estimated parameters R and V and their uncertainties from each investigator, we determined the aberration constant $A_G = V^2/(Rc)$ and its uncertainty. Table 2 shows the resulting estimates of the aberration constant A_G derived from the estimates of R and V. Based on the uncertainties of R and V, the formal uncertainties of A_G are in the range 0.3-0.8 µas/yr. The uncertainties have improved over the period 2009-2016, because more maser data became available. This also had the effect of reducing correlations between galactic parameters that were being estimated. To apply a model based on this aberration constant, technically one would need to transform source motion in the Galactic coordinate system to the equatorial system (Murray, 1983), but Malkin (2014) noted that errors induced by these matrix transformations are less than 0.04 uas/yr.

Table 2. A_G estimates based on recent V and R measurements from parallax and proper motions

	A_G µas/yr	Σ	V km/s	σ	R kpc	σ	# masers
Reid (2009)	5.4	0.8	254	16	8.40	0.60	18
Brunthaler (2011)	5.1	0.3	246	7	8.30	0.23	18
Honma (2012)	4.9	0.6	238	14	8.05	0.45	52
Reid (2014)	4.8	0.3	240	8	8.34	0.16	103
Rastorguev (2017)	4.8	0.3	238	7	8.24	0.12	136

weighted mean = 4.9±0.17 µas/yr, weighted rms = 0.2 µas/yr

Malkin (2014) averaged available estimates of R and V from 2010-2014 and obtained an average of 5.0 ± 0.3 µas/yr. This is consistent with the mean in Table 2.

3.3 IAU recommendation

Based on recent estimates from galactic astronomy, it appears that the IAU (1985) recommended values of R = 8.5 kpc and V = 220 km/s should be revised. These IAU values yield a value of A_G = 3.99 µas/yr which is significantly less than the estimates from recent (2009-2016) galactic VLBI astrometry and from recent estimates based on geodetic VLBI. IAU should adopt a value for the aberration constant A_G that is based on these recent independent determinations.

Possible options for the IVS working group recommendation for the aberration constant A_G are: 1) VLBI weighted mean, 2) galactic astronomy weighted mean, 3) the average of 1) and 2). If the two were equally weighted A_G = 5.3 ± 0.3 µas/yr. The average of the two sets of measurements differ from the means of each group by at most 0.4 uas/yr which is less than 10%

of the aberration effect. If we are uncertain about which group of measurements may be biased from the truth, this would appear to be the best option.

However, we recommend that the IAU ICRF3 working group should use a geodetic solution for the value of A_G when a galactic aberration contribution is applied. The rationale is that since the correction was derived via geodetic VLBI solutions, it should be applied in the analysis of geodetic VLBI sessions, specifically for the ICRF3 solution, in order to be self-consistent. We recommend the aberration constant 5.8 ± 0.3 µas/yr derived from a solution with all data (1979-May 2018) that was used to generate the ICRF3 solution, which is about two more years of data than any of the other working group solutions. This value is consistent with the mean 5.9 ± 0.2 µas/yr of solutions (Xu (2017), MacMillan (2017), and Titov and Krasna (2018)) in Table 1 that used data from 1979-2016.

3.4 Application of aberration in geodetic VLBI solutions

3.4.1 How to make a new ICRF catalog

In this section, we discuss how the aberration correction should be applied to determine a new ICRF catalog. Initially we thought that it was necessary to take an *a priori* catalog and adjust the positions to J2000.0 using the source mean epochs from the catalog and the aberration proper motions for each source. One problem with this method is that the mean epochs are not reflective of the true data distribution since sessions do not have the same number of observations. It is not known how much each session contributes to the estimated global source position. One could determine some effective mean epoch instead, but this is not required. One can simply run a solution with an aberration correction that has a reference epoch of $t_0 =$ J2000. The estimated positions will then be self-consistent with the correction. To verify this, the estimated positions from such a solution were used along with the aberration model to determine the *a priori* positions in a second solution. The resulting estimated global source positions agreed with the input a priori positions. When a new catalog is made, the aberration model should be appended as auxiliary information, but it is not necessary to add proper motions explicitly into the catalog. The aberration contributions to the *a priori* source positions are

$$\Delta\alpha(\alpha,\delta) = \Delta\mu_\alpha\,(t - t_0)$$

$$\Delta\delta(\alpha,\delta) = \Delta\mu_\delta\,(t - t_0)$$

where the aberration proper motions $(\Delta\mu_\alpha cos\delta, \Delta\mu_\delta)$ are given above in (1). For non-VLBI applications requiring positions at epoch t, the catalog positions at J2000 would be corrected by applying the Galactic aberration model correction for epoch t.

3.4.2 Effects of aberration: Source positions and EOP

We have investigated what is the effect of the aberration on estimated source positions and EOP. Figures 2a and 2b show the Calc/Solve differences in source positions (RA, DEC) versus RA and

DEC when the aberration constant A_G is a nominal 5 µas/yr. In this case the sources in the source NNR (no net rotation) constraint were uniformly weighted. The source position differences range over ±40-50 µas.

If a Calc/Solve solution is run weighting the contributions in the source NNR constraint using the uncertainties of source positions, the resulting declination differences shown in Figure 3a are not symmetric about RA=12 hours. The RA differences as shown in Figure 3a increase as RA approaches RA=0 hours and RA=12 hours. In this case, the asymmetry was correlated with nutation estimates. It was due to a rotation about the CRF X-axis which corresponds to nutation in obliquity. Alternatively, if nutation is not estimated, this asymmetry effect does not appear.

For comparison, VieVS solution differences where uniform NNR constraints were applied are also shown in Figures 3a and 3b. The VieVS differences were plotted in Figures 3 since they are closer to the Calc/Solve differences with weighted constraints than the differences with uniform weighting. The systematic patterns (e.g. the asymmetry noted above) of differences shown is more pronounced for the Calc/Solve solution than for the VieVS solution. At this point, it is not clear why the VieVS pattern of solution differences are not like those in Figures 2 since apparently uniform NNR constraints were used

Applying the aberration correction has a small effect on EOP. The largest effect is for nutation in obliquity. Using weighted NNR source constraints results in small biases in nutation. Table 3 summarizes the statistics of the differences.

Table 3. EOP with aberration minus EOP without aberration

Uniform NNR source constraints	Offset (2014.0)	Rate (per year)	WRMS
X-pole (µas)	0.43	-0.14	1.84
Y-pole (µas)	2.91	0.09	1.53
UT1 (µs)	0.14	0.01	0.10
Psi (µas)	-1.27	-0.08	3.36
Eps (µas)	-0.18	-0.46	2.75

Weighted NNR source constraints	Offset (2014.0)	Rate (per year)	WRMS
X-pole (µas)	-0.02	-0.15	1.86
Y-pole (µas)	2.81	0.08	1.53
UT1 (µs)	0.21	0.01	0.10
Psi (µas)	-6.49	-0.08	3.36
Eps (µas)	-15.3	-0.46	2.75

If aberration is applied in a solution, the resulting ICRF positions will be rotated. For the nominal aberration constant 5 µas/yr, the XYZ rotation angles are (52.8 µas, -1.8 µas, -1.3 µas)

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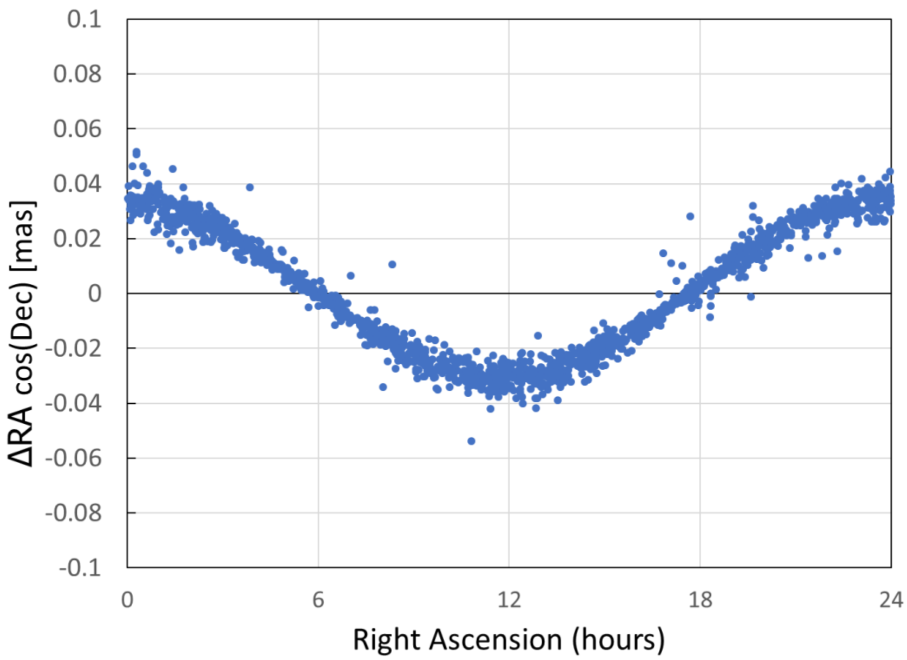


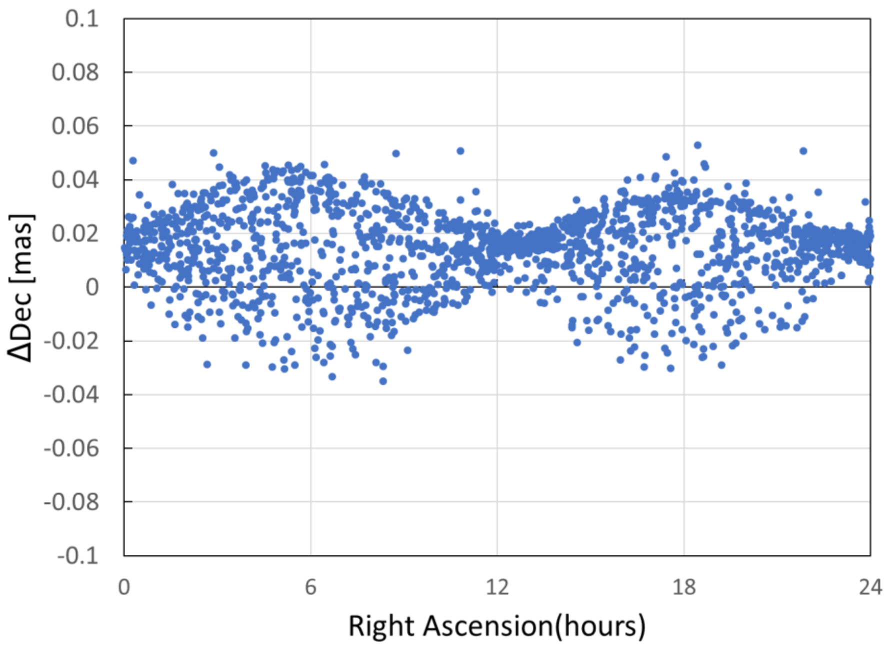
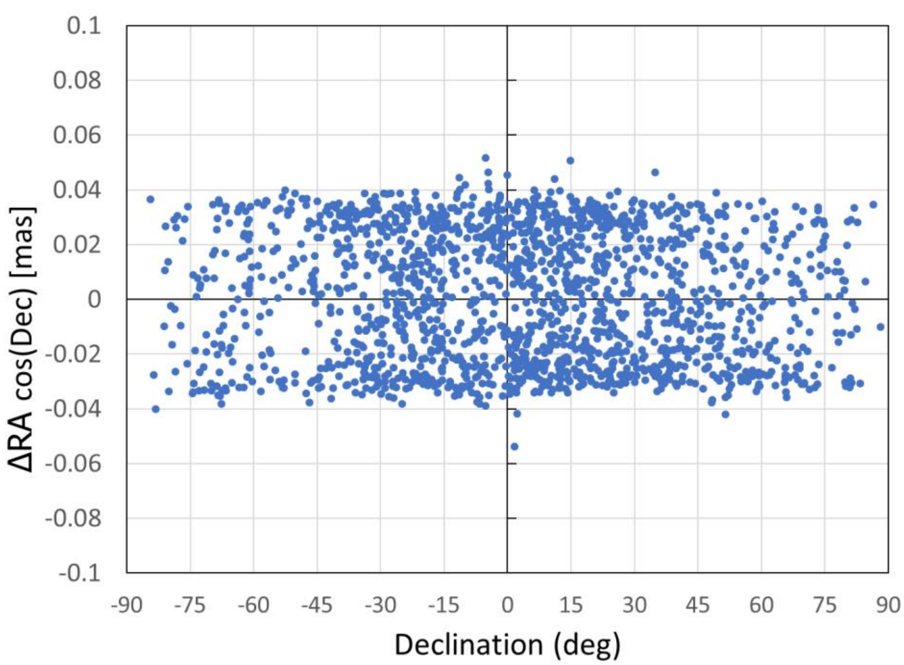


Figure 2a. Right Ascension and Declination differences versus right ascension between solution with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. A uniformly weighted NNR condition was applied in the solutions.



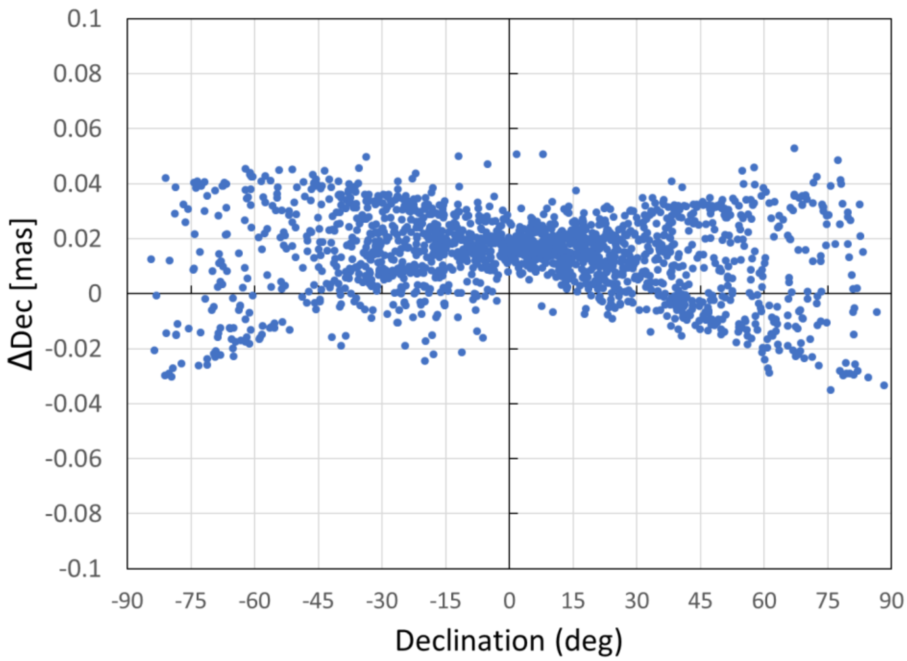
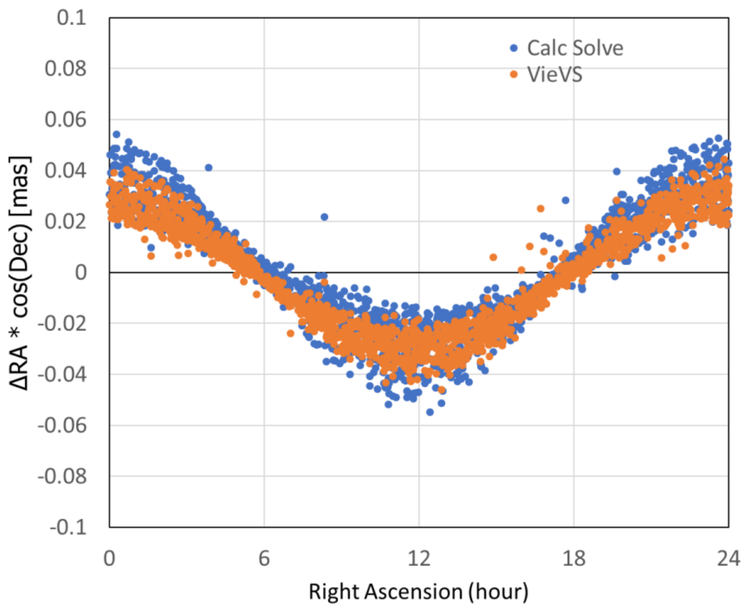


Figure 2b. Right Ascension and Declination differences versus declination between solution with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. A uniformly weighted NNR condition was applied in the solutions.



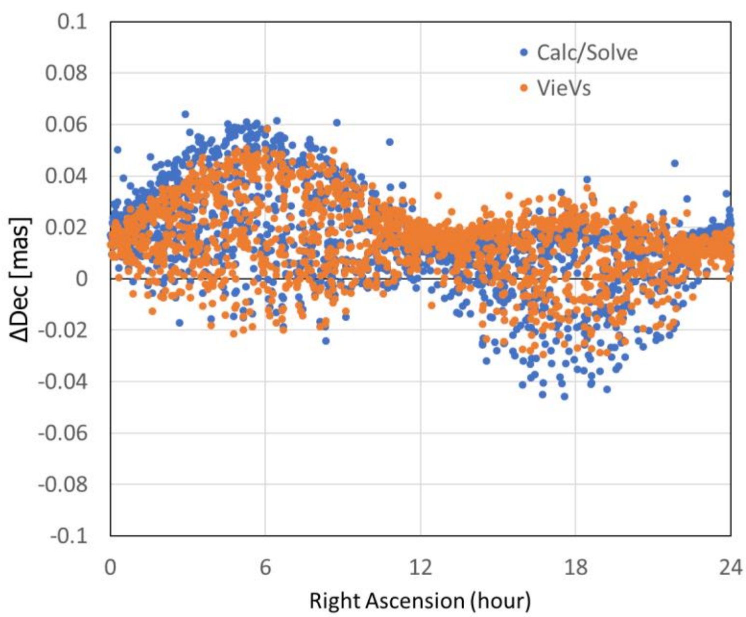


Figure 3a. Right Ascension and Declination differences versus right ascension between solutions with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. The NNR condition weighted the included sources by their uncertainties in the Calc/Solve solution but uniformly weighted sources in the VieVS solution.

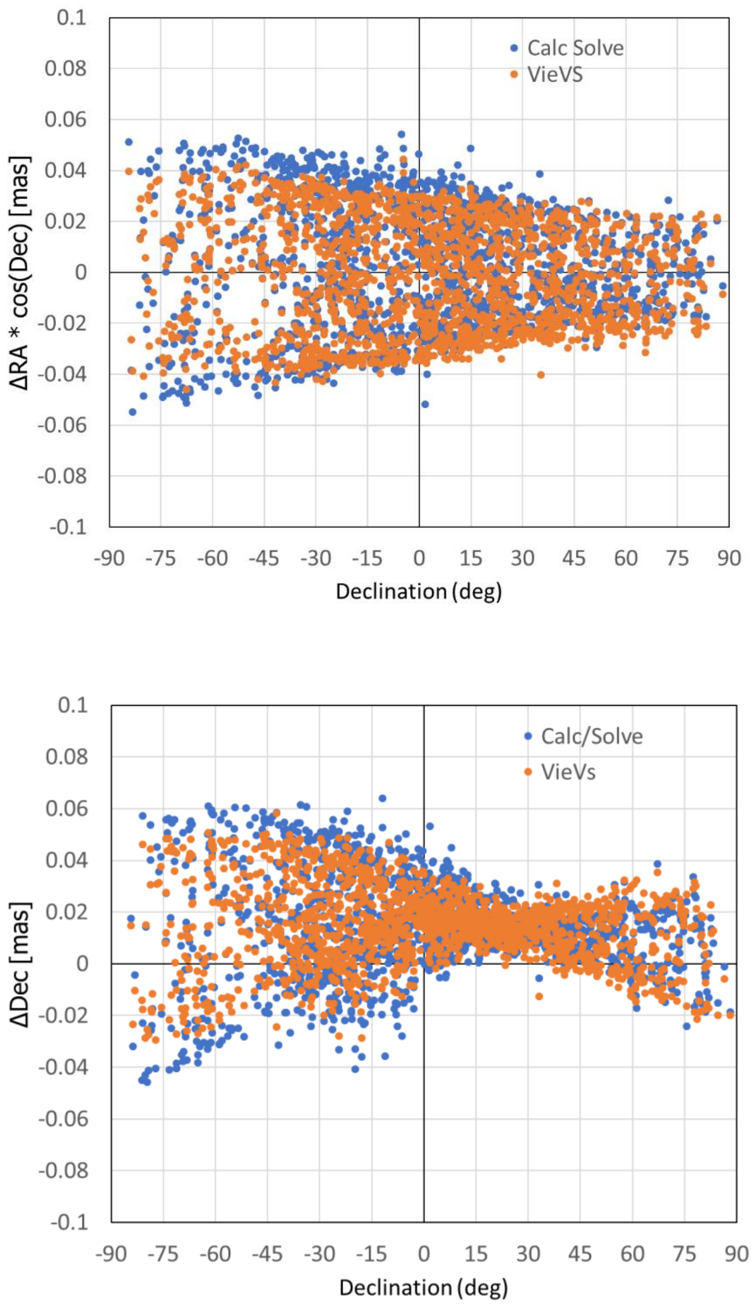


Figure 3b. Right Ascension and Declination differences versus declination between solutions with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. The NNR condition weighted the included sources by their uncertainties in the Calc/Solve solution but uniformly weighted sources in the VieVS solution.

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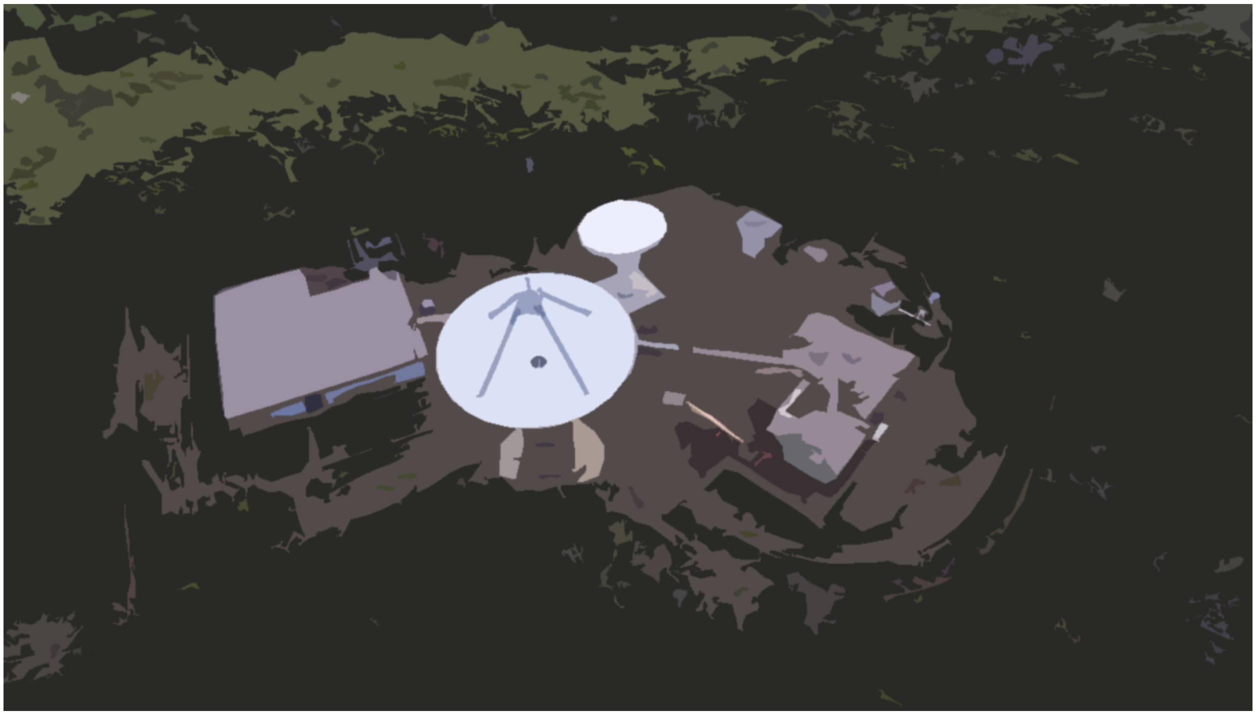

IVS Chair's Report

Axel Nothnagel

Another two years have passed with the IVS making considerable progress in its developments. As in many other disciplines, communities, and organizations, the individual steps might get lost in the overall complexity, but are necessary however small they may be. In this respect, the Biennial Report 2017–2018 once again documents the bigger achievements but not the tiny details—though the latter may have caused more headaches than the general concepts. I thank all of you for your efforts to develop the IVS further, with small and large pieces of the puzzle, and for documenting them in this report. It is always a very valuable reference for information, which may be hidden or even lost in the course of time.

Concerning the observations, the IVS network operated as planned by the IVS Observing Program Committee (OPC) heavily supported by the IVS Coordinating Center at NASA Goddard Space Flight Center. No major change in the overall program was introduced. With this, the IVS exploited all its observing and correlation capacity to the full extent. Another CONT campaign, CONT17, was observed during the period from November 28 to December 12, 2017. This time, the campaign consisted of three separate networks: two legacy S/X networks observing for 15 consecutive days and one VGOS broadband network observing for five consecutive days in the middle of the CONT17 period. This put again quite a heavy burden on the telescopes and on the correlators. The results are really noteworthy and a special issue on CONT17 is planned to be published in Journal of Geodesy.

Institut für Geodäsie und Geoinformation der Universität Bonn

Chair

IVS 2017+2018 Biennial Report

With the VGOS broadband system, a network of 3–7 stations has been observing VGOS Test (VT) sessions about every other week for 26 sessions each in 2017 and 2018. Level 1 data analysis (polarization combination and fringe fitting with ionosphere estimation) has not been trivial and might have been underestimated in its complexity. When you read this, the data of the 24-hour sessions should have been released to the community for further analyses. Although the IVS is far behind its own expectations concerning the VGOS developments, there are a couple of good news. The first publication on the VGOS processing chain appeared (Niell et al., 2018) and in Europe, a group started to look into VGOS observations and processing with alternative developments (Alef et al., 2019).

Under the guidance of the International Astronomical Union (IAU) Working Group on the Third Realization of the International Celestial Reference Frame (ICRF3), several IVS Analysis Centers (ACs) prepared CRF solutions as input to ICRF3. The new frame was adopted at the IAU General Assembly in Vienna, Austria, on August 30, 2018 under Resolution B2. ICRF3 contains positions of more than 4,000 extragalactic radio sources at three frequencies and became the current realization of the International Celestial Reference System (ICRS) on January 1, 2019.

With the advent of powerful and affordable terrestrial laser scanners (TLS), the issue of path delay variations and position changes due to gravitational deformations of the radio telescopes surfaced again lately. From earlier investigations, it is clear that gravitational deformations have a direct effect on the delay observables. As a consequence, these delay effects then change the vertical position of the telescope in a global frame by several millimeters. Within the report period, a few more telescopes were investigated

Table 1 Former IVS Directing Board members of the past two years.

Alessandra Bertarini	Reichert GmbH, BKG, Germany	Correlators and Operation Centers Representative	Feb 2015 – Sep 2017
Ludwig Combrinck	Hartebeesthoek Radio Astronomy Observatory, South Africa	IAG Representative	–
David Hall	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Feb 2017 – Feb 2019
Thomas Hobiger	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2017 – Feb 2019
Alexander Ipatov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2015 – Feb 2017
Ryoji Kawabata	Geospatial Information Authority, Japan	At Large Member	Feb 2015 – Feb 2017
Jim Lovell	University of Tasmania, Hobart, Australia	Networks Representative	Feb 2013 – Feb 2017
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	–
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2015 – Feb 2019
Bill Petrachenko	Natural Resources Canada, Canada	Technology Coordinator	–
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 – Feb 2019
Takahiro Wakasugi	Geospatial Information Authority, Japan	At Large Member	Feb 2017 – Feb 2019
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2017 – Feb 2019

by TLS measurements and subsequent data analysis. From these, empirical correction models were developed, which can now be applied in VLBI data analysis. Everybody should be aware that the radio telescope coordinates produced without these corrections suffer a severe systematic deficit. For this reason and for a full positive impact on the scale of the ITRF, possibly closing the scale gap between VLBI and SLR, all telescopes need to be measured and modeled. Therefore, I would like to encourage all of you to address this issue at your station and increase the endeavors that every telescope is surveyed appropriately. I am glad to give advice where needed.

The reporting period has seen a number of first-class IVS-related meetings, which were attended by many IVS colleagues. From April 30 to May 4, 2017, the 9th IVS Technical Operations Workshop took place at Haystack Observatory, Westford, MA, USA. The inauguration of the Onsala Twin Telescopes on May 18, 2017, brought us to Gothenburg, Sweden, where the 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA) and the 18th IVS Analysis Workshop were held the days before. The 6th International VLBI Technology Workshop on October 9–11, 2017, was hosted by Istituto di Radioastronomia at Bologna, Italy. The year 2018 saw another big event, the inauguration of the Ny-Ålesund Twin Telescopes embedded in the 10th IVS General Meeting at Longyearbyen, Norway, on June, 3–8, 2018, including the 19th IVS Analysis Workshop. Finally, the 7th International VLBI Technology Workshop was held at Krabi, Thailand, November, 12–15, 2018. The inaugurations of the telescopes were highlights of the IVS and the hosting agencies—Chalmers University of Technology and the Norwegian Mapping Authority—created memorable events for all who participated. They mark important steps on the growth of the VGOS network, which, hopefully, will soon start regular observations and streamlined processing for the determination of Earth orientation parameters and telescope coordinates.

The IVS Directing Board (DB) met in person three times: in Gothenburg, Sweden, on May 19, 2017; in Bologna, Italy, on October 12, 2017; and in Longyearbyen, Norway, on June 9, 2018. Many important decisions were made. One of them is the creation of an IVS Office for Outreach and Communications (OOC) at the end of 2018. The OOC is hosted by MIT Haystack Observatory and led by Nancy Kotary. It is established to promote awareness and understanding of the unique and vital role of geodetic VLBI and the IVS in science and society to the larger scientific community, decision makers, and the general public. Activities will include the creation of a dedicated Web site, of social media accounts, and of extensive educational materials. It is anticipated that the OOC will improve collaboration across institutions, sponsor organizations, and scientific associations on education and outreach work.

In the natural course of new elections but also for some unexpected resignations, the IVS DB said farewell to a few members over the last two years (Table 1). We are grateful for their service to the IVS and to the DB.

In early 2017, I was re-elected as chair of the IVS. I am honored by this trust and I hope that I can fulfill your expectations. Of course, there is always more on ones table to cope with in a satisfactory time frame and some good ideas may disappear under the pile of unattended tasks just for constantly changing priorities. The time ahead is dominated by a phase of transition to VGOS observations, but the legacy type of observations and processing will still play an important role. The IVS relies on every individual to keep up with all the challenges in the pipeline.

Coordinating Center Report

Dirk Behrend

Abstract This report summarizes the activities of the IVS Coordinating Center during the calendar years 2017 and 2018 and provides an outlook on activities planned for the next two years.

1 Coordinating Center Operation

The IVS Coordinating Center is based at the Goddard Space Flight Center and is operated by NEOS (National Earth Orientation Service), a joint effort for VLBI by the U.S. Naval Observatory and the NASA Goddard Space Flight Center.

The mission of the Coordinating Center is to provide communications and information for the IVS community and the greater scientific community and to coordinate the day-to-day and long-term activities of IVS.

The Web server for the Coordinating Center is provided by Goddard. The address is

`https://ivscc.gsfc.nasa.gov`.

2 Activities during 2017 and 2018

During the period from January 2017 through December 2018, the Coordinating Center supported the following IVS activities:

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Coordinating Center

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- **Directing Board support:** Coordinated, with local committees, three IVS Directing Board meetings: Gothenburg, Sweden (May 2017), Bologna, Italy (October 2017), and Longyearbyen, Svalbard, Norway (June 2018). Notes from each meeting were published on the IVS Web site.
- **Observing Program Committee (OPC):** Coordinated meetings of the OPC to monitor the observing program, review problems and issues, and discuss changes.
- **Master Schedules for 2017 and 2018:** Generated and maintained the Master Observing Schedules for 2017 and 2018. Coordinated VLBI resources for observing time, correlator usage, and disk modules. Coordinated the usage of Mark 5 systems at IVS stations and efficient deployment of disk modules.
- **2019 Master Schedule:** Generated the proposed Master Schedule for 2019 and received approval from the Observing Program Committee.
- **VGOS:** Supported the activities for establishing the VLBI Global Observing System (VGOS) through participation in the VGOS Technical Committee (VTC) and the VGOS Operations and Resources group.
- **Communications support:** Maintained the Web pages, e-mail lists, and Web-based mail archive files. The e-mail lists were migrated from the GSFC

Fig. 1 Logo of the ninth IVS Technical Operations Workshop.

Fig. 2 Banner of the tenth IVS General Meeting in Norway.

VLBI Group local server to a NASA-wide service in September 2017. In the migration step the membership subscriptions were carried over, and non-active lists were discontinued. Maintained the 24-hour and Intensive session Web pages including the data acquisition, correlation, analysis, and performance summaries.

- **Publications:** Published the 2015+2016 Biennial Report in fall 2017. Published six editions of the IVS Newsletter in the months of April, August, and December of 2017 and 2018. All publications are available electronically as well as in print form.
- **Meetings:** Coordinated, with the Local Committees, the ninth IVS Technical Operations Workshop, held at Haystack Observatory in May 2017, and the tenth IVS General Meeting, held in Longyearbyen, Svalbard, Norway in June 2018. Chaired the Program Committees of both meetings.

Fig. 3 Participants of the tenth IVS General Meeting visiting Ny-Ålesund.

3 CONT17 Campaign

In November/December 2017 the Continuous VLBI Campaign 2017 (CONT17) was successfully observed. The Coordinating Center, in collaboration with the OPC, was responsible for:

- the overall planning and coordination of the campaign,
- the media usage and shipment schedule, and
- the preparation of the detailed observing schedules and notes for the two legacy networks (CONT17-L1 and CONT17-L2).

The campaign consisted of three separate networks: two legacy S/X networks observing for 15 consecutive days and one VGOS broadband network observing for five consecutive days in the middle of the CONT17 period. The use of the two legacy networks allows study of the accuracy of VLBI estimates of EOP and investigation of possible network biases. A special issue on CONT17 is planned to be published in the Journal of Geodesy.

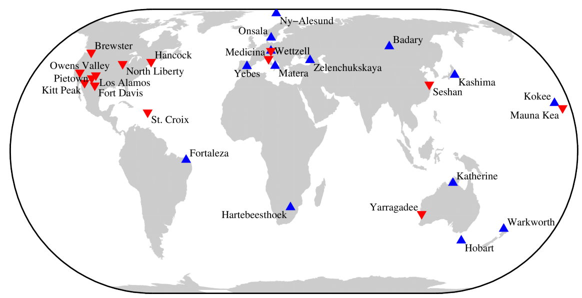

Fig. 4 The two 14-station legacy S/X networks of CONT17: blue triangles ▲ depict CONT17-L1, and red inverted triangles ▼ depict CONT17-L2.

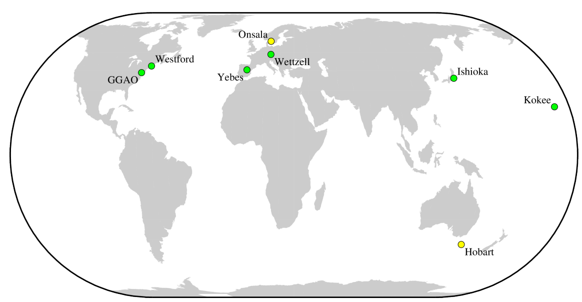

Fig. 5 The six-station CONT17 VGOS demonstration network CONT17-VGOS (green circles ●). The broadband signal chain roll-out for Onsala and Hobart (yellow circles ●) was not completed on time for their official inclusion in the campaign.

More information about the CONT17 campaign can be found on the IVS Web site under the URL https://ivscc.gsfc.nasa.gov/program/cont17.

4 Staff

The staff of the Coordinating Center was drawn from individuals who work at Goddard. The staff and their responsibilities are listed in Table 1.

Table 1 IVS Coordinating Center staff.

Name	Title	Responsibilities
Dirk Behrend	Director	Web site and e-mail system maintenance, Directing Board support, meetings, publications, session Web page monitoring
Cynthia Thomas	Operation Manager	Master schedules (current year), resource management and monitoring, meeting and travel support, special sessions
Frank Gomez	Web Manager	Web server administration, mail system maintenance, Data Center support, session processing scripts, mirror site liaison
Karen Baver	General Programmer and Editor	Publication processing programs, LaTeX support and editing, session Web page support and scripts, Data Center support
Kyla Armstrong	Data Technician and Editor	Publications support and Web site support

After supporting the Coordinating Center for almost twenty years, Frank Gomez began working in a different section of GSFC in May 2018. His responsibilities towards the Coordinating Center have been divided among other system administrators (Ross Asato and Brian Town for Web server administration and mail system maintenance), CDDIS Data Center personnel (Justine Woo for Data Center support and mirroring), and an offsite consultant (Mario Bérubé for session processing scripts).

5 Plans for 2019 and 2020

The Coordinating Center plans for 2019 and 2020 include the following:

- Maintain IVS Web site and e-mail system.
- Publish the 2017+2018 Biennial Report (this volume).
- Coordinate, with the local committee, the tenth IVS Technical Operations Workshop to be held at the MIT Haystack Observatory, MA, USA in May 2019.
- Coordinate, with the local committee, the eleventh IVS General Meeting to be held in Annapolis, MD, USA in March 2020.
- Publish the Proceedings volume of the eleventh IVS General Meeting.
- Support Directing Board meetings in 2019 and 2020.
- Coordinate the 2019 and 2020 master observing schedules and IVS resources.
- Publish Newsletter issues in April, August, and December.
- Support the VGOS activities within the VTC and the VGOS Operations and Resources group.

2017–2018 Analysis Coordinator Report

John Gipson

Abstract I summarize some of the important issues related to IVS Analysis over the last two years.

1 Transition to vgosDB

For many years the IVS had been working on transitioning from the MK3-database format to the vgosDB format. By the end of 2017 most of the IVS correlators could produce both MK3-DB and vgosDB versions of the data, and most of the analysis software could process vgosDB. In the Spring of 2018, the computer at the Bonn correlator which produced MK-DB failed. Instead of trying to resurrect the computer, or to install the software on a new computer, the Bonn correlator group made the decision to only produce vgosDB going forward. This forced the IVS to abruptly transition to the vgosDB format which was all to the good. Because of the abrupt transition, not all components of IVS were completely ready, and ad hoc arrangements were made to keep the data flowing.

- Most IVS Analysis Centers start with Version 4 datathe data has been edited and the ambiguities removed. However only the USNO and Goddard analysis groups were able to produce V4 vgosDB. Because of this the Goddard analysis group agreed to temporarily take on the responsibility for the remaining sessions.
- The IVS data centers were not ready to handle vgosDB. Because of this the Goddard VLBI group gathered the vgosDB sessions and made them publicly available for IVS use. CDDIS worked on updating their ingest software to be able to process vgosDB, but this software was not in place by the end of 2018, although it did become in available in early 2019.

As I write this the IVS has been using vgosDB for over a year, although there are still outstanding issues in the data processing.

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2 HF-EOP

One of the outgrowths of the 2017 IERS Unified Analysis Workshop in Paris, France, was the formation of a working group to evaluate models of tidally driven daily and sub-daily variation of EOP (HF-EOP), and to make a recommendation to the IERS for adoption of a new model. I was chair of this working group. The working group identified 10 potential models. At the conclusion of 2018 these models had been evaluated by several VLBI groups. Some of the models had been evaluated in GPS processing. The two most promising models was one derived empirically from VLBI data (Gipson) and a model due to Desai and Sibois of JPL. The working will make a recommendation by the summer of 2018.

3 Galactic Aberration

The IVS Aberration Working Group on Galactic Aberration (WG8) began its work in 2016 with the goal of investigating issues related to incorporating Galactic aberration in IVS analysis. Over time scales of several decades of geodetic observing, the circular motion of the solar system around the Galactic center causes a secular aberration drift. The results from WG8 were discussed in the IVS final report of the working group (MacMillan et al. 2018) and in an Astronomy and Astrophysics paper to be submitted in 2019. Using the data set (1979 - May 2018) that was to be used for the ICRF3 solution, the working group estimated a galactocentric acceleration constant of 5.8 as/yr in the direction of the galactic center. This value was adopted by the ICRF3 working group for the final ICRF3 solution. The estimated aberration acceleration vector was within 8 (less than 2 sigma) of the direction of the galactic center. This could be due to non-galactocentric acceleration or unmodeled source structure effects, but this will require future investigation.

4 ICRF3 Work

The third realization of the International Celestial Reference Frame (ICRF3) by VLBI was generated by a working group of the International Astronomical Union (IAU), composed mostly of IVS members. It was adopted by the IAU at its August 2018 meeting and became the official ICRF on January 1, 2019. ICRF3 contains precise catalogs of compact extragalactic radio sources at three frequencies: X/S (8.4/2.3 GHz) band (4536 sources), K (24 GHz) band (824 sources) and X/Ka (8/32 GHz) band (678 sources). Noise floors were determined at X/S band of 30 micro-arc-sec in RA and Declination and at K band of 30/50 micro-arc-sec in RA/Dec. The effect of galactic abberation was modeled in the three catalogs, using a galactic aberration constant of 5.8 micro-arc-sec/year, as was solved for using the ICRF3 X/S dataset. It was desired that the ICRF3 defining sources be as uniformly distributed around the sky as possible. To accomplish this, the celestial sphere was sub-dividing into 324 sectors of equal area and the best suitable source in each sector was picked. Defining sources from 303 sectors were selected, with 21 sectors having no suitable source. Using these 303 defining sources, the axis stability of ICRF3 is estimated to be approximately 10 micro-arc-sec.

The ICRF3 catalogs are available at https://iers.obspm.fr/icrs-pc/newwww/icrf/.

5 Preparation for ITRF2020

In 2017 Zuheir Altamimi published a call for participation in ITRF2020, and the IVS began preparing for this. There will be several changes compared to ITRF2014. Two of these apply to all of the techniques:

1. The new pole-tide mode which was introduced at the 2017 UAW.
2. The new HF-EOP which will be recommended by the IERS WG on HF-EOP. This model will become part of the IERS standards.

The following model change which apply only to VLBI.

1. Galactic aberration applied as an a priori correction to source positions.
2. Use of models of the gravitational deformation of VLBI antennas.

This IVS submission will differ from previous submissions in that the SINEX files will include source coordinate information. In addition, there is a proposal underway that the IVS could submit SINEX files where pressure loading is applied as a priori, as long as the effect can be removed a posteriori. The exact mechanism for doing this is unclear, but this has the advantage that it would save the IVS the trouble of having to generate special solutions for ITRF2020.

6 IVS Analysis Centers and Analysis Software

I am pleased to report that number of IVS Analysis Centers continues to increase. Currently there are over 30 IVS Analysis Centers using around 10 different VLBI analysis packages. Fifteen of these ACs regularly submit solutions to the IVS combination center. In addition, numerous groups have developed, or are developing, new VLBI analysis. I am a firm believer that this sort of friendly competition can only be beneficial to the IVS.

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2. Galactic Aberration in VLBI Analysis: Findings of the IVS WG8, D. S. MacMillan and IVS WG8, in IVS 2018 General Meeting Proceedings, D. Behrend, K. D. Baver, K. L. Armstrong (editors), 2018.

Network Coordinator Report

Mario Bérubé, Ed Himwich

Abstract This report includes an assessment of the network performance in terms of lost observing time for calendar years 2017 and 2018. Overall, the observing time losses were about 18.7% in 2017 and 21.5% in 2018. These high statistics are similar to the 2015–2016 period and are mainly due to stations that did not observe because of scheduling conflicts or maintenance but were not removed from the master schedule. A total of 120 (5.3%) and 123 (7%) station-days were in the master schedule but were not included in the final observing schedules in 2017 and 2018, respectively. RFI in S-band continues to be a significant source of data loss. A table of relative incidence of problems with various sub-systems is presented.

1 Observing Network

The 2017 and 2018 S/X observing network shown in Figure 1 consisted of 51 stations in total. The network includes 37 IVS Network Stations as official member components of the IVS as well as several cooperating sites that contributed to the IVS observing program, in particular the ten VLBA stations and four NASA DSN stations.

NASA Goddard Space Flight Center

IVS Network Coordinator

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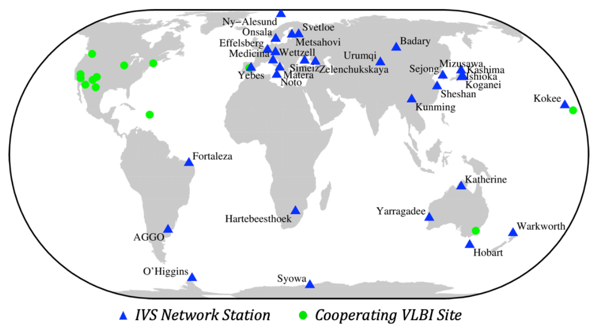


Fig. 1 Distribution plot of the VLBI stations that contributed to the 2017–2018 IVS Master Schedules.

2 Network Performance

The network performance is expressed in terms of lost observing time, or data loss. This is straightforward in cases where the loss occurred because operations were interrupted or missed. However, in other cases, it is more complicated to calculate. To handle this, a non-observing time loss is typically converted into an equivalent lost observing time by expressing it as an approximate equivalent number of recorded bits lost. As an example, a warm receiver will greatly reduce the sensitivity of a telescope. The resulting performance will be in some sense equivalent to the station having a cold receiver but observing for (typically) only one-third of the nominal time and therefore recording the equivalent of only one-third of the expected bits. In a similar fashion, poor pointing can be converted into an equivalent lost sensitivity and then equivalent fraction of lost bits. Poor recordings are simply expressed as the fraction of total recorded bits lost.

Using correlator reports, an attempt was made to determine how much observing time was lost at each station and why. This was not always straightforward to do. Sometimes the correlator notes do not indicate that a station had a particular problem, while the quality code summary indicates a significant loss. Reconstructing which station or stations had problems—and why—in these circumstances does not always yield accurate results. Another problem was that it is hard to determine how much RFI affected the data, unless one or more channels were removed and that eliminated the problem. It can also be difficult to distinguish between BBC and RFI problems. For individual station days, the results should probably not be assumed to be accurate at better than the 5% level.

The results here should not be viewed as an absolute evaluation of the quality of each station's performance. As mentioned above, the results themselves are only approximate. In addition, some problems such as weather and power failures are beyond the control of the station. Instead the results should be viewed in aggregate as an overall evaluation of what percentage of the observing time the network is collecting data successfully. Development of the overall result is organized around individual station performance, but the results for individual stations do not necessarily reflect the quality of operations at that station.

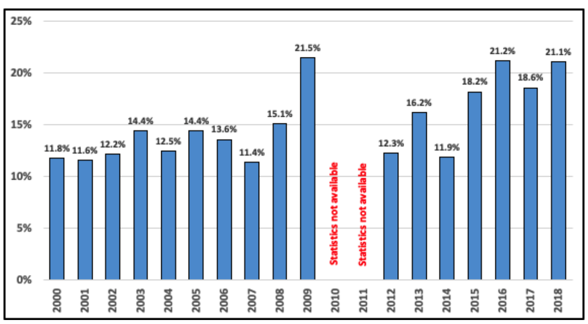


Fig. 2 Historical data loss since 2000.

The overall network performance for 2017–2018 is similar to 2015–2016 as shown in Figure 2. The results of this report are based on correlator and analysis reports for 376 24-hour sessions correlated as of June 7, 2019. The examined data set includes 2,534,980 dual-frequency observations. About 77% of these observations were successfully correlated, and over 70% were used in the final IVS Analysis Reports of 2017 and 2018. Sessions correlated at the VLBA were also included when data analysis reports were providing relevant information on reasons for data loss. A total of 19 T2, R&D, OHG, AOV, and AUM sessions have not been correlated yet.

Table 1 Data sets used for the 2017–2018 network performance report.

Year	Sessions	Station days	Observations	Correlated	Used
2017	202	2,246 (2,126)	1,533,182	78%	71%
2018	174	1,763 (1,640)	1,001,798	75%	68%

Table 1 summarizes the data set used for the 2017–2018 network performance report. The data in parentheses represent the station days processed by the correlators. The table also includes the percentage of successfully correlated and used observations. The reported successfully correlated observations have a higher loss than the lost observing time in Figure 2 because lost observing time at a station affects more than one baseline. The used observations have an even greater loss because there may be a mismatch between S and X successfully correlated single band observations. In addition, the analysts may remove observations for other reasons. The difference between successfully correlated and actually used represents a significant loss by itself. We plan to investigate the cause of this loss. This is probably due primarily to mismatched S and X observations. Possible causes include variations in the impact of RFI and source structure.

Table 1 also shows the number of sessions examined for this report. All 2017 sessions and 90% of the 2018 sessions were correlated at the time of writing this report. The average number of stations per session is 11.1 in 2017 and 10.1 in 2018 compared to 10.7 in 2016. More than 420 stations days (18.7%) were lost in 2017 and 379 (21.5%) in 2018. The observing time loss for 2017–2018 has been affected by stations that did not observe and were not removed from the master schedule. This loss accounted for 243 station-days, or 6%. Prior to 2015, this loss was smaller. When removing these non-observed station-days, the 2015–2018 data loss is around 14%, more in line with previous years. All data presented in figures and tables are uncorrected.

In 2017–2018, the network lost over 20% of its data as shown in Figures 3 and 4. To better understand this global performance, the network has been analyzed by

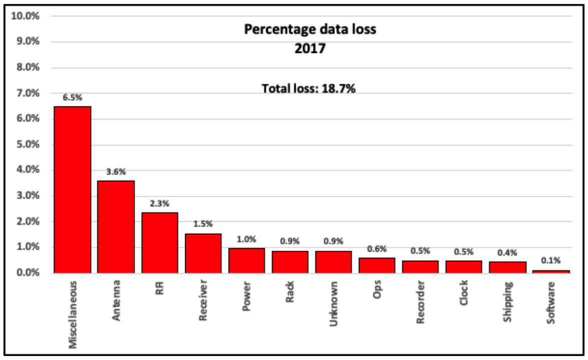


Fig. 3 Percentage of data loss for each sub-system in 2017.

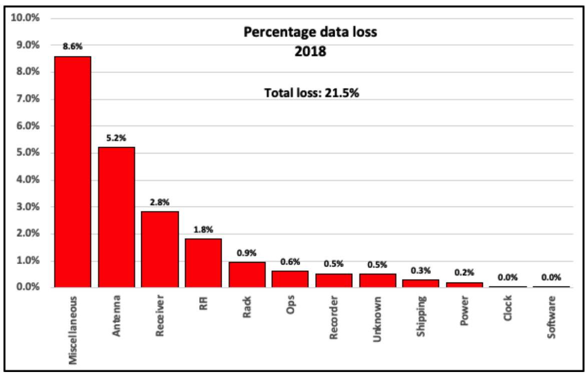


Fig. 4 Percentage of data loss for each sub-system in 2018.

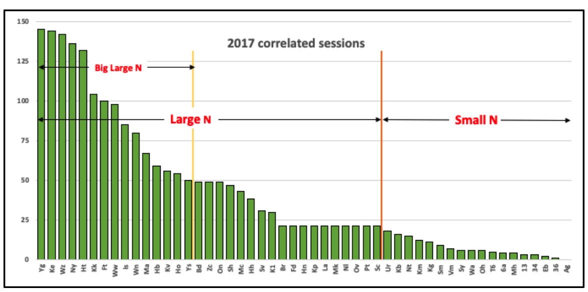


Fig. 5 Number of 24-hour sessions correlated in 2017.

Table 2 Group analysis for 2017.

Category	#stat	#days	Average	Median	>92%	<70%
Big Large N	16	1,568	15.4%	11.8%	7	2
Large N	33	2,068	15.5%	11.5%	13	4
Small N	17	133	41.8%	24.6%	1	12
Full network	50	2,201	18.7%	20.4%	14	16

groups based on the station usage as shown in Figures 5 and 6. Tables 2 and 3 provide information on the three groups: **Big Large N** (stations that were used in 51 or more sessions), **Large N** (stations that were used in 21

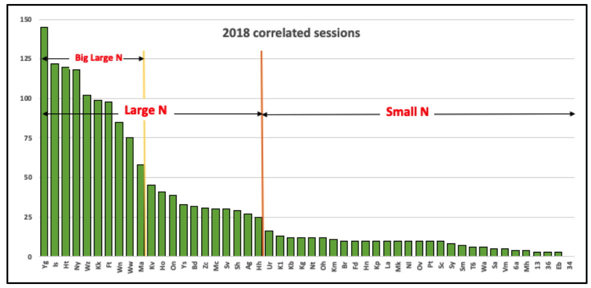


Fig. 6 Number of 24-hour sessions correlated in 2018.

Table 3 Group analysis for 2018.

Category	#stat	#days	Average	Median	>92%	<70%
Big Large N	11	1,167	17.4%	8.7%	3	2
Large N	22	1,529	20.0%	20.8%	4	6
Small N	28	242	30.9%	23.9%	6	12
Full network	50	1,771	21.5%	21.5%	10	18

or more sessions), and **Small N** (stations that were used in 20 or fewer sessions). The distinction between these groups was made on the assumption that results will be more meaningful for the stations with more sessions. The **Big Large N** group is a subset of **Large N** and is used to show the performance of the busiest IVS stations.

As expected, the 2017–2018 average observing time loss from the **Large N** group was much smaller than the average from the **Small N** group, 15% and 20% versus 42% and 31%. The **Large N** group accounts for more than 90% of the station days, so the **Large N** group is dominant in determining the overall performance. The last two columns of the group analysis tables indicate the number of stations that yield more than 92% and less than 70% of their data.

The higher number of stations in the 2017 **Large N** is due to CONT17 and CONTV17 involving 18 IVS Network stations and 10 VLBA stations. The stations in that group are more reliable, given that a good number of stations (seven in 2017 and four in 2018) had more than 92% of their recorded data make it through the correlators. Only a few stations in the 2017–2018 **Large N** groups collected less than 70% of the scheduled data. The statistics of the **Big Large N** group show very good results for IVS stations that participated in more than 50 sessions.

The 2017 **Small N** group has worse median loss than the 2018 **Small N** group. This is probably due to

Table 4 Percentages of data loss by sub-system. Percentages for 2010 and 2011 were not calculated.

Sub-System	2018	2017	2016	2015	2014	2013	2012	2009	2008	2007	2006	2005	2004	2003
Miscellaneous	8.6	6.5	3.3	4.7	4.2	1.5	0.8	3.3	1.9	0.9	2.4	1.2	1.0	0.9
Antenna	5.2	3.6	9.2	3.6	1.8	6.4	2.2	6.3	2.9	3.9	2.6	3.5	4.1	2.6
Receiver	2.8	1.5	0.6	1.8	1.7	1.2	1.4	4.0	2.1	1.7	2.8	3.5	2.3	3.6
RFI	1.8	2.3	2.3	1.6	1.6	1.0	1.5	1.3	2.2	1.2	1.6	0.9	0.6	1.3
Rack	0.9	0.9	0.6	2.3	1.4	3.2	2.7	1.4	1.3	1.3	2.2	0.7	0.9	0.7
Operations	0.6	0.6	0.5	1.1	0.5	0.4	0.2	0.3	0.3	0.0	0.3	0.7	0.8	0.5
Recorder	0.5	0.5	0.5	1.2	0.5	0.5	0.7	0.6	0.6	0.5	0.4	1.3	1.4	1.6
Unknown	0.5	0.9	1.0	1.1	0.2	0.9	1.7	3.1	2.7	1.7	0.5	0.5	1.3	1.8
Shipping	0.3	0.4	0.3	0.2	0.0	0.1	0.4	0.9	0.8	0.1	0.0	0.0	0.2	0.9
Power	0.2	0.9	0.4	0.2	0.0	0.3								
Clock	0.0	0.5	2.3	0.2	0.0	0.6	0.2	0.4	0.1	0.0	0.7	2.1	0.1	0.5
Software	0.0	0.1	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0

the VLBA stations that were moved to the 2017 **Large N** group due to the 15 CONTV17 sessions.

The losses were also analyzed by sub-system (category) as shown in Figures 3 and 4 for the 2017–2018 network. A summary of the percentage of losses by sub-system (category) for the entire network is presented in Table 4. This table includes results since 2003 sorted by decreasing loss in 2018.

The categories in Table 4 are rather broad and require some explanation, which is given below.

Antenna This category includes all antenna problems, including mis-pointing, antenna control computer failures, non-operation due to wind through 2013, and mechanical breakdowns of the antenna. It also includes scheduled antenna maintenance. Wind stows have been moved to Miscellaneous starting in 2014.

Clock This category includes situations in which correlation was impossible because the clock offset either was not provided or was wrong, leading to "no fringes". Maser problems and coherence problems that could be attributed to the Maser are also included in this category. Phase instabilities reported for Kokee are included in this category. DBBC clock errors are included in this category.

Miscellaneous This category includes problems that do not fit into other categories, mostly problems beyond the control of the stations, such as power (only prior to 2012), (non-wind) weather through 2013, wind stows (moved here from the Antenna category starting in 2014), cables, scheduling conflicts at the stations, and errors in the observing schedule provided by the Operation Centers. For 2006 and 2007, this category also includes errors due to tape operations at the stations that were forced to use tape because either they did not have a disk recording system or they did not have enough media. All tape operations have since ceased. This category is dominated by weather and scheduling conflict issues.

Operations This category includes all operational errors, such as DRUDG-ing the wrong schedule, starting late because of shift problems, operator (as opposed to equipment) problems changing recording media, and other problems.

Power This category includes data lost due to power failures at the sites. Prior to 2012, losses due to power failures were included in the Miscellaneous category.

Rack This category includes all failures that could be attributed to the rack (DAS), including the formatter and BBCs. There is some difficulty in distinguishing BBC and RFI problems in the correlator reports, so some losses are probably mis-assigned between the Rack category and the RFI category.

Receiver This category includes all problems related to the receiver, including outright failure, loss of sensitivity because the cryogenics failed, design problems that impact the sensitivity, LO failure, and loss of coherence that was due to LO problems. In addition, for lack of a more clearly accurate choice, loss of sensitivity due to upper X-band Tsys and roll-off problems are assigned to this category.

Recorder This category includes problems associated with data recording systems. Starting with 2006, no problems associated with tape operations are included in this category.

Table 5 Stations most affected by RFI in 2018.

Station	Data loss	Most affected channels (frequencies given in MHz)
Sejong	18.0%	SR4U (2295 MHz), SR5U (2345 MHz), SR6U (2365 MHz)
Kunming	13.9%	SR5U (2345 MHz), SR6U (2365 MHz), SR1U (2225 MHz)
Zelenchukskaya	13.0%	SR2U (2245 MHz), SR3U(2265 MHz), SR4U(2295 MHz)
Koganei11	12.5%	No fringes in some sessions due to weak S band signal affected by RFI
Yebes 40m	8.7%	SR2U (2245 MHz), SR4U (2295 MHz)
Medicina	6.0%	SR6U (2365 MHz)
Hobart26	5.1%	SR5U (2272 MHz) SR6U (2288 MHz) – AOV sessions
		SR5U (2281 MHz) SR6U (2297 MHz) – CRDS sessions
		SR5U (2345 MHz) SR6U (2365 MHz) – CRF, RD sessions
Matera	4.1%	SR6U (2365 MHz)
Wark12m	3.8%	SR5U (2345 MHz), SR6U (2365 MHz) – Intermittent
Fortaleza	3.1%	SR4U (2295 MHz) – Mostly in September–December

Channels: SR1U = band|polarization|BBC#|sideband

RFI This category includes all losses directly attributable to interference, including all cases of amplitude variations in individual channels, particularly at S-band. There is some difficulty in distinguishing BBC and RFI problems in the correlator reports, so some losses are probably mis-assigned between the Rack category and the RFI category.

Shipping This category includes all observing time lost because the media were lost in shipping or held up in customs or because problems with electronic transfer prevented the data from being correlated with the rest of the session's data.

Software This category includes all instances of software problems causing observing time to be lost. This includes crashes of the Field System, crashes of the local station software, and errors in files generated by DRUDG.

Unknown This category is a special category for cases where the correlator did not state the cause of the loss and it was not possible to determine the cause with a reasonable amount of effort.

An assessment of each station's performance is not provided in this report. While individual station information was presented in some previous years, this practice seemed to be counter-productive. Although many caveats were provided to discourage people from assigning too much significance to the results, there was feedback that suggested that the results were being over-interpreted. Additionally, some stations reported that their funding could be placed in jeopardy if their performance appeared bad, even if it was for reasons beyond their control. Last and least, there seemed to be some interest in attempting to "game" the analysis methods to apparently improve individual station results. Consequently, only summary results have been presented here. Detailed results are presented to the IVS Directing Board. Each station can receive its own results by contacting the Network Coordinator (Ed.Himwich@nasa.gov).

Some detailed comments on the most significant issues for this year's data loss are given below.

- The two largest sources of data loss for 2017–2018 are Miscellaneous and Antenna. The high values of Miscellaneous are highly affected by broadband testing at some stations and bad weather. Many hours were lost by antennas being stowed due to high winds, snow, hurricanes, thunderstorms, or typhoons. The Antenna sub-system loss is mainly due to repairs at antennas that were delayed by months waiting for replacement parts.
- The Receiver sub-system is mainly due to few stations observing a total of 136 station-days with warm receivers while waiting for replacement parts.
- Operator performance is very good with less than 0.6% of data loss.
- RFI due to commercial systems continues to be an important factor of data loss mostly in S-band given that correlators dropped over 2.1% of the recorded channels. RFI is mainly evaluated from dropped channels at correlation, but there are some difficulties in distinguishing BBC and RFI problems. Some stations were contacted to confirm RFI presence at their site. See Table 5 for a list of stations that were most affected by RFI in 2018.

3 Summary

Estimating station data losses could be subjective and some times approximative, but this is a useful tool for evaluating the health of the IVS network over the years. A station yielding over 80% of data is considered very good, and the statistics of the Large N group show that stations have been doing well in 2017–2018.

IVS Technology Coordinator Report

Gino Tuccari

Abstract Here the principal activities involving the Technical Coordinator are reported. The main points are related to the signal chain, because in the field there are different methods and approaches to produce the adopted VGOS data, and a harmonization is to be taken into proper account. This is useful for guaranteeing a good degree of compatibility. Advanced automatic or remote controlled observation and correlation could involve a large amount of effort in the future. It will be useful to harmonize the procedures to insert new equipment or existing instrumentation belonging to the signal chain when a new feature is introduced. This role could be covered by the VTC Working Group.

1 Introduction

This report focuses on three items:

1. Signal Chain: current status and evolution.
2. VGOS Tables.
3. Communication with EVN.

The main activity during the 2017–2018 period also included giving advice and assistance to stations, as was reported to the IVS Directing Board.

INAF - Instituto di Radioastronomia, Bologna, Italy
Max Planck Institut für Radioastronomie, Bonn, Germany

IVS Technology Coordinator

IVS 2017+2018 Biennial Report

2 Signal Chain: Current Status and Evolution

In the IVS network there is a variety of different solutions consolidated or under investigation. In previous years, on other occasions, definitions for a VGOS signal chain have been discussed in some detail, and this is reported in different previous IVS reports. Under these indications, developments were proposed and experimentally evaluated by the different Development Centers. As a result, there are a number of different solutions which need to be harmonized, along with considering new possibilities and technology solutions which in the meantime have appeared.

There are some elements which can be mentioned as basic points and to summarize:

- The actual frequency broad band, which is determined mainly by the local RFI. The 'official' 2.2–14 GHz VGOS band could actually present some restrictions or limitations to be actually covered as a site dependent element. For a VGOS network, any limitation at a site involves the entire network. In this respect more stations are experiencing increasing problems with the RFI present below 3 GHz. This is due mainly to the fact that no technology is used to limit such a harmful condition. A useful experience could come from the BRAND EVN project, which is covering a wider portion of the frequency spectrum.
- The number of antennas per station and the type of antenna in terms of the speed of the mechanical structure. A number of sites are planning or have available more than one VGOS antenna, which offers a great level of flexibility. Antenna types and

speeds are different, going from the slow legacy ones to the fastest fully VGOS compliant.
- The feed type having linear polarization output, even if the direct generated circular polarization at the feed stage is under investigation. A number of solutions are under study to consider the circular polarization reconstructed at the digital level at the station or at the correlator. The BRAND EVN project is again offering two types of solutions which could find an application for VGOS.
- LNA projects and commercial products. These are available from different sources with good performance. These components need to be further considered.
- Digital process. Mainly two backend systems are in the field, RDBE and DBBC in their different generations. Presently, backend systems developed by the IVS groups can be mainly distinguished as two types:

  1. The broadband input 2.2–14 GHz is flexibly tuned in pieces of 1 GHz afterwards sampled; then a number of 32 MHz channels with a 2-bit resampling are extracted for a maximum data rate of 16 Gbps, but the current common sustained data rate is 8 Gbps. Data representation can be either real or complex.
  2. The input band is fully sampled in pieces of prefiltered 4 GHz chunks, then sampled and available in digital format, from which narrow band channels (ex. 64, 32 MHz) are extracted. A full data rate of 128 Gbps for the entire eight bands of 4 GHz is also possible.

- Recording. For recording we can again distinguish different types:

  1. MK6, which allows a maximum of 16 Gbps per unit, making use of removable disk-packs which can be physically transferred from a station to a correlator and vice-versa.
  2. Flexbuffer-like types, developed or under development, which can permit an even larger sustained recording data rate (up to 32 Gbps), with a fixed pool of disks internally connected. Data transfer to the correlators is then performed asynchronously to the observations.

  Both types of recorders permit the real time transfer of observed data when the network connection between stations and correlator permits.
- Correlation process. The correlation process is currently software-based and performed with different software versions. The standard approach is to move the entire set of data from all the stations involved in an experiment to the correlator appointed for processing it.

Presently, we can envisage directions from which an evolution could come, bringing benefit to the VGOS network. Here are the main ones I would like to report:

- Direct full VGOS band sampling
  This method performed in multi-bit representation could be a quantum leap in the signal chain. A very advanced implementation comes from the BRAND EVN project where a 16 GHz full band direct 8-bit sampling has been implemented. This mode opens the possibility of having a simplified approach to broadband VGOS experimental observations, which could greatly simplify the signal chain with all the benefits broadband (1 GHz, 2 GHz, etc.) channels could offer.
- System interoperability
  As reported earlier, different systems developed and available in different stations are a reality in the VGOS scenario. Compatibility between those systems is an element involving not only each system in its individual structure, but also the capability of the entire system to accommodate different solutions offered to the community. In this respect, a normalization process has to deal with such capability under the supervision of the VTC Working Group. Such a group is going to be enlarged, including all the parts willing to actively cooperate for VGOS progress, in a fully shared and coordinated fashion.
- Broadband coverage / RFI status
  As mentioned earlier, the actual use of the entire band is problematic due to the presence of RFI, varying at different sites. On the other hand, for compatibility with the legacy S/X stations, observing the lower part of the band would be important. An effort is then to be dedicated to RFI handling and mitigation, as opposed to the trend to simply cut this portion of the band and move the lower observation edge of the band to higher frequencies. An important contribution could come from ad-hoc

HTS (High Temperature Superconducting) filters placed in front of the LNAs in order to limit the worst case unwanted signals able to saturate such an amplification stage.
- 24-hr/day continuous observation sessions must require a reduced contribution from the operators, so the efforts to introduce automatic and remote controlled observation sessions cover a fundamental aspect.
- The data rate as was planned since the initial phases of the VGOS project has to be increased to move the network at the planned goals. A first limitation looks to be the recording capability, with different others following immediately after, such as data storage capability, transfer data speed, and correlation capability.
- A distributed correlation is considered an important task to be explored, in perspective, to have an always-increasing amount of data to be correlated. Two test runs were organized involving a number of small correlators. Recently a new test run was performed, inviting all the correlators interested to join the experiment under the coordination of Laura La Porta. Useful evaluation and encouraging results available at the time of the General Meeting were reported. Additional small and standard correlators are expected to join additional test runs.

3 VGOS Tables

The VGOS tables indicating the detailed information about any relevant equipment in the existing and under construction VGOS stations are relevant for promoting compatibility in the IVS network and are guides for newcomer stations. The amount of information is relevant, and the form in the initial phase used, an Excel spreadsheet, was proved to be inadequate for a fast consultation and, in particular, for an easy and useful comparison. Dedicated Technology Coordinator Web pages have been suggested to place and maintain such data with the information provided by the single station personnel, using a write access and password protection.

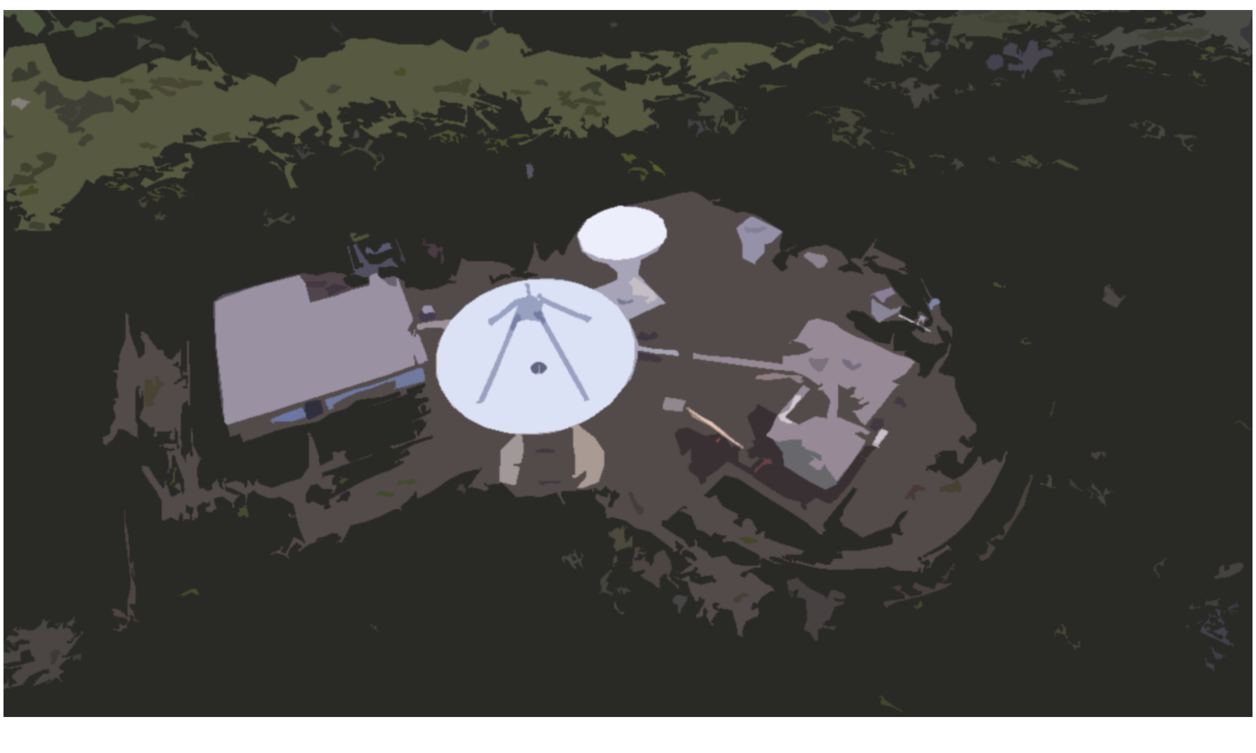
An important functionality for such a database consultation would be the possibility of implementing an advanced search capability in order to be able to select a number of parameters and stations to view; then it will be easy to be able to perform comparisons in those elements of interest under the search. Such a functionality is pretty complex in principle to be performed under a Web site belonging to a research institution, for different reasons, e.g. where they have the most rigorous Web site security. Therefore, a dedicated server was envisaged to be appropriate, with links indicated in relevant Web pages where this information can be easily found.

Different solutions were evaluated, and a professional Web server was finally selected to support such a functionality. Then in order to accommodate such information, the Web sites 'www.ivs-coordinator.info' and 'www.ivs-coordinator.cloud' were registered, and some databases began to be uploaded.

4 Communication with EVN

It was formally stated to maintain regular communication and contacts on technical issues between the IVS and EVN networks as defined in the agreed document which reports: "The EVN and IVS explicitly wishes to engender and stimulate convergent technological developments and innovative projects, and to aim for compatible or shared operational procedures between them. Structural contacts at a technical level will be maintained by the chair of the EVN Technical Operations Group (TOG) and the IVS Technology Coordinator." In this respect the IVS Technology Coordinator and the EVN TOG chair have begun periodic contact with the aim of sharing the relevant information of common interest for the best coordination of the technical efforts within the two VLBI networks.

NETWORK STATIONS



AGGO Coming Back to Operation

Argentinean-German Geodetic Observatory (AGGO) Report

Hayo Hase [1], Federico Salguero [3], José Vera [3], Augusto Cassino [3], Alfredo Pasquaré [3], Claudio Brunini [2]

Abstract The Argentinean-German Geodetic Observatory (AGGO) has been brought back to an operational status. Several VLBI test sessions were performed successfully.

1 General Information

The Argentinean-German Geodetic Observatory (AGGO) is a joint effort of the Argentinean National Scientific and Technical Research Council (CONICET) and the German Federal Agency of Cartography and Geodesy (BKG) to support the Global Geodetic Observing System (GGOS) by contributing a geodetic fundamental station located in South America [1].

The selected site is a plot of land owned by the science department of the provincial government of the Province of Buenos Aires about 25 km from the center of its capital town of La Plata (and about 50 km from the city of Buenos Aires); it is adjacent to the natural park Pereyra Iraola and next to the Argentinean Institute of Radio Astronomy (IAR).

1. Bundesamt für Kartographie und Geodäsie (BKG)
2. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Fac. Cs. Astronómicas y Geofísicas Universidad Nacional de La Plata (UNLP)
3. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)

AGGO Network Station

IVS 2017+2018 Biennial Report

Table 1 Useful data about the VLBI reference point at AGGO.

Parameter	Value
DOMES No.	41596S002
CDP No.	7641 (axis intersection)
4-char code	AGGV
IVS 2-char id	Ag
approx. longitude	W 58.51398°
approx. latitude	S 34.8739°
approx. height	35.8 m

Fig. 1 The 6-m primary focus offset radio telescope for VLBI observations of AGGO.

2 Activities During 2017–2018

VLBI became operational when the Dewar of the receiver returned from on overhaul at Yebes Observatory. The displacer of the coldhead needed to be exchanged after about 20 years of use. Several receiver maintenance tasks were carried out: RF window replacement, confection and replacement of RF semi-rigid cables at the IF-plate associated with gain chain measurements in S- and X-band in order to corroborate the performance of the amplifiers (including new dewar First Stage amplifiers), replacement of the X-band post-amplifier, replacement of an S-band filter, testing and new connectors for noise diodes.

With a working receiver a number of pointing tests were made in order to verify the Northern direction of the encoder and introducing the corresponding offset to the antenna control unit. A radiometric horizon mask was created based on own procedures for the Field System and a self-made Python program to visualize the result in a plot (Figure 2).

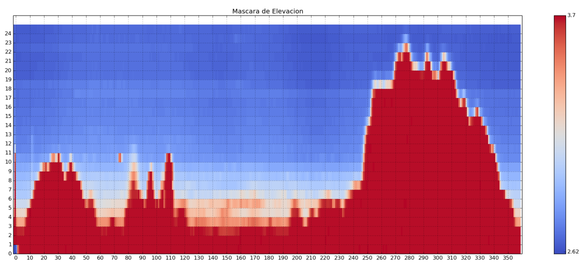


Fig. 2 The radiometric horizon mask at AGGO (azimuth [0°–360°] vs. elevation [0°–24°]; red is radiation, blue is cold sky). The detected radiation is basically due to vegetation. The graph suggests to cut back some eucalyptus trees in order to improve the horizon mask in the North-Northwest direction.

Improvements were made with the monitoring of cryogenic temperatures inside the Dewar by signal conditioning to the Beckhoff I/O modules with modbus connection to the Field System.

A complete overhaul of the Peltier cooling system of the receiver box was carried out. It included: removal of the Peltier units, test and replacement of not working Peltier cells modules, replacement of coolers for forced-air ventilation, power source maintenance and complete some modifications inside the Peltier controller box. The electrical circuit was changed and a new software for PLC control regarding the local ambient conditions was installed. As a result of this, we achieved temperatures inside the box not exceeding 25°C on hot summer days where the ambient temperatures exceeded 35°C. However, box temperatures below 22°C are necessary to keep the ambient temperature cycles independent of the receiver's system temperature.

The observatory was connected to optical fiber supporting technically up to 1-Gbps bandwidth. AGGO is an "e-transfer only" station. During 2018 the implementation of e-VLBI hardware and software took place. This task included: Fiber network cabling, modification of the local area network, installation of new servers, transfer-rate and performance tests covering different e-VLBI protocols, and finally the e-transfer of real VLBI sessions.

Some improvements were applied to five BBCs: The oscillator circuit was modified in order to cope with instabilities related to the temperature variations inside the BBC.

AGGO received two 400-MHz upconverters replacing the VLBA4 upconverter (running at 479.9 MHz). These modules require 100 MHz as reference frequency. Therefore it was necessary to install a 100-MHz reference cable between the H-maser and the upconverter. It is important that both reference frequencies, 5 MHz and 100 MHz, are supplied from the same H-maser.

On January 15, 2018, the "first light" VLBI operation was successfully carried out between AGGO and Wettzell (WB015).

For the commissioning the following test runs were performed with Wettzell and partly with O'Higgins: WB015, WB072, WB087, WB135, WB207, WB221, WB228, WB235, WB242, WB249, WB256, WB263, WB264, WB270, WB277, WB284, WB291, WB298, WB312, WB319, WB333, and WB354.

In addition, a few IVS test sessions were observed (limited by the lack of operators): R1849, R1871, R1877, and T2126.

In order to increase the operator staff, negotiations between CONICET and the Argentinean Minstery of Defense have started. Once an agreement is reached, operators will be made available, must be trained as operators, and AGGO will become part of the IVS observing programs on a regular base.

3 Current Status

The status reached by the end of 2018 is such that the major instruments of the observatory are working. Only the overhaul and modernization process of the SLR component is ongoing and will be finished during 2019.

Fig. 3 The VLBA5 and Mk5B+ equipment used for VLBI observations of AGGO inside the AGGO-2 container.

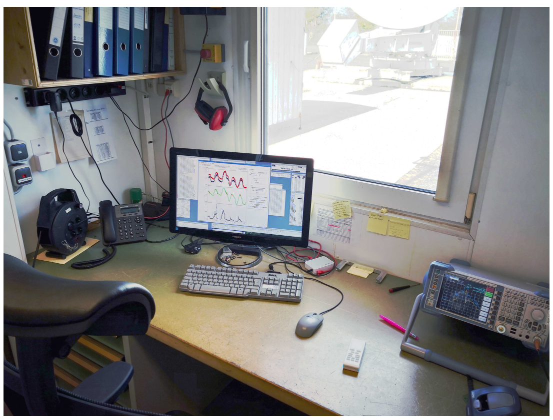


Fig. 4 Operator's desk with view on Field System screen and radio telescope.

Fig. 5 Servo cabinet with antenna control unit inside the AGGO-2 VLBI operation container.

Fig. 6 VLBI reference H-maser EFOS-24 and EFOS-20 at the time & frequency laboratory of AGGO.

AGGO operates its:

- time and frequency laboratory with two H-masers, three Cs normals, one GNSS receiver and one NTP-server
- VLBI radio telescope
- GNSS receiver (IGS)
- absolute gravity meter and super conducting gravity meter (IGFS)
- hydrological sensors
- meteorological sensors

Internet provision is available via a 1-Gbps optical fiber.

The power supply is still characterized by frequent interruptions due to the lack of vegetation pruning along the route of the line, adverse weather conditions, and the lack of maintenance of the power line by the supplier.

The construction of a new office building for the staff of AGGO has been initiated. Once finished, space of the operation building will be released to move the operation from the containers to the operation building.

The current staff situation is given in Table 2.

4 Future Plans

With the arrival of operators from the Ministery of Defense a training program will be carried out by the AGGO staff in order to familiarize the operators with VLBI operation and later with SLR operation.

Table 2 AGGO staff as of 2018.

Name	Background	Tasks	Email
Claudio Brunini	astronomer	scientific director	cbrunini@aggo-conicet.gob.ar
Hayo Hase	geodesist	head of operations	hayo.hase@bkg.bund.de
Augusto Cassino	electrical engineer	head of infrastructure and construction	acassino@aggo-conicet.gob.ar
Romina Galvan	geophysicist	local survey, scientist	rgalvan@aggo-conicet.gob.ar
Federico Salguero	electronic engineer	VLBI hardware	fsalguero@aggo-conicet.gob.ar
José Vera	electronic engnieer	VLBI software and system administrator	jvera@aggo-conicet.gob.ar
Alfredo Pasquaré	electronic engineer	time and frequency lab, GNSS	apasquare@aggo-conicet.gob.ar
Michael Häfner	physicist, engineer	SLR system	michael.haefner@bkg.bund.de
Florencia Toledo	optical engineer	SLR hardware	ftoledo@aggo-conicet.gob.ar
Federico Bareilles	electronic engineer	SLR software	fbareilles@aggo-conicet.gob.ar
Pablo Antico	meteorologist, scientist	climate modelling	pantico@aggo-conicet.gob.ar
Romina Ronchi	administrator	administration	rronchi@aggo-conicet.gob.ar

The plan to move the operations from the containers to the operations building will be coincide with putting a new VLBI backend into operation; a DBBC and a Flexbuff system will replace the VLBA5 and Mk5B equipment.

Later on the servo cabinet and the antenna control unit will follow. For this operation, a renewal of the cables between receiver and control room are considered.

An uninterruptable power supply for the entire observatory is requested and is foreseen to be realized. With an enhanced reliability of the power supply, a return to full operations is envisaged.

Concerning the mid-term future, a new VGOS radio telescope is considered to be important.

References

1. H. Hase et al., “Moving from TIGO to AGGO”, In K. D. Baver, D. Behrend, and K. Armstrong, editors, International VLBI Service for Geodesy and Astrometry 2015+2016 Biannual Report, NASA/TP-2017-219021, p. 43-47, 2017.

Effelsberg Radio Observatory 2017–2018 Biennial Report

Uwe Bach, Alex Kraus

Abstract The 100-m radio telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) is one of the largest fully steerable single-dish radio telescopes in the world and a unique high-frequency radio telescope in Europe. The telescope can be used to observe radio emissions from celestial objects in a wavelength range from 90 cm (300 MHz) down to 3.5 mm (90 GHz).

1 General Information

The Effelsberg radio telescope was inaugurated in 1971 and was (for almost 30 years) the largest fully steerable single-dish radio telescope in the world. It is situated in a protected valley near Bad Münstereifel (about 40 km southwest of Bonn) and operated by the Max-Planck-Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck-Society (MPG). To this day, it is the largest radio telescope in Europe and is mostly used for astronomical observations.

This extremely versatile and flexible instrument can be used to observe radio emissions from celestial objects in a wavelength range from about 1 m (corresponding to a frequency of 300 MHz) down to 3.5 mm (90 GHz). The combination of the high surface accuracy of the reflector (the mean deviation from the ideal parabolic form is ∼0.5 mm rms) and the construction principle of ‘homologous distortion’ (i.e., the reflector in any tilted position has a parabolic shape with a well-defined, but shifted, focal point) enables very sensitive observations to be made at high frequencies (i.e., $\nu > 10$ GHz).

The wide variety of observations with the 100-m radio telescope is made possible by the good angular resolution, the high sensitivity, and a large number of receivers which are located either in the primary or in the secondary focus. Together with a number of distinct backends dedicated to different observing modes, this provides excellent observing conditions for spectroscopic observations (atomic and molecular transitions in a wide frequency range), high time-resolution (pulsar observations), mapping of extended areas of the sky, and participation in a number of interferometric networks (e.g., IVS, mm-VLBI, EVN, and Global VLBI).

Table 1 Telescope properties.

Name	Effelsberg
Coordinates	6:53:01.0 E,+50:31:29.4 N
Mount	azimuthal
Telescope type	Gregorian (receivers in primary and secondary focus)
Diameter of main reflector	100 m
Focal length of prime focus	30 m
Focal length of secondary focus	387.7 m
Surface accuracy	0.55 mm rms
Slew rates	Azi: 25 deg/min, Elv: 16 deg/min
Receivers for Geodetic observations	3.6 cm/13 cm secondary-focus (coaxial)
T_{sys} (3.6 cm/13 cm)	25 K, 200 K
Sensitivity (3.6 cm/13 cm)	1.4 K/Jy, 0.5 K/Jy
HPBW (3.6 cm/13 cm)	81 arcsec, 350 arcsec
Tracking accuracy	∼ 2 arcsec

Max-Planck-Institut für Radioastronomie, Bonn, Germany

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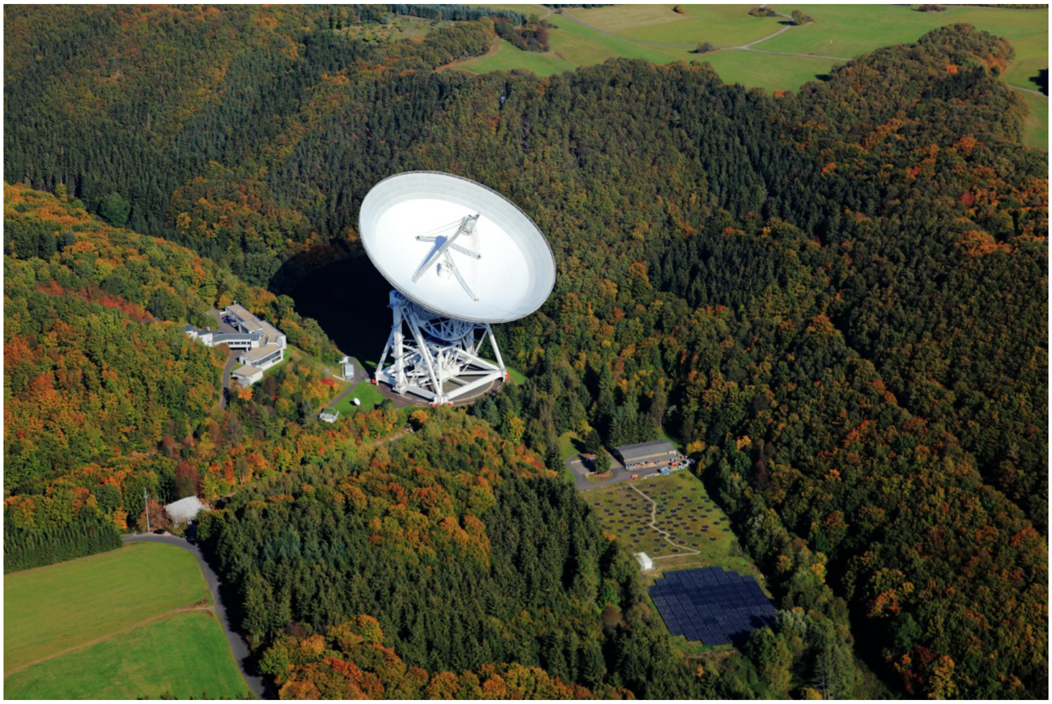

Fig. 1 Aerial image of the Effelsberg radio observatory. Shown are the 100-m Effelsberg antenna and the institute's building (left of the antenna). Effelsberg hosts also a station of the European Low Frequency Array (LOFAR), seen in the lower part of the picture.

2 Staff

The staff at Effelsberg consists of about 40 people, including telescope operators; technical personnel for receivers, electronics, and mechanics; scientists; and administrative personnel. Involved in IVS activities are, beside the telescope operators, **Dr. Alexander Kraus** as station manager and scheduler for the 100-m Effelsberg telescope, and **Dr. Uwe Bach** as support scientist and VLBI friend. Two of the telescope operators, **Marcus Keseberg** and **Peter Vogt**, are also involved in the preparation of schedules and disk management and shipping.

3 Activities during the Past Years

Effelsberg has participated regularly in the EUROPE IVS sessions since 1991. In 2017 and 2018, the experiments T2116, T2124, T2127, and T2128 were observed. About 30% of the observing time of the Effelsberg antenna is used for VLBI observations. Most of them are astronomical observations for the European VLBI Network (EVN), High Sensitivity Array (HSA), Global MM VLBI Array (GMVA) or other global networks, but also geodetic VLBI observations within the IVS are performed. Since 2011, the Russian Astro Space Center has been operating a 10-m space radio antenna on board the satellite SPEKTR-R (RadioAstron) to perform VLBI observations. Effelsberg was highly involved in the ground-based support of this mission for the last seven years, but the mission has now come to an end, as the satellite is no longer operational.

In 2017, two longer periods of downtime were caused by maintenance of the azimuth rail and roll bearings of the azimuth wheels. The maintenance of the azimuth rail was planned, as it suffered from a crack in the rail which goes back to 2009. A provisional repair worked well, but the foundation suffered over the years and proper welding became necessary. The azimuth track was repaired from April 5 – May 11, 2017 and caused operational restrictions. Only a small number of observations could be performed in a limited azimuth range. After May 11, the observatory started with normal operation again. Two of the roll bearings of the azimuth wheels broke in July, and more was unexpected in September 2017. Both times an external company was needed to help with the repair. Because the tool that is provided by the company was available, the repairs could be performed within a few days and did not cause much down time. The Effelsberg workshop has now bought its own tool for future repairs, so that repairs can be done independently and at any time. The bearings are about 30 years old and in total we have 64 (two for each of the 32 wheels). The bearings are checked regularly for degradation now.

In March 2018 a new Q-band receiver was installed in the secondary focus. It is a two-horn system and provides a tunable frequency range of 33 to 50 GHz with an IF bandwidth of 4 GHz. Commissioning of the receiver is finished and the system performance is very good. It provides an SEFD two times better than the old receiver ranging from about 100 Jy at 33 GHz to 150 Jy at 50 GHz. In Autumn 2018 a fringe test was organized between Effelsberg, KVN, Tian Ma (Shanghai), and Yebes to test the new Q-band receivers at Effelsberg and Tian Ma. Good fringes were found between all stations and proved that the new receivers work well. The new Q-band receiver at Effelsberg is now officially available for science observations.

4 Current Status

Effelsberg uses the DBBC2, Fila10G, and a Mark 6 recorder for all EVN, global, RadioAstron, and geodetic VLBI observations. The Mark 6 recorders provide 390 TB of storage capacity and most of the recorded data is e-transferred to the correlators in Bonn, at the ASC in Moscow, and JIVE. In addition there are two NRAO RDBEs and a Mark 5C recorder that are used for observations with the VLBA, HSA, and GMVA. Mark 5 diskpacks to Socorro are still being shipped. Both VLBI backends and their recorders are controlled by the Field System (current release FS-9.13.1). The observatory is connected via a 10 GE optical fiber to the e-VLBI network and can do real time e-VLBI observations (performed about monthly within the EVN) and e-transfers.

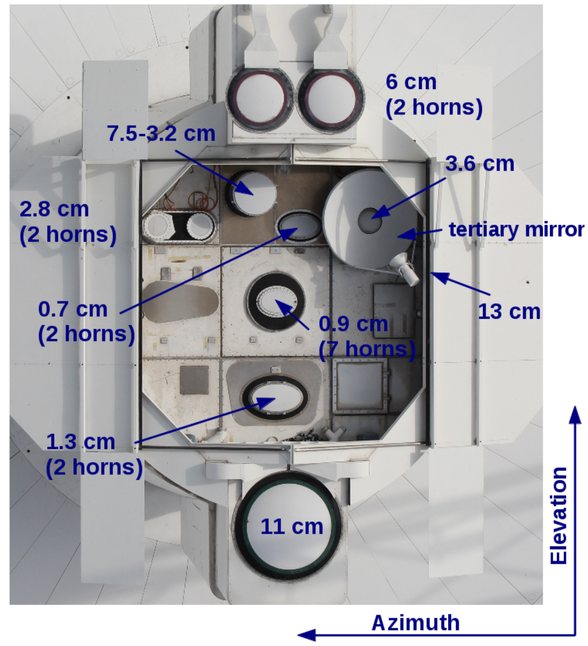

Fig. 2 Picture of the secondary focus cabin with several astronomical receivers, e.g. the new Q-band with two horns and the geodetic SX system with the 3.6-cm horn and the tertiary mirror for the 13-cm horn.

5 Future Plans

The VLBA is planning an upgrade to Mark 6 recorders in 2019 to allow 4-Gbps recordings and therefore also Effelsberg—as an HSA station—will change the recording of the RDBE data from Mark 5C to Mark 6 during the next month as well. Because there are two Mark 6 recorders, switching between the use of the Mark 6 as a recorder for disk module shipment and the use as a Flexbuff should not be a problem.

Effelsberg has bought a new maser from T4 Science. The new maser is currently commissioned and monitored against the old maser. Once the new housing and infrastructure to distribute the timing signals within the institute are being finished, the new maser will become the standard time and frequency reference for Effelsberg. The new maser was necessary, because the previous (much older) backup maser broke down in 2017.

Fortaleza Station Report for 2017 and 2018

Adeildo Sombra da Silva [1], A. Macilio Pereira de Lucena [2], Jean-Pierre Raulin [1]

Abstract This is a brief report about the activities carried out at the Fortaleza geodetic VLBI station (ROEN: Rádio Observatório Espacial do Nordeste), located in Eusébio, CE, Brazil, during the period from January 2017 until December 2018. The total observed experiments consisted of 192 VLBI sessions, including the CONT17 campaign and continuous GPS monitoring recordings. About 95% of VLBI recorded data was transmitted through a high-speed network.

1 General Information

The Rádio Observatório Espacial do Nordeste, ROEN, located at INPE facilities in Eusébio, nearly 30 km east of Fortaleza, Ceará State, Brazil, began operations in 1993. Geodetic VLBI and GPS observations are carried out regularly as contributions to international programs and networks. ROEN is part of the Brazilian space geodesy program, which was initially conducted by CRAAE (a consortium of the Brazilian institutions Mackenzie, INPE, USP, and UNICAMP) in the early 1990s. The program began with antenna and instrumental facilities erected, and with activities sponsored by the U.S. agency NOAA and the Brazilian Ministry of Science and Technology's FINEP agency.

ROEN is currently coordinated by CRAAM, Center of Radio Astronomy and Astrophysics, Engineering School, Mackenzie Presbyterian University, São Paulo, in agreement with the National Institute for Space Research (INPE). The activities are currently carried out under an Agreement of Cooperation which was signed between NASA—representing research interests of NOAA and USNO—and the Brazilian Space Agency (AEB) and which was extended until 2021. Under the auspices of the NASA–AEB Agreement, a contract was signed between NASA and CRAAM (Mackenzie Presbyterian Institute and University) to partially support the activities at ROEN. In 2014, the contract was renewed for five more years.

The counterpart of the operational costs, staff, and support of infrastructure are provided by INPE and by Mackenzie.

Fig. 1 14.2-m radio telescope.

2 Main Instruments

The largest instrument at ROEN is the 14.2-m radio telescope on an alt-azimuth positioner. It is operated at

1. Universidade Presbiteriana Mackenzie, CRAAM and INPE, Rádio Observatório Espacial do Nordeste, ROEN
2. Instituto Nacional de Pesquisas Espaciais, INPE

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S- and X-bands using cryogenic radiometers. The system is controlled by the Field System, Version 9.11.19. Observations are recorded with a Mark 5A system and transmitted via high-speed network to the correlators in the U.S. (WACO and Haystack), to Bonn in Germany, or to SHAO in China at rates about 220 Mbps.

The 1-Gbps link was accomplished in 2007. It is integrated into and sponsored by the Brazilian Research Network (RNP).

One Sigma-Tau hydrogen maser clock standard is operated at ROEN. GPS monitoring is performed within a cooperative program with NOAA (USA). There is a Leica System 1200 installed at the station that operates continuously. The collected data are provided to the NOAA/IGS center and to the Brazilian IBGE center. ROEN has all basic infrastructures for mechanical, electrical, and electronic maintenance of the facilities.

3 Staff

The Brazilian space geodesy program was coordinated by Dr. Pierre Kaufmann, who was Brazil's AEB representative in the NASA–AEB Agreement. Unfortunately Dr. Kaufmann passed away in February 2018. Dr. Jean-Pierre Raulin is the current coordinator of the geodesy program.

The coordination receives support from the São Paulo office at CRAAM/Instituto and Universidade Presbiteriana Mackenzie, with administrative support from Valdomiro M. S. Pereira and Lucíola Russi. The Fortaleza Station facilities and geodetic VLBI and GPS operations are managed on site by Dr. Antonio Macilio Pereira de Lucena (CRAAE/INPE), assisted by Eng. Adeildo Sombra da Silva (CRAAE/Mackenzie), and the technicians Emerson Costa (CRAAE/Mackenzie), Kelvin de Oliveria (CRAAE/Mackenzie), and Francisco Renato Holanda de Abreu (CRAAE/Mackenzie).

4 Current Status and Activities

4.1 VLBI Observations

In 2017 and 2018, Fortaleza participated in geodetic VLBI sessions as described in Table 1.

Table 1 2017 and 2018 session participation.

Session type	Number of sessions
IVS-R1	69
IVS-R4	84
IVS-T2	3
R&D	9
CRF	5
OHIG	10

4.2 CONT17 Campaign

In 2017, Fortaleza participated in the CONT17 campaign recording 12 days. Although a mechanical problem in the antenna occurred during the campaign, it was resumed after a complete evaluation of the antenna.

4.3 Operational and Maintenance Activities

The summary of activities performed in the period is listed below:

1. Repair and maintenance of the following equipments: cryogenic system, Mark 4 acquisition system, Mark 5A recorder, antenna mechanical and electrical systems, angle encoders system, receiver telemetry, man lift platform and thermoelectric receiver temperature control system.
2. Installation of a new Mark 5 unit that is being used exclusively for data transfers.
3. Evaluation of the current status of the main bearing through mechanical measurements and grease chemical analysis.
4. Installation of new grease lines circuit for main bearing lubrication.
5. Repair of electrical motors and gear boxes of antenna drives.
6. Operation and maintenance of geodetic GPS (NOAA within the scope of NASA contract).
7. Operation and maintenance of power supply equipment at the observatory (main and diesel driven standby).
8. Transferring of recorded data through high-speed network.

4.4 GPS Operations

The IGS network GPS receiver operated regularly at all times during 2017 and 2018. Data were collected and uploaded to IGS/NOAA.

5 In Memoriam

These few lines are a special homage to the memory of Prof. Pierre Kaufmann, a founder of the Brazilian space geodesy program, who went through all possible journeys and fights to make all this real.

6 Future Plans

Discussions are under way with Brazilian as well as international partners to raise funds for a new, VGOS-compatible system to be erected at the Fortaleza VLBI station facilities.

Goddard Geophysical and Astronomical Observatory

Chris Szwec, Katie Pazamickas

Abstract This report summarizes the technical parameters of the Very Long Baseline Interferometry (VLBI) systems at the Goddard Geophysical and Astronomical Observatory (GGAO) and provides an overview of the activities that occurred in 2017–2018, the outlook for 2019, and lists the outstanding tasks to improve the performance.

1 Location

The Goddard Geophysical and Astronomical Observatory (GGAO) consists of a 12-meter radio telescope for VGOS development, a 1-meter reference antenna for microwave holography development, an SLR site that includes MOBLAS-7, the SGSLR development system, a 48″ telescope for developmental two-color Satellite Laser Ranging, a GPS timing and development lab, a DORIS system, meteorological sensors, and a hydrogen maser. The 5-meter radio telescope for VLBI is no longer in service. In addition, the site is a fiducial IGS site with several IGS/IGSX receivers.

GGAO is located on the east coast of the United States in Maryland. It is approximately 15 miles NNE of Washington, D.C. in Greenbelt, Maryland.

- Longitude 76.4935
- Latitude 39.0118
- MV3
- Code 299.0
- Goddard Space Flight Center (GSFC)
- Greenbelt, Maryland 20771
- cddis.nasa.gov/ggao/

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2 Technical Parameters

The 5-m radio telescope for VLBI at MV3 was originally built as a transportable station; however, it was moved to GGAO in 1991 and has been used as a fixed station. In the winter of 2002 the antenna was taken off its trailer and permanently installed at GGAO. This antenna has not been operable for the past several years and it is not operable at the present time.

In October of 2010, construction of the new 12-meter VGOS developmental antenna was completed. This antenna features all-electric drives and a Cassegrain feed system. Integration of the broadband receiver and the associated sub-systems is underway as a joint effort between Peraton and the MIT Haystack Observatory. The technical parameters of the 12-m radio telescope are summarized in Table 1.

3 Staff of the VLBI Facility at GGAO

GGAO is a NASA research and development and data collection facility. It is operated under the Space Communication Network Services (SCNS) contract by Peraton. The staff at GGAO consists mainly of two operators. The Peraton staff includes Katie Pazamickas and Jay Redmond conducting VLBI operations and maintenance at GGAO with the support of the sustaining engineering Peraton team.

Table 1 Technical parameters of the GGAO 12-m radio telescope.

Parameter	12-m Antenna
Owner and operating agency	NASA
Year of construction	2010
Diameter of main reflector	12m
Azimuth range	±270 deg
Azimuth velocity	5 deg/sec
Azimuth acceleration	1.3 deg/sec/sec
Elevation range	5–88 deg
Elevation velocity	1.25 deg/sec
Elevation acceleration	1.3 deg/sec/sec
Focus	Cassegrain
Receive Frequency	2–14 GHz
Bandwidth	512 MHz, four bands
VLBI terminal type	VGOS
Recording media	Mark 6

4 Mission Support

Having ceased VLBI operations in May 2007, the MV3 5-m antenna is retired due to issues with the obsolete controller. The 12-m VGOS antenna has participated in many VLBI Global Observing System (VGOS) 24-hour experiments, including CONT17 and VGOS Trial observations on a regular, twice-a-month basis.

5 Recent Activities

Much of the 2017 and 2018 activities at GGAO have been focused on experiments using the VGOS 12-m antenna. However, there were some other activities worth noting:

- Conducted IVS observations using the Mark 6 recorders to demonstrate the VGOS capabilities on a regular, twice-a-month schedule
- Performed testing of the 16-Gbps VLBI recording capability, demonstrated using Mark 6
- Investigated movement of cables along the azimuth wrap to understand how and why it degrades cables
- Obtained cable delay measurements to use along with the observation data
- Participated in the CONT17 campaign
- Repaired both azimuth gearbox seals to prevent oil contamination and resolved the cold start problem
- Participated in mixed-mode test observations
- Supported developmental testing of video monitoring devices for the VLBI site at MGO in Texas.

6 Outlook

GGAO will continue to support VGOS, e-VLBI, and other developmental observations and activities during the upcoming year. Tentative plans for 2019 include:

- Conduct IVS observations using the Mark 6 recorders to demonstrate the VGOS capabilities on a regular, at least twice-a-month schedule
- Continue to investigate how and why the cables are degrading at the azimuth wrap
- Continue taking cable delay measurements for observation data correlation
- Support testing and implementation of MIT signal chain upgrade efforts at GGAO

Hartebeesthoek Radio Astronomy Observatory (HartRAO)

Marisa Nickola, Aletha de Witt, Jonathan Quick, Roelf Botha, Philip Mey

Abstract HartRAO is the only fiducial geodetic site on the African continent and participates in global networks for VLBI, GNSS, SLR, and DORIS. This report provides an overview of geodetic VLBI activities at HartRAO during 2017+2018, including progress with the VGOS project and the automated site tie system at HartRAO.

1 Geodetic VLBI at HartRAO

The Hartebeesthoek Radio Astronomy Observatory (HartRAO) now forms part of the larger South African Radio Astronomy Observatory (SARAO). Our director, Prof Ludwig Combrinck, took early retirement at the end of 2017. His position has not been filled. The Hartebeesthoek site is located 65 km northwest of Johannesburg, just inside the provincial boundary of Gauteng, South Africa. HartRAO is located 32 km away from the nearest town, Krugersdorp. The telescopes are situated in an isolated valley which affords protection from terrestrial radio frequency interference. HartRAO currently operates both a 15-m and a 26-m radio telescope. Construction of the new 13.2-m VGOS radio telescope has been completed, but further funding is required before it can become fully operational and start participating in VGOS observations (see Figure 2). The 26 m is an equatorially mounted Cassegrain radio telescope built by Blaw Knox in 1961. The telescope was part of the NASA deep space tracking network until 1974, when the facility was converted to an astronomical observatory. The 15 m is an az-el radio telescope built as a Square Kilometre Array (SKA) prototype during 2007 and converted to an operational geodetic VLBI antenna during 2012. The telescopes are co-located with an ILRS SLR station (MOBLAS-6), a Russian satellite laser and radio ranging system «Sazhen-TM+OWS», an IGS GNSS station (HRAO), a seismic vault, and an IDS DORIS station (HBMB) at the adjoining South African National Space Agency Earth Observation (SANSA EO) site. HartRAO is also a full member of the EVN.

Fig. 1 Farewell to Ludwig, the father of Geodesy at HartRAO. The legend lives on.

SARAO

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2 Technical Parameters of the 15-m and 26-m Telescopes at HartRAO

Table 1 contains the technical parameters of the HartRAO 15-m, 26-m, and VGOS radio telescopes, while Table 2 and Table 3 contain technical parameters of the HartRAO 15-m and 26-m receivers, respectively. The current data acquisition systems consist of a DBBC terminal and a Mark 5B+ recorder for both the 15-m and the 26-m antennas. A Mark 5C recorder is used for e-transfer of data and conditioning and testing of disk packs. A 258-TB Flexbuff reading system is also available for astronomical VLBI use. Currently, the hydrogen maser, iMaser 72, is being used for VLBI on both the 15-m and 26-m antennas. The EFOS-28 hydrogen maser, previously employed for VLBI on the 15-m antenna, developed an internal heater fault and has been taken out of service. It is unreliable but still usable. It is still used for running T2 sessions on the 15-m antenna when these sessions are observed with both antennas simultaneously. EFOS-28 will undergo repairs in July 2019. The older EFOS-6 hydrogen maser is completely down at the moment and is also awaiting repairs.

Table 1 Antenna parameters.

Parameter	Hart15M	HartRAO	VGOS
Owner and operating agency	HartRAO	HartRAO	HartRAO
Year of construction	2007	1961	2017
Mount type	Offset az-el	Offset equatorial	Az-El
Receiving feed	Prime focus	Cassegrain	Ring-focus
Diameter of main reflector d	15 m	25.914 m	13.2 m
Focal length f	7.5 m	10.886 m	3.7 m
Focal ratio f/d	0.5	0.42	0.4
Surface error of reflector (RMS)	1.6 mm	0.5 mm	0.1894 mm
Short wavelength limit	3 cm	1.3 cm	3 mm
Pointing resolution	0.001°	0.001°	0.0001°
Pointing repeatability	0.004°	0.004°	(unknown)
Slew rate on each axis	Az: 2° s^{-1} El: 1° s^{-1}	HA: 0.5° s^{-1} Dec: 0.5° s^{-1}	Az: 12° s^{-1} El: 6° s^{-1}

Table 2 Parameters of the 15-m co-axial receiver.

Parameter	X-band	S-band
Feeds	stepped horn	wide-angle corrugated horn
Amplifier type	cryo HEMT	cryo HEMT
T_{sys} (K)	40	42
S_{SEFD} (Jy)	1400	1050
PSS (Jy/K)	35	25
3 dB beamwidth (°)	0.16	0.57

Table 3 Parameters of the 26-m receiver (degraded performance due to dichroic reflector being used for simultaneous S/X VLBI).

Parameter	X-band	S-band
Feeds	dual CP conical	dual CP conical
Amplifier type	cryo HEMT	cryo HEMT
T_{sys} (K)	52	40
S_{SEFD} (Jy)	849	1190
PSS (Jy/K)	16.3	29.8
3 dB beamwidth (°)	0.096	0.418

3 Current Status

During 2017 and 2018, the 15-m antenna participated in 132 and 122 geodetic/astrometric IVS sessions, respectively (Table 4). The 26-m antenna participated in 38 and 30 sessions during 2017 and 2018, respectively (Table 4). In 2017, the antennas observed together in nine dual sessions (three R1s, two T2s, and four astrometric AUSTRALs) and in 2018 in four dual sessions (two T2s, one astrometric AUSTRAL, and one CRDS). During the dual geodetic VLBI sessions, the 15-m antenna's maser was offset in frequency to prevent PCAL cross-correlation. PCAL was usually turned off on the 15-m antenna for the astrometric AUSTRAL sessions. The 15-m antenna successfully participated in the CONT17 campaign from 28 November to 12 December 2017 with minimal loss of data and then only due to wind-stows. Astrometric single-baseline VLBI sessions in collaboration with Hobart (UTAS) to help improve the S/X- and K-band reference frames in the South and contribute to the ICRF-3 continued to be observed on the 26-m antenna. VLBI data for all sessions were e-transferred to the correlators.

The 15-m antenna suffered several antenna drive failures during this period. Various cable faults necessitated the replacement of cables. Damage to cables may be ascribed to continued problems being experienced with the cable wrap mechanism. We are in the process of investigating a suitable solution for the cable wrap on the 15-m antenna. The 26-m antenna's focus drive controller was refurbished and is now more stable. A linear encoder installed on the focus drive has improved repeatability.

Table 4 Geodetic VLBI sessions in which HartRAO participated during 2017+2018.

Session	No. of sessions on 15-m		No. of sessions on 26-m	
	2017	2018	2017	2018
R1	45	48	3	0
R4	46	47	0	0
AUST	17	11	6	2
RD	0	0	10	10
T2	4	6	4	3
CRDS	0	1	6	6
CONT17	15	0	0	0
RDV	0	0	6	6
OHIG	5	6	0	0
CRF	0	3	3	3
Total	132	122	38	30

4 Personnel

Table 5 lists the HartRAO station staff involved in geodetic VLBI. Jonathan Quick (VLBI friend) provides technical support for the Field System as well as support for hardware problems. Operations astronomer, Aletha de Witt, provides support for astrometric VLBI. Aletha is a member of the ICRF-3 Working Group and was elected to the IAU commission on astrometry in June 2018. The ICRF-3 was adopted by the IAU in September 2018. Aletha was elected to the IVS Directing Board, effective 1 March 2019. Aletha has also been coordinating the annual month-long AVN training program hosted by HartRAO since 2015. During this School, students from African VLBI Network (AVN) partner countries receive CHPC computer training and Observational and Technical Radio Astronomy training, the last week of the training program being dedicated to the topics of VLBI and geodesy (see Figures 4 and 7).

Table 5 Staff supporting geodetic VLBI at HartRAO.

Name	Function	Program
A. de Witt	Operations/ Scheduler	Fundamental Astronomy
J. Quick	Hardware/ Software	Astronomy
S. Basu	Operator	Student
J. Grobler	Operator	Technical
P. Mey	Operator	Technical
R. Myataza	Operator	Technical
M. Nickola	Logistics/ Operations	Fundamental Astronomy
P. Stronkhorst	Operator	Technical

5 New Developments

Our VGOS antenna arrived at the end of March 2017. Assembly was carried out by a team from MT Mechatronics and CETC 54. Assembly of the antenna and installation onto the concrete foundations took only 20 days (see Figure 3). Commissioning activities commenced thereafter with Site Acceptance Tests successfully completed during June 2018. Current efforts are geared towards interfacing and controlling the antenna through the Field System. While waiting for the required funding and a decision to be made with regards to a full broadband VGOS receiver and the associated signal chain, an in-house receiver is being developed for test purposes. A Mark 6 recorder was acquired in January 2018.

The HartRAO Operations Astronomer, Aletha de Witt, has become involved in planning for and scheduling of astrometric AUSTRAL and CRDS sessions (since AUA025 on 22 August 2017 and CRDS93 on 24 January 2018). This included improving schedules and setup for existing astrometric VLBI observations, e.g., an increase in data rate to 1 Gbps and revising the stations involved in the southern astrometric VLBI networks. A proposal for HartRAO to become an official Operation Center of the IVS was submitted to the IVS Directing Board in November 2018.

During the first half of 2017, short test experiments comprising VLBI observations of GNSS satellites were run in collaboration with Onsala and later Zelenchukskaya also, culminating in full 24-hour VLBI–GNSS test sessions on the 24th of July 2018, with HartRAO, Onsala, and Zelenchukskaya observing, and on the 8th of May 2018 with HartRAO, Onsala, Svetloe, and Zelenchukskaya participating.

Regarding determination of HartRAO local ties, a first short baseline test experiment was conducted on the 11th of May 2018 between the HartRAO 26-m legacy antenna and the co-located 15-m antenna with a view to testing the GGOS requirement of 1-mm accuracy in station coordinates and global baselines and to improve our understanding of the HartRAO complex. The site tie system has concluded initial tests and automation software implementation (see Figures 5 and 6).

The Russian Satellite Laser Ranger, Sazhen-TM, reached full operational status during 2018 and was accepted in the ILRS network on 3 May 2018 (see Figure 8). Two ESA GNSS reference stations, one at Hartebeesthoek and one at Matjiesfontein, were installed during the period of this report (see Figure 9). A new GNSS station was installed at the AVN partner site—the Ghana Radio Astronomy Observatory, at Kutunse, Ghana—during May 2018.

6 Future Plans

Of the 146 geodetic VLBI sessions scheduled for 2019, 108 sessions are allocated to the 15-m antenna, 36 sessions to the 26-m antenna, and two sessions will be run on both antennas.

Participation in VGOS obervations is dependent upon obtaining the necessary funding for the receiver and backend instruments. Until such time, in-house receivers will be employed to test operational capabilities.

The site tie measurement and product delivery is planned for 2019/20. GeoStations (GNSS, Seismometer, and weather station) installations are planned for the following locations during 2019 and 2020: Thomas River (near East London), Aliwal-North, Gamsberg (Namibia), Vaalputs (nuclear waste dump site), and Grabouw.

Acknowledgements

HartRAO forms part of SARAO, which is a National facility operating under the auspices of the National Research Foundation (NRF), South Africa.

The Space Geodesy Programme is an integrated program, combining VLBI, SLR, and GNSS, and it is active in several collaborative projects with GSFC, JPL, GFZ (Potsdam), and «Roscosmos» as well as numerous local institutes. Collaboration also includes OCA/NASA and the ILRS community in a Lunar Laser Ranger (LLR) project with local support from the University of Pretoria, amongst others. General information as well as news and progress on geodesy and related activities can be found at `http://geodesy.hartrao.ac.za/`.

Fig. 2 The HartRAO VGOS radio telescope—mechanically functional but awaiting funding for receiver and backend.

Fig. 3 The Big Lift—the VGOS telescope's azimuth cabin and main reflector being lifted and bolted onto the concrete structure.

Fig. 4 Chris Jacobs in action during the last week of the 2018 February/March AVN Training School hosted by HartRAO.

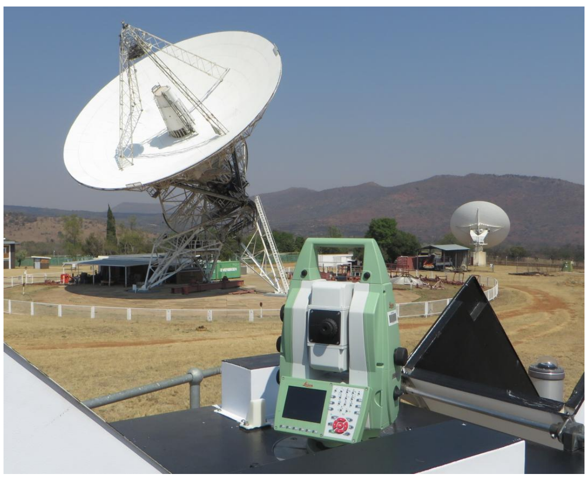

Fig. 5 Leica MS50 Total Station—the local automated site tie system under test with measurements and calibrations being carried out.

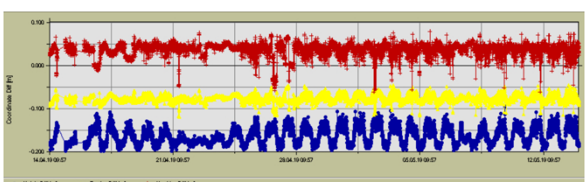

Fig. 6 Automated site tie system—data collection of 30 days from one of the measurement network targets showing coordinate offsets. A daily oscillation is clearly visible.

Fig. 7 2018 February/March AVN Training School students from Botswana, Namibia, and Zambia together with VLBI and Geodesy lecturers.

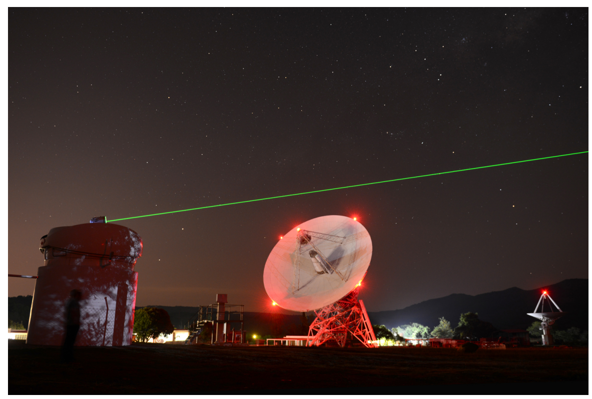

Fig. 8 The Sazhen-TM laser ranger.

Fig. 9 The ESA GNSS reference station antenna at Matjiesfontein.

AuScope VLBI Array and Hobart 26-m Antenna

Jamie McCallum, Lucia McCallum, Guifré Molera Calvés, Brett Reid, Simon Ellingsen, John Dickey

Abstract This is a report on the activities carried out at the University of Tasmania in support of the three AuScope VLBI observatories and the Hobart 26-m antenna in 2017 and 2018. Our current and completed research programs are outlined, as is our planned development of the array.

1 General Information

The AuScope VLBI array consists of three 12-m telescopes operated by the University of Tasmania as part of the AuScope project (www.auscope.org.au) and has been part of regular IVS observations since 2011. The telescopes span the Australian continental plate, located in Hobart (Tasmania), Katherine (Northern Territory), and Yarragadee (Western Australia). The Hobart 26-m telescope is co-located with the Hobart 12-m.

2 Activities during the Past Years

The AuScope array of telescopes has been participating in the regular IVS sessions, aiming to observe whenever it is possible and useful to do so. In 2017 and 2018 the AuScope and Hobart 26-m antennas participated in 175 and 170 IVS sessions, respectively, (compared to 166 in 2016, 185 in 2014, and 72 in 2012) for a total of 393 and 378 antenna days, respectively. A summary of the sessions is presented in Table 1.

School of Natural Sciences, University of Tasmania

Hobart 12-m and 26-m, Katherine, and Yarragadee

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Table 1 AuScope and Hobart 26-m antenna participation (number of experiments) in IVS sessions in 2017 and 2018.

Session	2017	2018
AOV	6	12
APSG	2	2
AUA & AUG	19	13
CONT17	15	0
CONTV17	15	0
CRDS	6	6
CRF	3	6
OHIG	5	6
R&D	10	10
R1/R4	90	101
T2	2	4
VLBA	2	0
AUM	0	10
Total	175	170

The total number of antenna days observed has decreased from 2015/2016, largely due to the Hobart12 having replaced the S/X receiver with the newly supplied VGOS receiver manufactured by Callisto in mid-2017. This has not been removed since its installation, and it has been tested and improved throughout this period.

The transition to VGOS has been slower than hoped, with some unexpected problems and a shortage of personnel at various times. As of 2019, we have confirmed an operational system capable of obtaining fringes across the VGOS frequency range in fringe tests with the Japanese Ishioka telescope. The most critical issues have been resolved, but there is still work to be done to optimize the sensitivity and improve the reliability of the system. Once we have confirmed reliable operation within our network, we look forward to contributing to the VGOS sessions.

3 Current Status

There have been a number of issues related to the timing stability of the Katherine data over 2017–2018, presenting as a large number of clock breaks within a session. The hydrogen maser located on site needed a major service in late 2018, during which time a number of other problems in the timing distribution system were addressed. The performance since the repairs has been much improved.

New cable wrap systems were installed in the Hobart12 and Katherine telescopes in early 2017 and mid-2018, respectively. These replace the existing twister-style cable wraps that may have caused some issues with cable stretching. A new cable wrap is on site at Yarragadee and will be installed in early 2019.

Several of the Mark5B+ units have developed faults over the last year and are to be replaced by a Fila10G/Flexbuff system. This will be installed in 2019 ahead of the upgrade to VGOS. The systems will continue to be used after the transition to VGOS for recording the S-band data.

The Hobart26 has continued participating in IVS sessions throughout 2017 and 2018. There have been a number of issues with the drives over this time though, leading to the cancelation or failure of a number of experiments. Failures of the cryogenic system leading to the warming of the receiver have also reduced the sensitivity of the antenna in several experiments. Ongoing maintenance has improved the situation, but further work will be required in the future.

In late 2018, the correlation facilities at the Hobart observatory were significantly improved with the acquisition of a cluster of 10 Flexbuff-like machines with 10 GbE interfaces and access to fast internal storage arrays. This replaced the existing cluster, which was significantly I/O-bound, particularly when working with data recorded in VGOS modes. The new cluster has not been rigorously benchmarked, but it correlates at better than real-time when processing sessions with a total data rate of 4 Gbps.

A deformation survey of the Hobart 26-m telescope was carried out in late 2018 by David Schunck of Bonn, as part of a research visit. The aim was to investigate some unusual residual errors seen on the short Hobart12–Hobart26 baseline. The results indicate that while the dish surface and focus cabin of the XY-mount telescope are remarkably well behaved, there does appear to be some deformation in the back structure, possibly affecting the stability of the rotation axes. Further work on this matter is required.

3.1 Observing Programs

With the Hobart12 unavailable for regular use in the S/X network, it was no longer practical to carry out the intensive geodetic schedules as part of the AUSTRAL program. However, the regular sessions have been repurposed to support the SOuthern Astrometry Program (SOAP, http://astrogeo.org/soap/) which carries out observations of Southern hemisphere quasars with the aim of improving the source position accuracy by a factor of 5–10. Initial results show improvements, although telescope sensitivity is a severely limiting factor when observing weak sources.

The absence of the Hobart12 for regular use prompted us to investigate the use of the VGOS system in mixed-mode (using the VGOS system to observe the S/X frequencies) observations. In mid-2018, a series of mixed-mode experiments were carried out using the AUSTRAL array. With Katherine and Yarragadee observing in the standard AUSTRAL S/X configuration, Hobart12 used the new DBBC3 to record the X-band frequencies, while the S-band data were captured using the DBBC2 and Fila10G card. The data were then correlated in DiFX and processed through Fourfit to combine the cross-hand polarizations. An initial examination of the results shows this to be apparently successful with no obvious errors or systematic variations. The correlation reports and data will be made available once final checks are complete.

4 Future Plans

The next major development for the AuScope array is the transition to VGOS which has been delayed from our initial expectations. The current timeline is for the upgrade to be made in mid-to-late 2019, with Katherine to be the first remote site to have the new system installed.

The dynamic observing program, where schedules are developed in real-time to suit the available network of telescopes, will be restarted in 2019. Initially, the main focus will be using the Hobart12 telescope in mixed-mode observations. Frequent experiments will drive further improvements to our observing efficiency and logistical arrangements.

Ishioka Geodetic Observing Station – 13.2-m Radio Telescope

Haruka Ueshiba [1], Saho Matsumoto [1], Michiko Umei [1], Takahiro Wakasugi [1], Shinobu Kurihara [1], Kentaro Nozawa [1,2]

Abstract The Ishioka Geodetic Observing Station is owned and operated by the Geospatial Information Authority of Japan. The 13.2-m radio telescope at the station successfully contributed to IVS regular observations during 2017 and 2018, succeeding the Tsukuba 32-m telescope, which was decommissioned at the end of March 2017. In addition to the regular observations, VGOS broadband observations were also performed.

1 General Information

The Ishioka Geodetic Observing Station (Figure 1) is located at about 70 km to the northeast of Tokyo and 17 km to the northeast of the headquarters of the Geospatial Information Authority of Japan (GSI) in Tsukuba (Figure 2). The observing station is owned and operated by GSI. It stands on firm ground atop a hill. It is equipped with a 13.2-m radio telescope which consists of a VGOS compliant antenna designed by MT Mechatronics (MTM), and two GNSS observation stations, one of which is registered as an IGS station. The telescope and the operation building had been completed by March 2016, and the VLBI station had participated in IVS regular observations as a network station in parallel with the Tsukuba 32-m radio telescope. Since 2017, the station has been fully participating in S/X legacy 24-hour and Intensive sessions as a successor to the Tsukuba 32-m telescope, which was decommissioned at the end of 2016 [1]. As a VGOS station, the station also participated in VGOS campaign sessions and some VGOS Trial sessions coordinated by IVS.

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co., Ltd.

Ishioka Network Station

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Fig. 1 Ishioka 13.2-m radio telescope at the Ishioka Geodetic Observing Station.

2 Component Description

The specifications of the Ishioka 13.2-m radio telescope are summarized in Table 1. The Ishioka station uses two different types of feed depending on the type of observing, namely, tri-band feed for S/X observations and QRFH for broadband observations. The QRFH is equipped with a 3 GHz high-pass filter to mitigate the effect of RFI around the 2 GHz band. It takes about one week to replace feeds and adjust the equipment.

In both S/X and broadband observing, the RF signal is transmitted to the operation building directly with-

Fig. 2 Location of Ishioka Geodetic Observing Station.

out frequency conversion. Then, the RF signal is down-converted to an IF signal and digitized. In S/X observing, a down-converter is used, and the frequency of the IF signal is 512–1,024 MHz. In broadband observing, the RF signal is down-converted by an Up/Down Converter (UDC), and the frequency of the IF signal is 1,024–2,048 MHz.

The Field System ver. 9.10.5 (FS9) is used to control the antenna and relevant devices.

3 Staff

Regular staff members belonging to the VLBI group of GSI are shown in Table 2. As of December 2018, the VLBI group of GSI consists of seven staff members and a contract operation staff member.

Table 1 Specifications of the Ishioka 13.2-m radio telescope.

Parameter	Ishioka 13.2-m radio telescope
Owner and operating agency	GSI
Latitude	N36°12'33.09"
Longitude	E140°13'8.24"
Altitude	112.8 m
Year of construction	2014
Radio telescope mount type	Az-El
Antenna optics	Ring focus
Diameter of main reflector	13.2 m
Azimuth range	180° +/- 250°
Elevation range	0-90°
Azimuth drive velocity	12°/sec
Elevation drive velocity	6°/sec
Tsys at zenith (X/S)	50 K / 300 K
Tsys at zenith (Broadband)	H-pol:100 - 150 K (3 - 8 GHz) 200 - 400 K (8 - 14 GHz) V-pol : 100 - 200 K (3 - 8 GHz) 200 - 500 K (8 -14 GHz)
SEFD (X/S)	1500 Jy / 2200 Jy
SEFD (Broadband)	H-pol : 2000 - 3000 Jy (3 - 10 GHz) 3000 - 5000 Jy (10 - 14 GHz) V-pol : 3000 - 4000 Jy (3 - 10 GHz) 3000 - 5000 Jy (10 -14 GHz)
RF range (X)	8192-9104 MHz
RF range (S with BPF)	2170-2425 MHz
RF range (Broadband)	3-14 GHz
Recording terminal	ADS3000+ sampler & K5/VSI data recording terminals
Data capacity	93 TB
Hydrogen maser	VCH-1003M (VREMYA-CH) SD1T03A (Anritsu, backup)

Table 2 Member list of the VLBI group of GSI (2017–2018).

Name	Main Function	Remarks
Hiroshi MUNEKANE	Supervisor	Apr. 2018 -
Tadao KIKKAWA	Operation	Nov. 2018 -
Shinobu KURIHARA	Management	Apr. 2017 -
Takahiro WAKASUGI	Correlation and Analysis IVS Directing Board member Chair of AOV	
Michiko UMEI	Correlation and Analysis	Operation (-Aug. 2018)
Haruka UESHIBA	Operation	Apr. 2018 -
Saho MATSUMOTO	Operation	Nov. 2018 -
Kentaro NOZAWA	Operation (AES)	Apr. 2018 -

4 Current Status

4.1 S/X Observations

Since January 2017, the Ishioka station has regularly participated in Intensive one-hour sessions instead of the Tsukuba 32 m. Since April 2017, Ishioka has also participated in 24-hour sessions frequently. The number of regular sessions in which Ishioka was involved following the IVS Master Schedules of 2017 and 2018 is shown in Table 3. Note that AOV sessions are observations designed for enhancing positioning accuracy in the Asia-Oceania region, and GSI contributes as a scheduler through preparing the schedules of some of the AOV sessions. Most of the AOV sessions are carried out at a total recording rate of 1 Gbps. In addition, the Ishioka station participated in two geodetic VLBI observations with the Usuda 64-m telescope operated by JAXA in order to determine the geocentric coordinates of the telescope for their deep space mission.

The Ishioka station is connected to a broadband network called *SINET5*, operated by the National Institute of Informatics (NII), with a 10 Gbps dedicated cable. The observation data is converted from K5 to Mark 5 format as necessary and sent to a correlator by jive5ab or tsunami. Observations are remotely operated from the headquarters of GSI at Tsukuba. The observation procedure is automated, and operations at night or on a holiday are unattended. If trouble occurs at night or on a holiday, a notification e-mail is sent to operators.

Several problems which affected observations have occurred so far. From May to August 2017, some observations are missing due to an error with releasing the brake or stow pin. Regarding the error of releasing the brake, we increased the number of times to execute the FS9 command *ant_act* in a snap file because the brake is sometimes not released, depending on the timing of executing the command. On the other hand, it is still not clear what caused the error with releasing the stow pin. However, the error has become less frequent after September 2017 and has occurred only once every few months on average. Antenna control trouble caused by condensation around the elevation encoder has occurred several times. In order to prevent dew condensation, two fans were installed around the encoder to circulate the air in the Azimuth cabin. More antenna control trouble occurred in September 2018. At that time, the station could not observe for about ten days. The trouble was caused by the breaking down of one of the communication modules to the antenna control. After replacing the module, the trouble was resolved.

Table 3 The number of regular sessions in 2017 and 2018.

Sessions	2017	2018
IVS-R1	44	31
IVS-R4	30	29
IVS-T2	4	4
APSG	2	1
AOV	3	9
IVS-INT1	19	-
IVS-INT2	91	71
IVS-INT3	40	32

4.2 Broadband Observations

The Ishioka station carried out broadband observations from November to December in 2017 and from June to September in 2018. The Ishioka station participated in the CONT17 campaign as one of the six VGOS stations and in some 24-hour VT sessions. The numbers of VT sessions in which Ishioka participated are two in 2017 and seven in 2018. In addition, the Ishioka station participated in international collaborative broadband observations with the Kashima 34-m antenna and the Hobart 12-m antenna. From August through September 2018, Ishioka carried out three collaborative observing sessions with the Hobart 12 m. The observing frequency setup was the same as for VT sessions, and the observation time was 30 minutes or one hour. At the third session, fringes were detected on all frequency bands.

In August 2018, the Ishioka station also participated in experiments for the distant frequency comparison project conducted by National Institute of Information and Communications Technology (NICT), as the only VGOS station in Japan. In the experiments, broadband observations (6, 8.5, 10, and 11 GHz with a bandwidth of 1 GHz) were carried out between Ishioka and small telescopes which were set by NICT at Koganei and the Medicina Radio Astronomical Station (National Institute for Astrophysics; INAF) [2]. Fringes were successfully detected for each band.

4.3 Co-location Survey

In November 2018, we performed a field co-location survey at the station in order to measure an accurate local tie vector between the Ishioka 13.2-m radio telescope and the antenna of the IGS tracking station ISHI. To determine the invariant point of the telescope, we carried out two different ways. One is the conventional *outside* method in which we put a target enclosing a retro reflector outside of the telescope and measure its position from pillars around the telescope (Figure 3) [3]. The other is called the *inside* method, in which we put a target mirror inside of the azimuth cabin and measure its position from the stage near the Az-El intersection of the telescope (Figure 4). The data is currently undergoing processing, and we will soon compare the results by the two methods.

Fig. 3 Picture of field co-location survey by *outside* method.

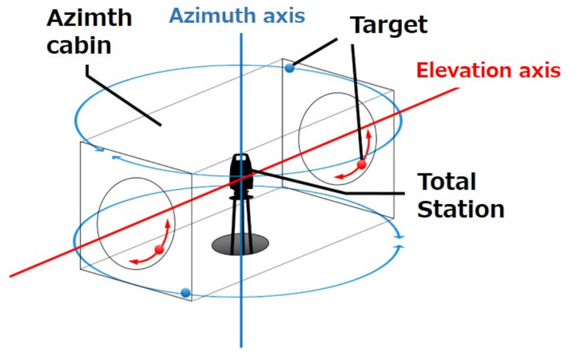

Fig. 4 Schematic diagram of the *inside* method.

5 Outlook

The Ishioka 13.2-m radio telescope will continue to participate in S/X legacy 24-hour and Intensive sessions and in VGOS experiments from 2019 on. In parallel with that, we are planning to start an investigation for "Mixed Mode" observing with the QRFH. To receive an S-band signal by QRFH, it is necessary to update its band pass filter to extend its lower limit to 2 GHz from the current 3 GHz, while avoiding the effect of RFI around 2 GHz.

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Kashima 34-m VLBI Network Station Report for 2017–2018

Mamoru Sekido, Eiji Kawai

Abstract The NICT Kashima 34-m diameter radio telescope has been regularly participating in VLBI sessions organized by the IVS with a standard S/X band receiver. The station is maintained by the VLBI group of the Space Time Standards Laboratory of NICT. The VLBI application for precision frequency transfer is the main project of this group. The broadband feed of narrower beam width was originally developed for the 34-m antenna with Cassegrain optics. Broadband VLBI experiments for the evaluation of the receiver and data acquisition system have been conducted with the Kashima 34-m antenna of NICT and with two small diameter VLBI stations located in Medicina (Italy) and NICT (Koganei, Japan). In addition to geodetic and time transfer VLBI observing, the Kashima 34-m antenna has been used for astronomical VLBI observing and for single dish observing of Jupiter and pulsars.

Fig. 1 The Kashima 34-m radio telescope.

1 General Information

The 34-m diameter radio telescope (Figure 1) has been maintained and operated by the VLBI group of Space Time Standards Laboratory (STSL) in the National Institute of Information and Communications Technology (NICT). It is located in the Kashima Space Technology Center (KSTC), which is at about 100 km east of Tokyo, Japan. The STSL includes groups of Japan Standard Time and Atomic Frequency Standard. They are engaged in keeping the national time standard JST and development of advanced optical frequency standard, respectively. The other group of STSL is working on frequency transfer using communications satellites and GNSS observations. Our VLBI group is sharing the task of development of precision time transfer technique by means of VLBI. A new broadband VLBI system is being developed for application of time transfer and to be compatible with the VGOS system.

NICT Space-Time Standards Laboratory/Kashima Space Technology Center

NICT Kashima 34-m Network Station

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2 Component Description

2.1 Receivers

The Kashima 34-m antenna has multiple receiver systems from 1.4 GHz up to 22 GHz. A Q-band (43 GHz) receiver is mounted, although it has not been available since 2017 due to a phase-locked oscillator problem. The performance parameters for each frequency are listed in Table 1. The receiving bands are changed by exchanging receiver systems at the focal point of the

Table 1 Antenna performance parameters of the Kashima 34-m telescope.

Receiver	Pol.	Frequency	SEFD [Jy]
L-band	RHCP/LHCP	1405-1440MHz 1600-1720 MHz	∼ 300
S-band	RHCP/LHCP	2210-2350 MHz	∼ 350
X-band	RHCP/LHCP	8180-9080 MHz	∼ 300
Wideband	V-Linear Pol.	3.2-11 GHz	∼ 1000 – 2000
K-band	LHCP	22 - 24 GHz	∼ 2000
Q-band **		42.3-44.9 GHz	∼3000

** Q-band is currently not available.

antenna. Each receiver is mounted on one of four trolleys, and only one trolley can be at the focal position. The focal point is adjusted by the altitude of the subreflector with five axes actuators.

2.2 Data Acquisition System

Three types of data acquisition systems (DAS) have been developed and installed at the Kashima 34-m station.

K5/VSSP32 is a multi-channel data acquisition system with narrow frequency width up to 32 MHz [1]. One unit of the K5/VSSP32 sampler (Figure 3) has four analog inputs. Each analog signal is digitized at a 64 MHz sampling rate in the first stage, then frequency shaped by digital filter at the second stage. A variety of sampling rates (0.04–64 MHz) and quantization bits (1–8 bit) are selectable. Four units of the K5/VSSP32 compose one set of geodetic VLBI DAS with 16 video channels. The observed data is recorded in K5/VSSP data format. Software tools for observation and data conversion to the Mark 5A/B format are freely available. Please visit our Web site[1] for details on the K5/VSSP sampler specification and software resources.

Fig. 2 A broadband NINJA feed has been installed in the receiver room of the Kashima 34-m telescope.

Fig. 3 One unit of the K5/VSSP32 sampler has four video signal inputs. Data output and remote control are made via a USB2.0 interface. One geodetic terminal of 16 video signals is composed of four units of this device.

K5/VSI is a data recording system composed of a computer with a 'PC-VSI' data capture card, which receives a VSI-H data stream as input and transfers it to the CPU of the computer via a PCI-X interface (Figure 4). Thanks to the standardized VSI-H interface specification, this system can be used to record any data stream of a VSI-H interface[2] [2]. The NICT Kashima 34-m station is equipped with three kinds of VSI-H samplers (ADS1000 and ADS3000+ [3]). The ADS3000+ sampler is capable of both broadband observations (1024 Msps/1ch/1bit, 128 Msps/1ch/8bit) and multi narrow channel observations using the digital BBC function, where one of 2, 8, 16, or 32 MHz video band widths are selectable.
The K5/VSSP32 samplers and analog frequency video converter was used for observations of IVS sessions at NICT. Since 2016, the Kashima 34-m station has begun to use ADS3000+ with the DBBC function for IVS sessions.

[1] http://www2.nict.go.jp/sts/stmg/K5/VSSP/index-e.html
[2] http://vlbi.org/vsi/

Fig. 4 Upper panel shows PC-VSI card, which captures VSI-H data stream. Up to 2048 Mbps data stream is captured by one interface card. Lower panel shows ADS3000+, which is capable to extract 16 channels of narrow band signals via DBBC function, and it outputs data stream through VSI-H interface.

K6/GALAS is the new high speed sampler for the broadband VLBI observation project GALA-V [4]. An analog radio frequency signal is converted to digital data at a 16.384-GHz sampling rate. Four digital data streams of 1024-MHz frequency width at any frequencies selected by 1-MHz step resolution are extracted by digital frequency conversion and filtering function of the sampler. This is a new aspect of K6/GALAS, so-called 'RF-Direct Sampling', in which a radio frequency (RF) signal is directly captured without frequency conversion. This 'RF-Direct Sampling' technique has advanced characteristic in precision delay measurement by VLBI. Output data comes out via a 10 Gbit-Ethernet interface with VDIF/VTP/UDP packet streams.

3 Staff

The staff members contributing to running and maintaining the Kashima 34-m station are listed below in alphabetical order:

- HASEGAWA Shingo is the supporting engineer for IVS observation preparation and maintenance of file servers for e-VLBI data transfer.
- ICHIKAWA Ryuichi is in charge of keeping GNSS stations.
- KAWAI Eiji is the main engineer in charge of the hardware maintenance and the operation of the 34-m station. He is responsible for the routine geodetic VLBI observations for IVS.
- KONDO Tetsuro is maintaining the K5/VSSP software package and working on the implementation of the ADS3000+ control function in FS9.
- MIYAUCHI Yuka is in charge of the data acquisition software.
- SEKIDO Mamoru is responsible for the Kashima 34-m antenna as the group leader. He maintains the FS9 software and operates the Kashima and Koganei 11-m antennas for IVS sessions.
- TAKEFUJI Kazuhiro is a researcher using the 34-m antenna for the GALA-V project and pulsar observations. He worked on the installation of the broadband NINJA feed system, and made subreflector position adjustments and performance measurements of the new receiver.
- TSUTSUMI Masanori is the supporting engineer for the maintenance of data acquisition PCs and the computer network.
- UJIHARA Hideki is a researcher designing the new broadband IGUANA-H and NINJA feeds.

4 Current Status and Activities

4.1 IVS Sessions

The Kashima 34-m station is participating in geodetic VLBI sessions (T2, CRF, RD, APSG, AOV, and R1). All the data provision to the correlator is made via e-transfer using the data servers listed in Table 2.

Table 2 VLBI data servers for exporting data by e-transfer to correlation centers.

Server name	Data capacity	Network Speed
k51b.jp.apan.net	44 TByte	1 Gbps
k51c.jp.apan.net	22 TByte	10 Gbps

Thanks to collaboration with Research Network Testbed JGN, a 10-Gbps network connection is available to Kashima Space Technology Center. The server *k51c* is able to transfer the data at 10 Gbps, while *k51b* is limited to 1 Gbps due to its network interface card.

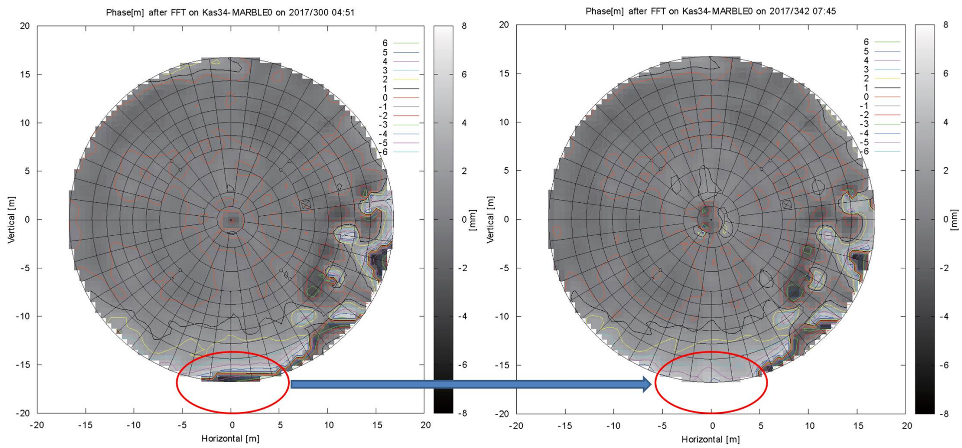

Fig. 5 Contour map of surface height distribution obtained by holography test in 2017. The large deviation of flatness found in the initial measurement (left) was adjusted (right). We confirmed the accuracy of the holographic measurement in preparation of the repair work in 2018.

4.2 Broadband VLBI Experiments

As the mission of our project, we have been conducting broadband VLBI experiments for frequency transfer. Broadband VLBI is performed by using the Kashima 34-m antenna (O), a small diameter broadband VLBI antenna (A) installed at National Metrology Institute of Japan (NMIJ), and another one (B) at headquarters of NICT at Koganei. From the VLBI delay data of OA and OB baselines, that of AB baseline is computed by closure delay relation. This observation scheme is named 'Node-Hub' Style (NHS) VLBI [5]. After testing this NHS VLBI, one of the small antennas was exported to Medicina observatory in Italy in July 2018. Under collaboration with Italian National Metrological Research Institute INRiM and INAF, we have started an optical clock frequency transfer experiment between the Yb optical clock at INRiM in Italy and the Sr optical clock at the headquarters of NICT (Koganei) in Japan.

4.3 Maintenance Work

Holographic Reflector Surface Measurement and Adjustment

Repair work of the main reflector backup structure damaged by corrosion was made in the period between June and September 2018. Damage due to rust was found via inspection with an aerial vehicle by ourselves in October 2016. Then we made an effort to keep a budget and design and finally carried this out in 2018. Because it was supposed that some part of the steel angle supporting the main reflector needs to be replaced during the work, we have to prepare for reflector height adjustment after the work. In 2017, we did test observing with a 12.5 GHz geostationary satellite signal and confirmed the accuracy of the measurement (Figure 5) [6].

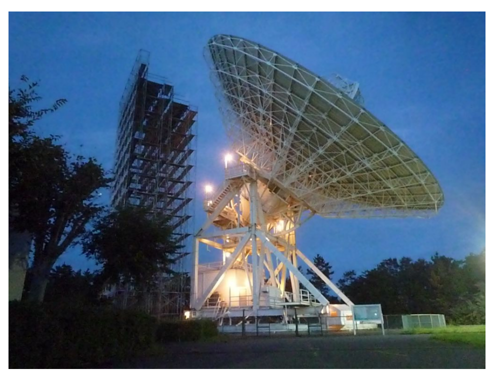

Fig. 6 The Kashima 34-m antenna in holographic observing after reflector adjustment. We carried out the reflector adjustment during day time and the holography observing in the evening. We repeated this procedure for a week. For safety, we watched the antenna during the holography observing for about 1.5 hours to avoid an accidental smash with the scaffolding.

Just after the repair work in September 2018, we carried out reflector height adjustment using scaffolding for repair work in 2018. Surface height measurement by holography and adjustment of the panel was repeated by ourselves. Figure 6 shows the scaffolding standing on the north side of the 34-m antenna. Reflector flatness (pp 12.7 mm, RMS 1.2 mm) just after the repair work was improved (pp 2.3 mm, RMS 0.3 mm) by the holographic measurement and adjustment.

Helium Gas Leakage Trouble Shooting

A helium gas leak was found in February 2017. The cause of the leak was identified on one pipe running at the elevation cable wrap section. Finally we fixed the leakage by replacing four 25-m length helium tubes in October 2017. For some part of this period, the cooled receiver system had to be operated at room temperature.

5 Future Plans

We have started an optical clock time transfer experiment between the Yb optical clock at INRiM in Italy and the Sr optical clock at the headquarters of NICT (Koganei) for the period between 2018–2019. The small telescope at Medicina will be returned back to Japan by August 2020.

We are really regretful that the Kashima 34-m antenna has been planned to be dismantled from the middle of 2020. The background reasons are aging of the antenna, maintenance costs, and difficulty in obtaining repair parts.

Acknowledgements

We thank H. Mikoshiba and K. Handa of NAOJ for advice on holographic reflector surface measurement. The high-speed network environment is supported by the High Speed R&D Network Testbed JGN. We thank K. Namba and Y. Okamoto of the Information System Group of NICT for support for network security and a high-speed LAN environment.

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[3] http://www2.nict.go.jp/sts/stmg/ivstdc/news_37/pctdc_news37.pdf

Kokee Park Geophysical Observatory

Chris Coughlin

Abstract This report summarizes the technical parameters of the VLBI systems at the Kokee Park Geophysical Observatory and provides an overview of the activities that occurred in 2017–2018.

1 Location

The Kokee Park Geophysical Observatory (KPGO) is located in Kokee State Park on the island of Kauai in Hawaii at an elevation of 1,100 meters near the Waimea Canyon, often referred to as the Grand Canyon of the Pacific. KPGO is located on the map at longitude 159.665° W and latitude 22.126° N.

2 Technical Parameters

The 20-m receiver is of NRAO (Green Bank) design (a dual polarization feed using cooled 15 K HEMT amplifiers). The antenna is of the same design and manufacture as those used at Green Bank and Ny-Ålesund. A Mark 5B+ recorder is currently used for all data recording.

The 12-m receiver is of MIT design. The ultra wideband receiver uses a Quadruple-Ridged Flared Horn (QRFH) and LNAs, developed at the California Institute of Technology, cooled to $\sim$15K and is dual polarization. The antenna is a prototype that was developed by InterTronic Solutions Inc. A Mark 6 recorder is currently used for all data recording.

Timing and frequency is provided by a Sigma Tau Maser with a second Sigma Tau Maser as a backup and a NASA NR Maser providing a second backup. Monitoring of the station frequency standard performance is provided by a CNS (GPS) Receiver/Computer system. The Sigma Tau performance is also monitored via the IGS Network.

3 Staff

The staff at Kokee Park consists of six full time people and one part time person employed by Peraton Corporation under the SCNS contract to NASA for the operation and maintenance of the observatory. Chris Coughlin, Lawrence Chang, Kiah Imai, and Morgan Goodrich conduct VLBI operations and maintenance. Ben Domingo is responsible for antenna maintenance, and Amorita Yaris provides administrative, logistical, and numerous other support functions. Kelly Kim also supports VLBI operations and maintenance during 24-hour experiments and as backup support.

4 Mission Support

Kokee Park has participated in many VLBI experiments including IVS R4 and R1 experiments. KPGO also participates in the RDV, CRF, APSG, RD, and OHIG experiments. KPGO averaged two experiments of a 24-hour duration each week, with weekday Intensive experiments in 2017 and 2018.

1. USNO
2. NASA GSFC

Kokee Park Geophysical Observatory

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Fig. 1 Newly installed 12-m VGOS telescope at KPGO.

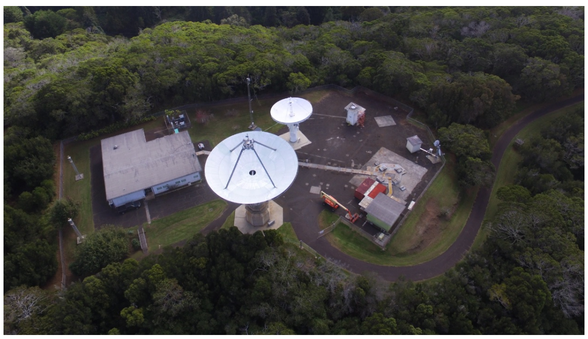

Fig. 2 KPGO site overview after installation of the 12 m, removal of the 9 m, and removal of the 7 m.

Kokee Park hosts other systems, including the following: a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacon and remote control, a Quasi-Zenith Satellite System (QZSS) monitoring station, a Two-Way Satellite Time and Frequency Transfer (TWSTFT) relay station, and a TurboRogue GPS receiver. Kokee Park is an IGS station.

5 Recent Activities

The KPGO VGOS 12-m radio telescope passed the operational readiness review (ORR) early in 2017 and officially joined the VGOS Observing Schedule in May of 2017. Since May of 2017 there have been several improvements for the 12-m system. The most significant was having InterTronic Solutions Inc. (ISI) onsite in 2018 to perform antenna controller modifications introducing active torque bias. This dramatically improved the antenna servo performance and provided more reliable operations for the system. The KPGO 12-m system successfully completed many VT sessions in 2017 and 2018, yielding very good data acquisition metrics thus far.

The KPGO 20-m radio telescope has been in service now for 26 years and was able to get another upgrade completed in 2018. The 20-m Frontend Cryogenics System was completely overhauled in December of 2018. This included replacement of all rigid and flex helium lines, a newly refurbished Coldhead, and a new Trillium M700 Helium Compressor. The 20-m system successfully participated in the VLBI Observing Schedule for 2017 and 2018 while maintaining a very high data acquisition metric throughout.

USNO, MIT, KPGO, and DREN were able to work together in 2017 and 2018 to ensure that e-transfer capability at the site was functional. There were no major e-transfer link outages during 2017 or 2018, providing quicker delivery of INT1 data to the WACO Correlator and better latency results.

For the majority of 2018, the site Ops Building underwent a major upgrade that was in planning for many years, finally getting completed in January 2019. The Ops building HVAC System was upgraded along with the site Utility Power Electrical Infrastructure. This was a major effort involving many contractors and vendors spanning May 2018 to January 2019. The Ops building is now equipped with a new redundant HVAC system to ensure that operational equipment is in a suitable environment.

Fig. 3 Newly installed HVAC system for KPGO Operations Building.

Table 1 Technical parameters of the radio telescopes at KPGO.

Parameter	20-m	12-m
Owner and operating agency	USNO-NASA	USNO-NASA
Year of construction	1993	2015
Diameter of main reflector d	20 m	12 m
Azimuth range	$\pm 270^\circ$	$\pm 270^\circ$
Azimuth velocity	$2^\circ/s$	$12^\circ/s$
Azimuth acceleration	$1^\circ/s^2$	$1^\circ/s^2$
Elevation range	$\pm 90^\circ$	$\pm 90^\circ$
Elevation velocity	$2^\circ/s$	$6^\circ/s$
Elevation acceleration	$1^\circ/s^2$	$1^\circ/s^2$
Receiver System		
Focus	Primary Focus	Cassegrain
Receive Frequency	2.2–8.9 GHz	2–14 GHz
T_{sys}	40 K	40 K
$S_{SEFDRange}$	500–2000 Jy	1500–3000 Jy
G/T	40 dB/K	43 dB/K
VLBI terminal type	VLBA4	RDBE
Recording media	Mark 5B+	Mark 6
Field System version	9.11.7	9.12.2

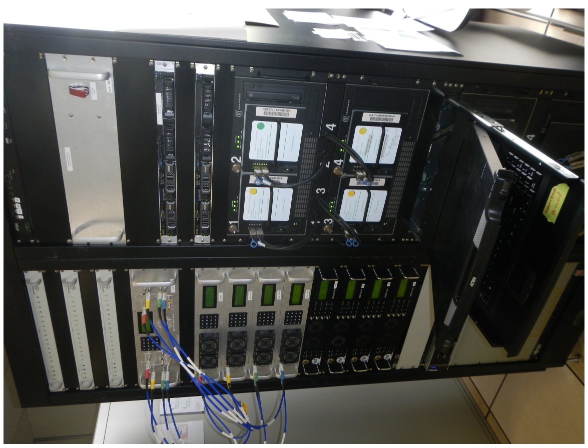

Fig. 4 MIT Digital Backend for KPGO 12-m VGOS System.

6 Outlook

KPGO has several improvements planned for the site in the near future. General Dynamics Mission Systems (GDMS) is scheduled to be at KPGO in July of 2019 to refurbish the 20-m Frontend Focus System. Once completed, this will restore the ability to adjust the focal point for the 20-m Frontend Receiver. This ability will also allow us to upgrade to the new Broadband Signal Chain when ready. The original 20-m 15kW backup genset used for backup power for cryogenics and frontend electronics is due to be upgraded to 60kW genset. This will allow for the newly installed M700 Helium Compressor to be on the standby power circuit, limiting warmups due to site power outages. This upgrade is tentatively scheduled for August of 2019. The site network upgrade to new compliant network configuration, hardware, and protocols is due to take place in September of 2019. The network upgrade should improve operational data e-transfer speeds, as well as the general network speed for the site. For the KPGO 12-m system, we are planning to rebalance the antenna counter weights so the reflector will be misbalanced towards zenith rather than the horizon. The 12 m rebalance effort is due to take place in late 2019 along with a controller modification to allow more connections to the 12-m antenna controller over the network.

Kashima 11 m and Koganei 11 m VLBI Stations
Report for 2017-2018

M. Sekido, E. Kawai

Abstract The Kashima 11-m and Koganei 11-m stations have been participating in R1, T2, CRF, APSG, and AOV sessions conducted by the IVS and AOV. In addition to these regular sessions, the Kashima 11-m antenna has participated in CONT17. In recent years, the S-band receiver of the Koganei 11-m station has suffered from radio frequency interference, and we found sensitivity degradation. The Kashima and Koganei sites are designated as a member of the GGOS Space Geodetic Network. Co-location is an important subject for GGOS; thus, local survey information on co-location among the VLBI 11-m antenna, GPS, and SLR reference points in 1996—1999 and an additional survey conducted in 2013 are briefly described as a reminder.

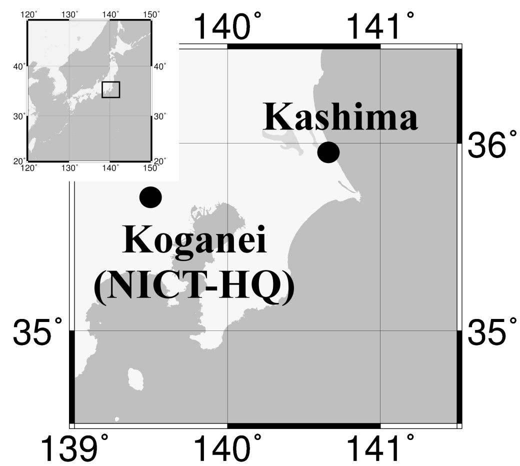

Fig. 1 Location of NICT-Koganei Headquarters and Kashima.

1 General Information

A pair of 11 m diameter antennas are operated by the VLBI group of the Space-Time Standard Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT). The Kashima 11-m antenna is located at the Kashima Space Technology Center (KSTC), on the east coast of the Japanese main island. The 11-m antenna is in the same campus as the Kashima 34 m diameter radio telescope [1] at a 240 m distance. The Koganei 11-m diameter antenna is located at the headquarters of the NICT in Koganei Tokyo (Figure 1). These 11-m VLBI antennas at Kashima and Koganei (Figure 2) were built together with two other VLBI stations for the Key Stone Project (hereafter referred to as KSP). The aim of the KSP [2] was monitoring of crustal deformation around the Tokyo metropolitan area by using multiple space geodetic techniques; VLBI, GPS, and SLR. That project was operated in the period between 1995 and 2001. After the KSP project was terminated in 2001, two other 11 m diameter antennas were transferred to Gifu University and Hokkaido University, respectively, for astronomical research and education. The Kashima and Koganei 11-m stations remained at NICT, and they have been used for technology development and geodetic observations. Participation in the IVS sessions of these two stations on a regular basis started after the "Great East Japan Earthquake" occurred in March 2011. Post-Seismic Deformation (PSD) mod-

NICT Space-Time Standards Laboratory/Kashima Space Technology Center

NICT KSP Network Station

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Fig. 2 11-m VLBI antennas at Kashima (left panel) and Koganei (right panel).

els for Kashima 11 m and Koganei are included in ITRF2014.

2 Component Description

2.1 Kashima 11-m Antenna

The antenna parameters of Kashima-11 and Koganei-11 are summarized in Table 1. The receiving frequency bands are the S and X bands, and room temperature LNAs are used. Then the signal is converted to three intermediate frequency (IF) signals, which have a frequency range of 500-1000 MHz. The X-band signal is divided into two IFs, which are XL for 7.7-8.2 GHz and XH for 8.1-8.6 GHz.

Bandpass filters for S-band (2212-2360 MHz) were additionally installed in 2010 at both stations for mitigation of radio frequency interference (RFI) from cell phone stations.

The local oscillator (LO) frequency for XH at the Kashima 11-m station has been changed from 7600 MHz to 7680 MHz since 2008, so that the observing frequency range changed from 8100–8600 MHz to 8180–8680 MHz.

Table 1 The antenna parameters of the 11-m antennas.

		Kashima	Koganei
Antenna Type		Cassegrain type	
Diameter		11 m	
Mount Style		Az El mount	
Latitude		N 35° 57' 19.46"	N 35° 42' 37".89
Longitude		E 140° 39' 26.86"	E 139° 29' 17".06
Altitude		62.4 m	125.4 m
Rx Freq. [MHz]	S band	2212 ∼ 2360	2212 ∼ 2360
	X Low band	7700 ∼ 8200	7700 ∼ 8200
	X High band	8180 ∼ 8680	8100 ∼ 8600
Local Freq. [MHz]	S band	3000	3000
	X Low band	7200	7200
	X High band	7680	7600
SEFD [Jy]	X-band	5700	9500
	S-band	3300	5500

2.2 Koganei 11-m Antenna

The Kashima and Koganei 11-m stations have been participating in IVS sessions with a frequency of about once in a month. In recent years, we have received a series of warnings from IVS correlator reports that the S-band fringe detection rate is getting lower at the Koganei 11-m station. The cause of the issue was clearly recognized by monitoring of the first low noise amplifier (LNA) output. In February 2018, we checked the S-band LNA output of the Koganei 11-m station for all the azimuthal antenna directions in 30-degree steps with the elevation angle at 5 degrees. Strong RFI at 2.1 GHz and 2.6 GHz (hereafter referred to as f_1, and f_2 for these frequencies) was received at +3dBm as the peak level. Higher order inter-modulations of these two frequencies ($f_2 - f_1, f_1 + f_2, 2f_2 - f_1, 2_f2 - f_1, 2f_1 + f_2, 2f_2 + f_1$) were detected for the majority of all directions, and they were stronger in the direction of Az=270 $\sim$ 360. These data indicate that LNA gain is saturated by the RFI. Figure 3 shows the radio frequency spectrum of the LNA output obtained by Maxhold measurement for 30 seconds with 3 MHz resolution bandwidth. The bandwidth of the RFI signal was about 60 MHz. From these measurement data, power levels of each RFI (f_1, f_2) are estimated to be around +16dBm. The receiver system of the KSP 11-m station is composed of an S/X-band dual frequency waveguide system equipped with a high gain (50dB) waveguide type room temperature LNA. Then the input power level to the LNA is estimated to be no less than -34dBm per signal. A possible counter measure to this problem would be replacement of the receiver system by a cooled LNA with a superconductor filter in front of it; however, it is not allowed due to the budgetary condition.

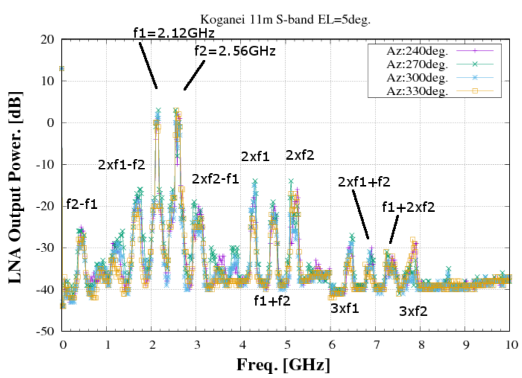

Fig. 3 Frequency spectrum of receiving power at the S-band first LNA output of the Koganei 11-m station. The antenna was pointing to the west direction with the elevation angle at 5 degrees. Maxhold measurement was made for 30 seconds with 3 MHz resolution bandwidth. Higher order harmonics and inter-modulation of strong RFI at 2.1 GHz (f_1) and at 2.6 GHz (f_2) indicate saturation of the first LNA.

Table 2 VLBI data sampler/DAS systems equipped at the Kashima 11 m and Koganei 11 m stations.

System	K5/VSSP32 (4 units)	ADS3000+(K5/VSI)
Video Converter	K4/KSP 16ch	not necessary
# of Input Channels	4 /unit x 4 units	1 or 2
# of Output Channels	16	1, 2, 16
Input Freq. Range	0 - 300 MHz	0 - 2 GHz
Sampling Rate [Msps]	0.04,0.1,0.2,0.5,1, 2,4,8,16,32,64	128, 256, 1024, 2048,4096
Quantization bit	1,2,4,8 bit	
Max. data rate [Mbps]	256/unit x 4	4096
Output Interface	USB 2.0	VSI-H

2.3 Data Acquisition Systems

The K5/VSSP32 [3] has four channels of video band signal input per unit. Four units of K5/VSSP32 constitute one geodetic VLBI terminal with 16 video channels. This system is constantly used for geodetic VLBI observations including IVS sessions. This K5/VSSP32 sampler has digital filter functionality inside. The input video signal is digitized with 8-bit quantization with 64 MHz sampling. Then the signal is shaped for the recording bandwidth by a digital filter. The data come out from a USB 2.0 interface at the data rate corresponding to the observation mode. The data stream is recorded on a standard Linux file system in K5/VSSP32 format[1]. Data format conversion from K5/VSSP32 to Mark IV, VLBA, and Mark-5B are available with conversion tools[2].

Another sampler ADS3000+ [4, 5] and PC-VSI data recording system are available at the Koganei station (Table 2); however, geodetic VLBI observing has been mostly done by using the K5/VSSP32. The ADS3000+ is used only at the Kashima 34-m station [1] but not used at the 11-m stations yet.

2.4 Network for e-Transfer

VLBI observation data recorded in the K5/VSSP32 format is converted to Mark5B before submission to a cor-

[1] Please see `http://www2.nict.go.jp/sts/stmg/K5/VSSP/vssp32_format.pdf`

[2] Observation and data conversion software for K5/VSSP are freely available from `http://www2.nict.go.jp/sts/stmg/K5/VSSP/index-e.html`

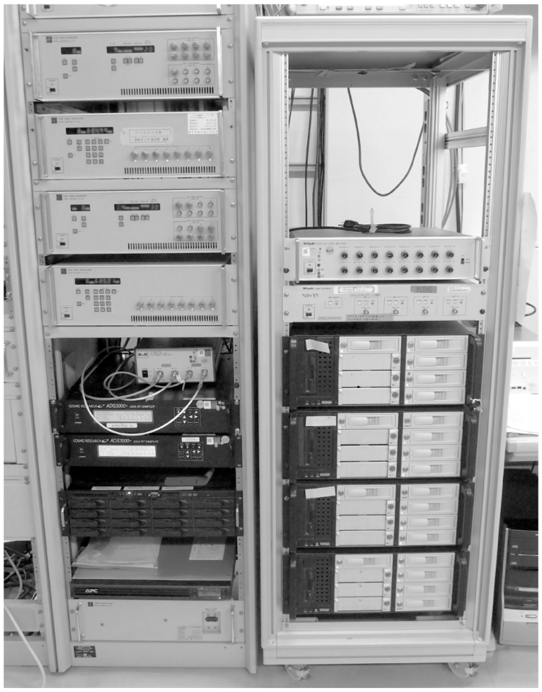

Fig. 4 Data acquisition terminal (K5/VSSP and K5/VSI).

relation center if necessary. All the VLBI data in NICT are transported to correlation centers by e-transfer from the data server at Kashima. The 10 Gbps network connection is provided by the High Speed R&D Network Testbed JGN. All the VLBI stations of NICT (Kashima 11 m, Koganei 11 m, and the Kashima 34 m) share the same 10 Gbps network. Figure 5 shows the schematic diagram of the local network connection and outbound network.

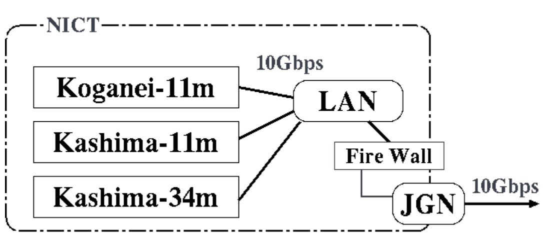

Fig. 5 Network environment of the VLBI stations at NICT (Kashima 11 m, Kashima 34 m, and Koganei 11 m). The nominal network speed is 10 Gbps. The data transfer rate available in practice is 5 Gbps at maximum.

Fig. 6 The Kashima 11-m antenna and GNSS receiver pillar of the IGS tracking station KSMV.

2.5 GNSS Station and Co-location of VLBI, SLR, and GPS

GPS receivers had been installed at the Kashima and Koganei sites in the Key Stone Project. Currently, the GNSS stations 'KSMV00JPN' at Kashima (Figure 6) and 'KGNI00JPN' at Koganei are operated in the observation network of the International GNSS Service (IGS). Their observation data is routinely submitted to the IGS Data Center. The importance of the local ties of the different space geodetic techniques has been recognized in the KSP. A local survey to link SLR, VLBI, and GPS stations has been conducted in the project for the period 1996–1999. Measurement precision of 1.5 mm standard deviation and details of the local survey are summarized by Hasegawa et al. [6] In addition, another local survey was conducted only for the Koganei site in 2013. This survey was triggered by the installation of a new 1.5-m optical telescope, which is for an optical satellite communication experiment of other project. The local survey data of the Kashima and Koganei sites are available from the KSP homepage [3] 'Survey' `http://ksp.nict.go.jp/survey/contents.htm` and 'Supplement' `http://ksp.nict.go.jp/survey/Supplment/KSP-colloc.html`.

[3] `http://ksp.nict.go.jp/`

3 Staff

The following staff members (alphabetical order) contribute to running the Kashima 11-m and Koganei 11-m stations.

Hasegawa Shingo: Supporting staff for IVS observing, operation of data conversion, and maintenance of file servers for e-transfer.
Ichikawa Ryuichi: In charge of GNSS station.
Kawai Eiji: In charge of maintenance of the Kashima 11-m and Koganei 11-m stations.
Kondo Tetsuro: Maintaining the K5/VSSP software package, which is used for data acquisition and conversion from K5 to Mk5B data.
Miyauchi Yuka: In charge of data acquisition software.
Sekido Mamoru: In charge of observation operation and overall activities of the Kashima and Koganei VLBI stations.
Tsutsumi Masanori: In charge of network security and maintenance of computers used in the project.

4 Current Status and Activities during the Past Years

The Kashima and the Koganei 11-m stations are participating in geodetic VLBI IVS-T2, APSG, CRF, and AOV sessions. Kashima 11 m participated in the CONT17 campaign.

Degradation of S-band receiver sensitivity due to RFI at the Koganei 11-m antenna is a serious issue, although there is no plan for a counter measure yet. The Koganei 11-m antenna has been operated under time sharing with the Space Environment Laboratory (SPEL). When the antenna is free from VLBI observing, its X-band receiver is used for receiving down-link signals from the STEREO satellite [4] by the SPEL.

Confirmation of antenna pointing has been made before every session, and no significant error has been reported. The last update of the antenna pointing model was on DOY 36 2017 and DOY 11 2015 for the Kashima 11 m and the Koganei 11 m, respectively.

[4] http://www.nasa.gov/mission_pages/stereo/main/index.html

Acknowledgements

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Matera CGS VLBI Station 2017–2018 Biennial Report

Giuseppe Bianco [1], Giuseppe Colucci [2], Francesco Schiavone [2]

Abstract This report presents the status of the Matera VLBI station. An overview of the station, some technical characteristics of the system, and staff addresses are also given.

1 General Information

The Matera VLBI station is located at the Italian Space Agency's 'Centro di Geodesia Spaziale G. Colombo' (CGS) near Matera, a small town in the south of Italy. The CGS came into operation in 1983 when the Satellite Laser Ranging SAO-1 System was installed. Fully integrated into the worldwide network, SAO-1 was in continuous operation from 1983 up to 2000, providing high precision ranging observations of several satellites. The new Matera Laser Ranging Observatory (MLRO), one of the most advanced Satellite and Lunar Laser Ranging facilities in the world, was installed in 2002, replacing the old SLR system. The CGS also hosted mobile SLR systems MTLRS (Holland/Germany) and TLRS-1 (NASA).

In May 1990, the CGS extended its capabilities to Very Long Baseline Interferometry (VLBI), installing a 20-m radio telescope. Since then, Matera has observed in 982 sessions up through December 2016.

In 1991 we started GPS activities, participating in the GIG 91 experiment and installing at Matera a permanent GPS Rogue receiver. In 1994, six TurboRogue SNR 8100 receivers were purchased in order to create the Italian Space Agency GPS fiducial network (IGFN). Currently, 15 stations are part of the IGFN, and all data from these stations, together with 24 other stations in Italy, are archived and made available by the CGS Web server GeoDAF (http://geodaf.mt.asi.it). Six stations are included in IGS network, while 12 stations are included in the EUREF network.

In 2000, we started activities with an Absolute Gravimeter (FG5 Micro-G Solutions). The gravimeter operates routinely at CGS and is available for external campaigns on request.

Thanks to the co-location of all precise positioning space-based techniques (VLBI, SLR, LLR, and GPS) and the Absolute Gravimeter, CGS is one of the few "fundamental" stations in the world. With the objective of exploiting the maximum integration in the field of Earth observations, the ASI extended CGS' involvement in the late 1980s to include remote sensing activities for present and future missions (ERS-1, ERS-2, X-SAR/SIR-C, SRTM, ENVISAT, and COSMO-SkyMed).

The Matera VLBI antenna is a 20-meter dish with a Cassegrain configuration and an AZ-EL mount. The AZ axis has ± 270 degrees of available motion. The slewing velocity is 2 deg/sec for both the AZ and the EL axes.

The technical parameters of the Matera VLBI antenna are summarized in Table 1.

The Matera time and frequency system consists of three frequency sources (two Cesium beam and one H-maser standard) and three independent clock chains. The iMaser 3000 H-maser from Oscilloquartz is used as a frequency source for VLBI.

1. Agenzia Spaziale Italiana
2. e-geos - an ASI/Telespazio company

Matera Network Station

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Fig. 1 Matera VLBI antenna.

2 Activities during the Past Year

The VLBI frequency standard is a T4SCIENCE iMaser 3000, installed in 2013.

Specifications for this new maser can be found here: http://www.t4science.com/product/imaser_3000.

3 Current Status

In 2017 and 2018, 68 and 60 sessions were observed, respectively. During 2017, Matera participated in the CONT17 campaign observing all 15 days. During 2018, heavy maintenance activities were necessary due to the aging of the antenna and many sessions were not acquired due to major failures occurring in the system. Figure 2 shows a summary of the total acquisitions per year, starting in 1990.

In 2004, in order to fix the existing rail problems, a complete rail replacement was planned. In 2005, due to financial difficulties, it was instead decided that only the concrete pedestal under the existing rail would be repaired. From then on, no rail movements have been noted [1, 2, 3].

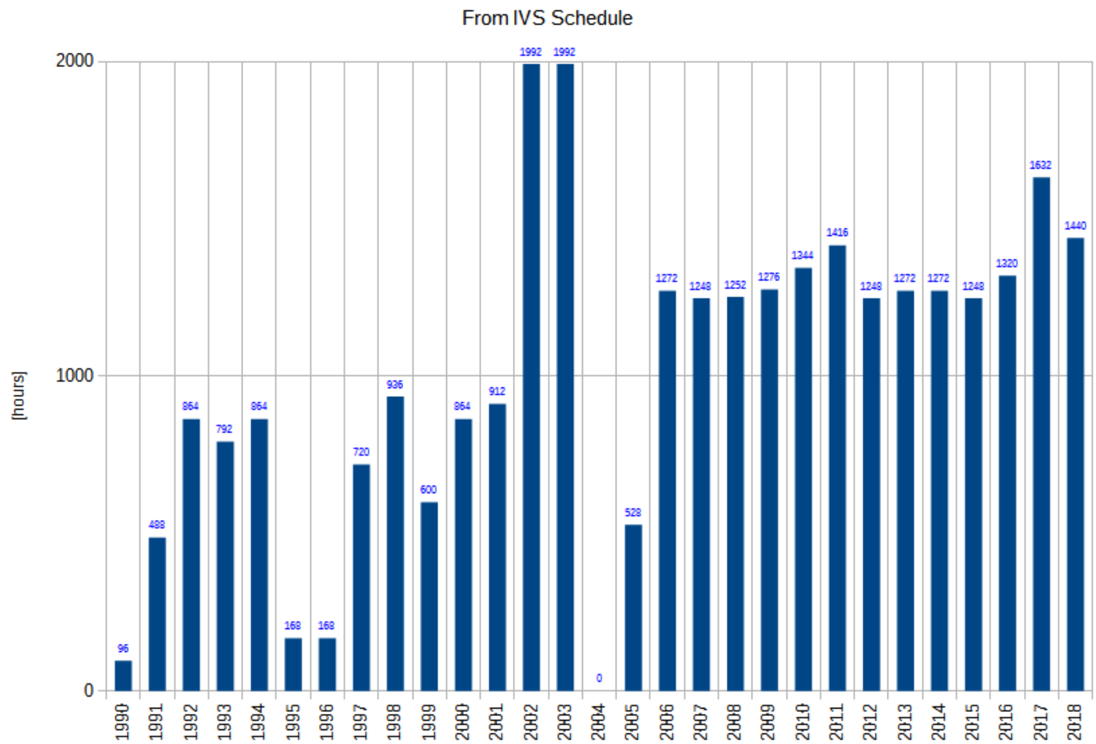

Fig. 2 Matera VLBI observation time.

Table 1 Matera antenna technical specification.

Parameter name	Values (S/X)
Input frequencies	2210−2450 MHz 8180−8980 MHz
Noise temperature at dewar flange	<20 K
IF output frequencies	190−430 MHz 100−900 MHz
IF Output Power (300 K at inp. flange)	0.0 dBm to +8.0 dBm
Gain compression	<1 dB at +8 dBm output level
Image rejection	>45 dB within the IF passband
Inter modulation products	At least 30 dB below each of two carriers at an IF output level of 0 dBm per carrier
T_{sys}	55/65 K
SEFD	800/900 Jy

4 Future Plans

In order to plan the building of a VGOS system, the fundraising investigation process has ended. Financing has been approved.

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Medicina Station Status Report

Alessandro Orfei, Giuseppe Maccaferri

Abstract General information about the Medicina Radio Astronomy Station, the 32-m antenna status, and the VLBI observations are provided. Updates to the hardware were performed and are briefly described.

1 The Medicina 32-m Antenna: General Information

The Medicina 32-m antenna is located at the Medicina Radio Astronomy Station. The station is run by the Istituto di Radioastronomia and is located approximately 33 km east of Bologna. The Consiglio Nazionale delle Ricerche was the funding agency of the Istituto di Radioastronomia until the end of 2004. Since January 1, 2005, the funding agency has been the Istituto Nazionale di Astrofisica (INAF). The antenna, which was inaugurated in 1983, has regularly taken part in IVS observations since 1987 and is an element of the European VLBI Network.

A permanent GPS station (MEDI), which is a part of the IGS network, is installed in the vicinity. Another GPS system (MSEL) is installed near the VLBI telescope and is part of the EUREF network.

Istituto di Radioastronomia INAF, Medicina

Medicina Network Station

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2 Current Status and Activities

- Antenna – In the two year period 2017–2018, antenna maintenance has been carried out by painting the panels of the primary mirror (see Figure 1) and by replacing the rail track. Preventive maintenance has also been done on the second driving wheel, the same maintenance having been done in 2014 on the first wheel. At the same time, the air conditioning system of the rooms located on the antenna was replaced, and the control rooms were completely renovated.
- Receivers – Medicina routinely makes observations in the 18, 21, 6, 5, 3.6, and 1.3 cm bands. A dual-feed receiver is under construction in the 13.5–18 GHz band (2 cm band).
- VLBI back-end – The DBBC firmware version is currently DDC V106 and V106E, PFB v16_1. The release 2.8.1-p of jiveab is currently installed. The Flexbuff system of Medicina has been upgraded with new disks. The capacity available is 360 TB. Medicina has also provided the same amount of TB for the JIVE correlator.
- e-VLBI – Medicina routinely ran e-VLBI experiments and EVN sessions.
- Space VLBI – Medicina continued to participate in Radioastron observations (on average 24 experiments/month).
- Field System – i) The workstation has been upgraded to FSL9. We are running FS 9.11.19. ii) The Continuous_cal system is working for the Cassegrain receivers (6, 5, and 1.3 cm). It was not possible to complete the same job for the Primary focus (21, 18, 13, and 3.6 cm); it will be done in 2019.

Fig. 1 A recent photo of the 32-m Medicina antenna (October 2017).

3 Geodetic VLBI Observations

Despite long periods of maintenance in both 2017 and 2018, Medicina participated in 67 regular 24-hour geodetic sessions: 15 CONT17, ten IVS-R1, 22 IVS-R4, three IVS-T2, six EUROPE, seven R&D, two RDV, and two VITA experiments.

VERA 2017 and 2018 Geodetic Activities

Takaaki Jike, Yoshiaki Tamura

Abstract The geodetic activities of VERA in the years 2017 and 2018 are briefly described. The regular geodetic observations were carried out both in K- and S/X-bands. The frequency of regular observations is three times a month–twice for the VERA internal observations in K-band. The networks of the S/X sessions are AOV and IVS-T2. The recorders used are K5VSSP for IVS-T2 and OCTAD-OCTADISK2 for AOV. The raw data of the T2 and AOV sessions are electronically transferred to the Bonn, SHAO, and GSI correlators via Internet. Gravimetric observations are carried out at the VERA stations. SGs are installed at Mizusawa and Ishigakijima in order to monitor precise gravity changes, and the observations continued for two years.

Fig. 1 The front view is the Mizusawa 10-m antenna, and the back is the VERA Mizusawa 20-m antenna.

1 General Information

VERA is a Japanese domestic VLBI network consisting of the Mizusawa, Iriki, Ogasawara, and Ishigakijima stations. Each station is equipped with a 20-m radio telescope and a VLBI back-end. The VERA Mizusawa 20-m antenna is shown in Figure 1. The VERA array is controlled from the Array Operation Center (AOC) at Mizusawa via Internet. The primary scientific goal of VERA is to reveal the structure and the dynamics of our galaxy by determining three-dimensional force field and mass distribution. Galactic maser sources are used as dynamical probes, the positions and velocities of which can be precisely determined by phase referenced VLBI relative to extragalactic radio sources. The distance is measured as a classical annual trigonometric parallax. The observing frequency bands of VERA are S-, C-, X-, K-, and Q-bands. Geodetic observations are made in S/X- and K-bands. C- and Q-band are currently not used for geodesy. Only a single beam is used even in K-band in geodetic observations, although VERA can observe two closely separated ($0.2^\circ <$ separation angle $< 2.2^\circ$) radio sources simultaneously by using the dual beam platforms.

General information about the VERA stations is summarized in Table 1, and the geographic locations are shown in Figure 2. The lengths of the baselines range from 1,080 km to 2,272 km. The skyline at Ogasawara station ranges from 7° to 18° because it is located at the bottom of an old volcanic crater. The northeast sky at Ishigakijima station is blocked by a nearby high mountain. But, the majority of the skyline is below 9°. The skylines at Mizusawa and Iriki are low enough

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to observe sources with low elevation. Because Ogasawara and Ishigakijima are small islands in the open sea and their climate is subtropical, the humidity in the summer is very high. This brings about high system temperatures in the summer, in particular in K- and Q-bands. Iriki, Ogasawara and Ishigakijima stations are frequently hit by strong typhoons. The wind speed sometimes reaches up to 60–70 m/s.

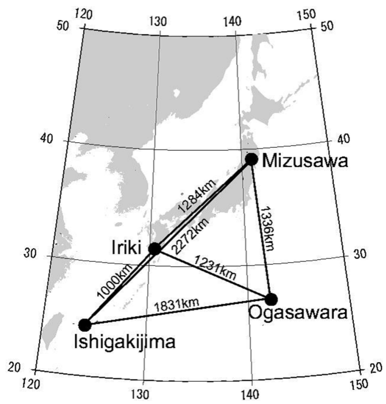

Fig. 2 Distribution of the stations in the VERA Network.

Table 1 VERA station locations.

Site name	Longitude	Latitude	Altitude
Mizusawa	141° 07' 57".199 E	39° 08' 00".726 N	75.7 m
Iriki	130° 26' 23".593 E	31° 44' 52".437 N	541.6 m
Ogasawara	142° 12' 59".809 E	27° 05' 30".487 N	223.0 m
Ishigakijima	124° 10' 15".578 E	24° 24' 43".834 N	38.5 m

2 Current Status

The parameters of the antennas and front- and back-ends are summarized in Tables 2 and 3, respectively. The actual receiver temperature at S-band is much higher than the notation in the table due to the influence of interference. Two observing modes are used for geodetic observations. One is VERA internal observing in K-band with the recording rate of 1- or 2-Gbps using OCTADISK. The other is conventional S/X-band observing with K5-VSSP (128 Mbps) and OCTAD-OCTADISK2 (1 Gbps). The AOV and IVS-T2 sessions belong to this class. Only Mizusawa participated in these sessions.

Table 2 Antenna parameters.

Diameter of main reflector	20 m
Mount type	AZ-EL
Surface accuracy	0.2 mm (rms)
Pointing accuracy	$< 12''$(rms)

	Azimuth	Elevation
Slew range	$-90°$–$450°$	5°–85°
Slew speed	2.1°/sec	2.1°/sec
Acceleration	2.1°/sec^2	2.1°/sec^2

	S	X	K
HPBW	$1550''$	$400''$	$150''$
Aperture efficiency	0.25	0.4	0.47

Table 3 Front-end and back-end parameters.

Front-end parameters			
Frequency band	S	X	K
Frequency range (GHz)	2.18–2.36	8.18–8.60	21.5–24.5
Receiver temperature	>100°K	100°K	39±8°K
Polarization	RHC	RHC	LHC
Receiver type	HEMT	HEMT	cooled HEMT
Feed type	Helical array		Horn

Back-end parameters			
Observation type	VERA Intl.	T2	AOV
Sampling/ch [MHz-bit]	32-2 or 1024-2	4-1	32-2
Channel	16 or 1	16	16
Filter	Digital	Analog	Digital
Recorder	OCTADISK	K5VSSP	OCTADISK2
Rec. rate [Mbps]	1024 or 2048	128	1024
Deployed station	4 VERA	Mizusawa	

3 Activities during the Past Year

VERA observes seven days a week, except during a maintenance period from the middle of June to the middle of August. The 24-hour geodetic sessions are allocated two or three times in a month. Among these geodetic sessions, VERA internal geodetic observations in K-band are performed once or twice per month, and Mizusawa participates in AOV or IVS-T2 sessions in S/X-band on a once-a-month basis. The main purpose of the VERA internal geodetic observations is to determine relative positions of the VERA antennas accurately enough for astrometric requirements. The purpose of the S/X sessions is to link the VERA coordinates into the reference frame built by VLBI.

In the VERA internal geodetic sessions, the regularly-used frequency changed from S/X-band to K-band in 2007. The reason for the shift of the observing frequency band from S/X-band to K-band is to avoid the strong radio interference by mobile phones in S-band, particularly at Mizusawa. The interfering signal which has line spectra is filtered out. But this filtering considerably degrades the system noise temperature. The interference zone is increasing, so it is likely that S-band observing will become almost impossible in the near future. On the other hand, VERA has the highest sensitivity in K-band as shown in Table 2. Thanks to the high sensitivity in this band, the maximum number of scans in K-band is 800/station/24-hours, while that in S/X-band is 500 at most. It has been confirmed that the K-band observations are far more precise. In fact, standard deviations of the individual determinations of the antenna positions in K-band are less than half of those in S/X-band.

In 2017 and 2018, a long maintenance period from the middle of June to the middle of August was allocated for each year. Except for this period, VERA carried out internal geodetic VLBI observations 33 times. Mizusawa participated in eight T2 sessions, and six AOV sessions. The final estimation of the geodetic parameters are derived by using the software developed by the VERA team.

Continuous GPS observations were carried out at each VERA station throughout the year. The superconducting gravimeter (SG) installed within the enclosure of the Mizusawa VLBI observatory, in order to accurately monitor gravity change for the purpose of monitoring height change at the VERA Mizusawa station, continued acquisition of gravity data. Four water level gauges surrounding the SG were used for monitoring the groundwater level. The preliminary results show that gravity variation due to the variation of the water table can be corrected as accurately as the 1 micro gal level. An SG was newly installed also at the VERA Ishigakijima station, and observing started in January 2012. The observing continued also during 2017–2018. The observing aims at solving the cause of the slow slip event which occurs frequently around the Ishigaki island.

4 State of the Crustal Movement after Earthquakes

After the 2011 earthquake off the Pacific coast of Tohoku (Mw=9.0) [Epoch=11 March 2011, 14:16:18 JST], Mizusawa was displaced by co-seismic crustal movement and post-seismic creeping. Also from 2017 to 2018, the post-seismic creeping continued, although the speed declined. According to the newest analysis, the co-seismic steps on March 11, 2011 are X= -2.066 m, Y= -1.407 m, and Z= -1.054 m, and the displacement by creeping during two years, 2017 and 2018, is X= -0.112 m, Y= -0.048 m, and Z= -0.024 m. Due to the 2016 Kumamoto Earthquake (Mw=7.0) [Epoch=14 April 2016, 01:25:05 JST], crustal deformation changed the position and rate of Iriki. Displacement of Iriki by co-seismic step and post-seismic creeping due to the 2016 Kumamoto Earthquake is more than 1 cm toward the south, in total.

5 Future Plans

The examination of increasing a recording rate to 8 Gbps from 1 Gbps by using a high speed sampler (OCTAD) is being carried out. Experimental geodetic VLBI observing was carried out in February 2016 using the high speed sampler. In November 2017, a second experimental session was carried out at all VERA stations for the purpose of improvement of parameter fitting performance, and we can get the geodetic solutions.

VERA installed new frequency band receivers, L- and K(RCP)-band, and performance investigation of these receiving systems is being conducted now.

6 Staff

Mareki Honma is the director of the Mizusawa VLBI Observatory. The geodesy group consists of Yoshiaki Tamura (scientist) and Takaaki Jike (scientist).

Noto Station Status Report

Pietro Cassaro

Abstract The Noto VLBI Station has been operational in the past two years, except for the last part of 2018 due to the S/X receiver degradation. The current status of the antenna is provided.

1 The Noto 32-m Antenna: General Information and Current Status

The Noto 32-m antenna is a Cassegrain radiotelescope in operation since 1989 by the Istituto di Radioastronomia, part of the INAF (Istituto Nazionale di AstroFisica).

The main feature of this instrument is an active surface, allowing continuous correction of gravitational deformation during observations.

The radiotelescope has receivers that span the frequency range of 2.3–45 GHz, but presently the radiotelescope can observe at 5, 6, and 22 GHz.

A new receiver at 1.4–1.6, 2.3, and 8 GHz is nearing completion and will be operating by July 2019. Our 43 GHz receiver had to be checked and is still under evaluation for LNA problems and subreflector performance issues.

The DBBC + FILA10G, is operating for VLBI observations. The ESCS (Enhanced Single-dish Control System) has become DISCOS, that unified the control systems of the antennas of Medicina, Noto, and SRT. Presently, the DISCOS system manages the single dish observations and test, calibration, and configurations of the receivers.

The geodetic observations were stopped in the last part of 2018 due to the heavy degradation of the S/X receiver; it is forecast to resume observations once the new receiver is mounted.

2 Geodetic VLBI Observations

In 2017 and 2018, Noto participated in 28 24-hour routine geodetic sessions: ten IVS-T2, 11 IVS-CRF, four EUROPE, one AUS-AST, and two VITA experiments.

Istituto di Radioastronomia INAF, Noto

Noto Network Station

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Ny-Ålesund Geodetic Observatory

Piotr Kupiszewski

Abstract In 2017/2018, the 20-m telescope at Ny-Ålesund, Svalbard, operated by the Norwegian Mapping Authority (NMA), was scheduled in 259 24-hour and 80 one-hour observations of the IVS program. The new geodetic observatory with twin 13-m VGOS telescopes was officially inaugurated in 2018 and will gradually take over from the 20-m telescope.

1 General Information

The Geodetic Observatory of the Norwegian Mapping Authority (NMA) is situated at 78.9° N and 11.9° E in Ny-Ålesund, in Kings Fjord, on the west side of the island Spitsbergen. This is the biggest island in the Svalbard archipelago. In 2017/2018, Ny-Ålesund was scheduled for 259 24-hour VLBI observations, including R1, R4, EURO, RD, and T2 sessions, and a two-week CONT session (in November–December 2017). Ny-Ålesund also participated in 80 one-hour observations within the Intensives program.

In addition to the 20-meter VLBI telescope, the Geodetic Observatory has two GNSS receivers in the IGS system and a Super Conducting Gravimeter (SCG) in the Global Geodynamics Project (GGP) installed at the site. A second SCG is installed at the new geodetic observatory at Brandal, approximately 1.5 km away. The French Institut Geographique National operates a DORIS station close by. In 2018, the beacon was moved from the center of Ny-Ålesund to the vicinity of the light sensitive cabin, approximately 2.75 km NW of its previous location, placing it closer to the new geodetic observatory and ensuring better co-location of the geodetic techniques on site. Instrumentation at the observatory also includes a GPS Ionospheric Scintillation and TEC Monitor (GISTM; running since 2004), which is operated in the frame of ISACCO, a research project on ionospheric scintillation observations led by the Italian Institute of Volcanology and Geophysics (INGV). Another Real-Time Ionospheric Scintillation (RTIS) Monitor was set up by the NMA in November 2012.

Norwegian Mapping Authority, Geodetic Institute

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Fig. 1 Geodetic observatory, 20-m telescope, and the GFZ's satellite station.

2 Component Description

The antenna with 20-m diameter is intended for geodetic use and receives in S- and X-band. Its design and construction are similar to those at Green Bank and

Kokee Park. A DBBC2 streams the data to a Mark5B+ recorder, having replaced the previously used analog rack. Another Mark5B+ unit is used to transfer data via network to the correlators. Timing and frequency is provided by a NASA NR maser, which is monitored by a CNS system.

3 Staff

The staff in Ny-Ålesund consists of four people (see Figure 2) employed at 75-100%, with 3.5 full-time positions currently covered. Station staff are part of the Department for Global Geodesy at the Geodetic Division of the Norwegian Mapping Authority, which has its main office in Hønefoss (near Oslo).

Axel Meldahl has been working as an operating engineer at the observatory since 2015, while Trond Sandmo and Simon L'orange joined as operating engineers in 2017 and 2018, respectively. Piotr Kupiszewski joined the team in mid-2018 as operations manager and has been acting head of the Department for Global Geodesy since November 2018.

The staff in Ny-Ålesund work closely with colleagues located on the mainland at NMA's Hønefoss and Oslo offices: Ann-Silje Kirkvik (VLBI data analyst), Leif Morten Tangen (VLBI technical manager), Gro Grinde (project leader for the new geodetic observatory), and Laila Løvhøiden (head of department) (see Table 1 for an overview).

Fig. 2 Ny-Ålesund geodetic observatory core team: Trond Sandmo, Piotr Kupiszewski, Simon L'orange, Axel Meldahl.

Table 1 Staff related to VLBI operations in Ny-Ålesund.

Head of department	Laila Løvhøiden
Acting head of department	Piotr Kupiszewski
Project leader (new observatory)	Gro Grinde
Technical manager	Leif Morten Tangen
Operations manager	Piotr Kupiszewski
Operating engineer	Axel Meldahl
Operating engineer	Simon L'orange
Operating engineer	Trond Sandmo
VLBI data analyst	Ann-Silje Kirkvik

4 Current Status and Activities

4.1 Maintenance

The 20-m telescope has been in operation for 25 years, and considerable maintenance is required to keep it operational. Among the maintenance carried out in 2017 and 2018 were installation of new tachometers and motor brushes, exchanging the X-band waveguide window in order to fix dewar leakage issues, and exchanging a malfunctioning azimuth encoder.

In March 2017, maser power supply issues caused many sessions to be lost. Due to the leaking dewar, the receiver was operated warm for most of the sessions from July to November 2018. Furthermore, during summer 2018, false alarms triggered by electrical faults during antenna operation in humid conditions hampered observations on a regular basis. The latter issue unfortunately remains unsolved, and a proper fix requires a major overhaul of the cabling. In order to increase the lifetime of the radio telescope, wind speed limits for operation have been decreased, with the threshold now set to $15\frac{\mathrm{m}}{\mathrm{s}}$. Wind speeds over this value prompt an alarm, and the observation is stopped.

In addition to maintenance of the telescopes, a major clean-up and re-organization of the office and storage space has been carried out. A new fire escape double door has been installed at the Rabben office, providing a grand view of the fjord and mountains. Finally, a new internet site for the geodetic observatory has been set up: (https://www.kartverket.no/en/About-The-Norwegian-Mapping-Authority/geodetic-earth-observatory/).

4.2 New Observatory

In June 2018, the new geodetic observatory at Brandal (see Figure 3) was officially opened, coinciding with the 10th conference of the International VLBI Service for Geodesy and Astrometry, IVS2018, in Longyearbyen. 110 delegates were invited to participate in the official opening and were transported to Ny-Ålesund by boat for the inauguration.

The new observatory features fast-slewing VGOS (VLBI Global Observing System) twin telescopes and will have a broadband (2-14 GHz) signal acquisition chain. The telescopes are 13.2 meters in diameter and are 18 meters above the ground.

A tri-band feed is currently installed and will be used for testing of the facility and transfer of the data series from the 20-meter radio telescope at Rabben. Backend equipment consisting of a DBBC3 and flexbuff is already in place for the first telescope.

Fig. 3 The new geodetic observatory at Brandal.

5 Future Plans

Fully operationalizing the twin telescopes at the new geodetic observatory is at the center of attention for the upcoming couple of years. Most notably, completion and installation of the broadband signal acquisition chain is planned for 2019–2020. Work is currently ongoing to complete the first broadband feed at Yebes, Spain, with shipping to Ny-Ålesund planned for summer 2019. Delivery of the second broadband feed is planned for summer 2020. Efforts to operate the first telescope with a tri-band feed are ongoing, and the station will hopefully join in tag-along mode in the very near future, so that connection of the time series from the old 20-m telescope and from the new facility can begin. Concurrently, it is aimed to keep the 20-m telescope operational for a few more years in order to carry out parallel observations with the new telescope and to provide the best possible contribution to the ITRF2020. Nonetheless, due to limited resources, operationalizing the new observatory is prioritized, and it has to be expected that down-time for the 20-m telescope will increase when technical issues are encountered.

German Antarctic Receiving Station (GARS) O'Higgins

Christian Plötz [1], Theo Bachem [1], Reiner Wojdziak [1], Thomas Klügel [1], Alexander Neidhardt [2], Torben Schüler [1]

Abstract A new firmware of the antenna control unit (ACU) with an enhanced remote operations capability was installed and tested in the 9 meter radio telescope. The operational parameters of the VLBI receiver are monitored automatically. The thermal stability of the hydrogen maser EFOS-50 was improved by an enclosing box, which lowers the impact of ambient temperature variations. The workflow and the integration of the VLBI observations into the Satellite Monitor and Control Software (SMCS) of our partner institution DLR is now seamlessly implemented.

1 General Information

The German Antarctic Receiving Station (GARS) is jointly operated by the German Aerospace Center (DLR) and the Federal Agency for Cartography and Geodesy (BKG, belonging to the duties of the Geodetic Observatory Wettzell (GOW)). The Institute for Antarctic Research Chile (INACH) coordinates the logistics. The 9-meter radio telescope at GARS O'Higgins is mainly used for downloading of remote sensing data from satellites such as TanDEM-X and for the commanding and monitoring of spacecraft telemetry. DLR operating staff and a Chilean team for maintaining the infrastructure (e.g., power and freshwater generation, technical support) attend the station the entire year. BKG staff was on site from the end of January to mid-March 2017 and from the end of October until mid-December 2017. During these two campaigns, a total of seven 24-hour IVS sessions were scheduled. In addition, the O'Higgins VLBI radio telescope participated in four 24-hour BKG sessions by remote control.

Carriage of passengers and cargo by air and by ship was organized by the Chilean Antarctic Institute (INACH) in close collaboration with the Chilean Army, Navy, and Airforce and with the Brazilian Airforce. All technical material and food for the entire stay are delivered from Punta Arenas via Base Frei on King George Island to O'Higgins on the Antarctic Peninsula. The conditions for landing on the glacier are strongly weather dependent. In general, transport of staff and cargo is always a challenging task. Arrival and departure times strongly depend on the current meteorological conditions and on the logistic circumstances.

The VLBI system is continuously operational, and maintenance and potential repair work is only possible when BKG staff is present. Frequent damages resulting from the rough climate conditions and strong storms have to be identified and repaired, e.g., damages to wind sensors. Shipment of each kind of material, such as special tools, spare parts, or upgrade kits, has to be carefully prepared in advance. The most important station and system parameters are permanently monitored remotely.

2 Activities during the Past Years 2017–2018

The hydrogen maser EFOS-50 had a stability problem with variable ambient temperature. The installation of

1. Bundesamt für Kartographie und Geodäsie (BKG)
2. Forschungseinrichtung Satellitengeodäsie (FESG), Technische Universität München

GARS O'Higgins Network Station

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Fig. 1 View of the 9-m radio telescope, GNSS sites, and corner cube.

a specially designed housing box solved this problem. The mounting adapter for the GNSS site OHI2 was replaced with a new adapter for an improved mechanical stability. The wind sensor on top of the neighboring station was replaced twice due to the impact of strong storm winds. The VLBI receiver monitoring was completely automatized. The antenna control unit (ACU) of the 9-meter radio telescope was upgraded with a new firmware version, specially enhanced for remote operations. The command interface is now completely accessible by TCP/IP interface. The existing sea level gauge was uninstalled, and the complete equipment was prepared for sending back.

Fig. 2 Integrated VLBI and satellite operations.

3 Staff

The staff members responsible for the operation, maintenance, and upgrade of the VLBI system and other geodetic devices are summarized in Table 1.

4 Current Status

Besides the 9-m VLBI antenna, which is used for the dual purposes of receiving data from and sending

Table 1 Staff members.

Name	Affiliation	Function	Mainly working for
Torben Schüler	BKG	head of the GOW	GOW
Thomas Klügel	BKG	deputy head of the GOW	administration laser gyro/ local systems Wettzell
Christian Plötz	BKG	electrical engineer (chief engineer RTW)	O'Higgins, RTW, TTW
Reiner Wojdziak	BKG	software engineer	O'Higgins, IVS Data Ctr Leipzig
Theo Bachem	BKG	electrical engineer	SLR Wettzell, operator O'Higgins
Swetlana Mähler	BKG	geodesist	survey, SLR Wettzell, logistics O'Higgins
Olaf Lang	BKG	electrical engineer	local systems/ SLR Wettzell, logistics O'Higgins
Alexander Neidhardt	FESG	head of the microwave group, VLBI chief	RTW, TTW
Gerhard Kronschnabl	BKG	electrical engineer (chief engineer TTW)	TTW, RTW

commands to remote sensing satellites and performing geodetic VLBI, other geodetic-relevant instruments are also operated on site:

- currently two H-masers (EFOS-11 and EFOS-50), an atomic Cs-clock, a GPS time receiver, and a Total Accurate Clock (TAC) offer time and frequency.
- two GNSS receivers, OHI2 and OHI3, operating in the frame of the IGS network, while both are Galileo enabled. The receivers worked without failure.
- a meteorological station providing pressure, temperature, humidity, and wind information, as long as the temporarily extreme conditions did not disturb the sensors.
- two SAR corner reflectors, which were installed in March 2013 as part of a network to evaluate the localization accuracy of the TerraSAR-X mission.

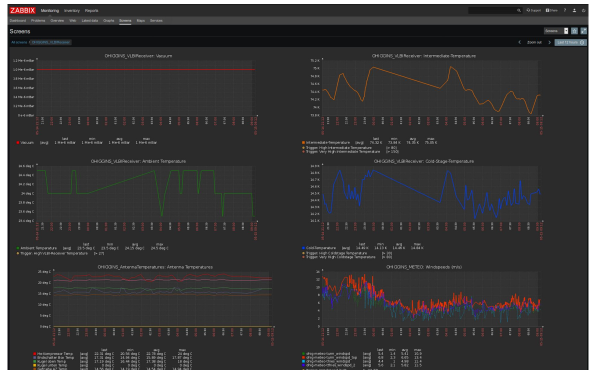

Fig. 3 VLBI receiver monitoring using Zabbix.

5 Future Plans

The cold head of the VLBI receiver needs to be replaced, after more than two years of continuous operation. This maintenance is planned within the first presence of BKG staff beginning 2019. A new UPS for buffering the power supplies of the masers EFOS-11 and EFOS-50 is foreseen to replace the old one. The buffer batteries of the old one have no more electrical capacity to provide support for power interruptions.

References

1. D. Behrend, "Coordinating Center Report", In K. D. Baver, D. Behrend, and K. Armstrong, editors, International VLBI Service for Geodesy and Astrometry 2012 Annual Report, NASA/TP-2013-217511, pages 55–57, 2013.

Onsala Space Observatory – IVS Network Station Activities during 2017–2018

Rüdiger Haas, Thomas Hobiger, Gunnar Elgered, Niko Kareinen, Grzegorz Klopotek, Joakim Strandberg, Periklis-Konstantinos Diamantidis, Hans-Georg Scherneck, Maxime Mouyen, Peter Forkman

Abstract During 2017 and 2018 we participated in 87 legacy S/X sessions with the Onsala 20-m telescope. Additionally, we observed a number of VGOS test sessions with one or both of the Onsala twin telescopes.

1 General Information

The Onsala Space Observatory is the national facility for radio astronomy in Sweden with the mission to support high-quality research in radio astronomy and geosciences. The geoscience instrumentation at Onsala includes equipment for geodetic VLBI, GNSS, a superconducting gravimeter, a platform for visiting absolute gravimeters, several microwave radiometers for atmospheric measurements, both GNSS-based and conventional tide gauge sensors, and a seismometer. The Onsala Space Observatory can thus be regarded as a fundamental geodetic station.

During the last years the Onsala twin telescopes (OTT) were installed. The telescopes were inaugurated in connection with the 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry, held in Gothenburg 14–16 May 2017. A ceremonial event with more than 200 international and national guests was held on 18 May 2017 (see Figure 1).

On Thursday 18 April 2018, the observatory arranged an event to celebrate the first transatlantic geodetic VLBI experiment done 50 years earlier. A corresponding activity was carried out at Haystack Observatory. At Onsala retired colleagues that participated in the first experiment were invited (see Figure 2). Bert Hansson gave a lecture, describing both the extensive preparations as well as the execution of this first experiment.

The staff members associated with the IVS Network Station at Onsala are listed in Table 1.

Chalmers University of Technology, Department of Space, Earth and Environment, Onsala Space Observatory

Onsala IVS Network Station

IVS 2017+2018 Biennial Report

Fig. 1 The inauguration of the Onsala twin telescopes was held on 18 May 2017.

2 Legacy S/X VLBI Observations

In total, we participated in 51 and 37 legacy S/X sessions during 2017 and 2018, respectively (see Table 2). The majority were standard IVS sessions, but there were a small number of special sessions, too. During 2018 a lower number of sessions were observed, because the subreflector control electronics was replaced in January, and between June and the middle of Au-

Table 1 Staff members associated with the IVS Network Station at Onsala. All e-mail addresses have the ending @chalmers.se, and the complete telephone numbers start with the prefix +46-31-772.

Function	Name	e-mail	telephone
Responsible P.I.s for geodetic VLBI observations	Rüdiger Haas	rudiger.haas	5530
	Thomas Hobiger (–2018.06.30)	thomas.hobiger	5549
Ph.D. students involved in geodetic VLBI	Niko Kareinen (–2018.08.15)	niko.kareinen	5566
	Grzegorz Klopotek	grzegorz.klopotek	5575
	Joakim Strandberg (–2018.05.31)	joakim.strandberg	5566
	Periklis-Konstantinos Diamantidis (2018.01.15–)	periklis.diamantidis	5575
Responsible for the VLBI Field System	Michael Lindqvist	michael.lindqvist	5508
	Rüdiger Haas	rudiger.haas	5530
Responsible for the VLBI equipment	Karl-Åke Johansson	karl-ake.johansson	5571
	Leif Helldner	leif.helldner	5576
Responsible for the VLBI operators and data recording and transfer equipment	Roger Hammargren	roger.hammargren	5551
	Simon Casey	simon.casey	5529
Telescope scientist	Henrik Olofsson	henrik.olofsson	5564
Software engineer	Mikael Lerner	mikael.lerner	5581
Responsible for gravimetry	Hans-Georg Scherneck (–2018.09.30)	hans-georg.scherneck	5556
	Maxime Mouyen (2018.10.01–)	maxime.mouyen	5549
Responsible for tide gauge and radiometry	Gunnar Elgered	gunnar.elgered	5565
Responsible for aeronomy and radiometry	Peter Forkman	peter.forkman	5577
Observatory director	John Conway	john.conway	5503

gust the control room was rebuilt. All sessions were recorded with the DBBC2/Flexbuff system, and the data were e-transferred for correlation.

At the end of the last day of the CONT17 campaign the 20-m telescope got stuck in elevation. This caused the last 4.5 h of this session to be lost. During one of the R1 sessions in 2018, we lost the last 10 h of data because the Fila10G had stopped working, and thus no data were recorded.

Fig. 2 Onsala veterans involved in the first transatlantic geodetic VLBI experiment in early April 1968. Left to right: Anders Winnberg, Lars-Göran Gunnarsson, Christer Andersson, Bert Hansson, Gustaf Rydbeck, Göran Netzler, Magne Hagström, Monica Hansen with her dog Moss, and Ingvar Samulesson.

3 VGOS Observations

In September 2017 we started to participate in VGOS test sessions (see Table 3). Most of these sessions were observed with ONS13NE (OE), but some also with ONSA13SW (OW), or both systems. We participated in international VGOS sessions (VT), European VGOS session (VGT), and sessions together with Kashima where we used the Japanese VGOS setup (OK). We experienced a steep learning curve both in terms of the new technical equipment and in the VGOS operations as such. The majority of the sessions were affected by different technical problems, e.g., due to the PCAL systems, the DBBC3, or recording. Our ambitious goal to already participate in the VGOS CONT17 could unfortunately not be achieved. However, improvements and fine-tuning of the VGOS systems led to a stabilization, so that at the end of 2018, finally, rather successful and reliable VGOS observations could be performed.

Table 2 Geodetic VLBI observations at Onsala during 2017 and 2018. The third and sixth columns give some general remarks and information on the percentage of the scheduled Onsala (On) observations that were used in the analysis (as reported on the Web pages for the IVS session analyses), compared to the station average (StAv) percentage per experiment.

Exp.	Date	Remarks	Exp.	Date	Remarks
R1.773	17.01.03	OK: 87.1 % (StAv 79.1 %)	R1.829	18.02.12	OK: 96.0 % (StAv 94.2 %)
R1.774	17.01.10	OK: 77.7 % (StAv 54.0 %)	T2.123	18.02.13	OK: 76.4 % (StAv 56.1 %)
R1.776	17.01.23	OK: 84.4 % (StAv 69.8 %)	EUR.147	18.02.14	OK
RV.121	17.01.31	OK: 93.0 % (StAv 87.1 %)	R1.830	18.02.19	OK: 77.4 % (StAv 54.3 %)
R1.778	17.02.06	OK: 82.5 % (StAv 72.3 %)	RV.128	18.02.20	OK: 81.1 % (StAv 65.6 %)
T2.116	17.02.07	OK	R1.831	18.02.26	OK: 87.6 % (StAv 86.0 %)
EURD.01	17.02.08	OK	R1.832	18.03.05	OK: 84.3 % (StAv 60.1 %)
R1.780	17.02.21	OK: 70.5 % (StAv 55.9 %)	R1.834	18.03.19	OK: 77.5 % (StAv 73.6 %)
WHISP.6	17.02.22	OK	R1.836	18.04.03	OK: 77.5 % (StAv 86.1 %)
R1.785	17.03.27	OK: 73.0 % (StAv 68.7 %)	RV.129	18.04.04	OK: 94.2 % (StAv 75.2 %)
R1.788	17.04.18	OK: 77.7 % (StAv 71.2 %)	R1.839	18.04.23	OK: 96.6 % (StAv 95.1 %)
RD.17.05	17.04.19	OK	T2.124	18.04.24	OK: 64.0 % (StAv 49.6 %)
R1.789	17.04.24	OK: 85.5 % (StAv 69.3 %)	R1.840	18.05.02	OK: 86.9 % (StAv 75.4 %)
RV.122	17.04.25	OK: 84.1 % (StAv 65.6 %)	EURD.05	18.05.07	OK
R1.790	17.05.02	OK: 93.4 % (StAv 89.9 %)	T2.125	18.05.15	OK: 58.5 % (StAv 70.5 %)
R1.793	17.05.22	OK: 90.8 % (StAv 77.8 %)	R1.843	18.05.22	OK: 54.8.5 % (StAv 77.9 %) (10 h lost)
R1.798	17.06.26	OK: 93.0 % (StAv 90.4 %)	R1.856	18.08.20	OK: 79.5 % (StAv 65.3 %)
RV.123	17.06.28	OK: 88.8 % (StAv 75.0 %)	RV.130	18.08.21	OK: 55.1 % (StAv 72.8 %)
R1.799	17.07.03	OK: 91.8 % (StAv 89.2 %)	RD.18.06	18.08.22	not correlated yet
WHISP.7	17.07.05	OK	R1.857	18.08.27	OK: 58.1 % (StAv 48.2 %)
R1.800	17.07.10	OK: 85.0 % (StAv 81.8 %)	R1.858	18.09.03	OK: 62.8 % (StAv 45.4 %)
T2.119	17.07.11	OK	T2.127	18.09.04	OK: 79.9 % (StAv 62.1 %)
R1.808	17.09.05	OK: 90.0 % (StAv 85.7 %)	EUR.148	18.09.05	not correlated yet
R1.809	17.09.11	OK: 95.0 % (StAv 93.9 %)	R1.859	18.09.10	OK: 83.8 % (StAv 67.2 %)
T2.120	17.09.12	OK: 78.6 % (StAv 64.8 %)	R1.863	18.10.08	OK: 88.0 % (StAv 80.3 %)
EURD.02	17.09.13	OK	EURD.07	18.10.09	OK: 94.8 % (StAv 93.2 %)
R1.811	17.09.25	OK: 82.7 % (StAv 67.8 %)	R1.868	18.11.12	OK: 81.8 % (StAv 69.0 %)
RD.17.10	17.10.04	OK: 84.8 % (StAv 75.4 %)	T2.128	18.11.13	OK
AUA.029	17.10.07	OK	RV.132	18.11.14	OK: 82.8 % (StAv 69.9 %)
R1.814	17.10.16	OK: 96.4 % (StAv 91.6 %)	VT.007	18.11.23	not correlated yet
T2.121	17.10.17	OK: 52.9 % (StAv 34.4 %)	R1.870	18.11.26	OK: 90.3 % (StAv 87.3 %)
R1.819	17.11.20	OK: 92.5 % (StAv 91.2 %)	R1.872	18.12.10	OK: 84.6 % (StAv 80.5 %)
R4.819	17.11.21	OK: 87.3 % (StAv 81.0 %)	EURD.08	18.12.11	not correlated yet
EURD.03	17.11.23	OK	RD.18.10	18.12.12	not correlated yet
C17.01	17.11.28	OK: 92.3 % (StAv 86.4 %)	R1.873	18.12.17	OK: 83.8 % (StAv 67.4 %)
C17.02	17.11.29	OK: 94.1 % (StAv 90.7 %)	T2.129	18.12.18	not correlated yet
C17.03	17.11.30	OK: 81.6 % (StAv 75.0 %)			
C17.04	17.12.01	OK: 80.6 % (StAv 61.7 %)			
C17.05	17.12.02	OK: 87.8 % (StAv 77.8 %)			
C17.06	17.12.03	OK: 83.2 % (StAv 74.0 %)			
C17.07	17.12.04	OK: 76.5 % (StAv 68.7 %)			
C17.08	17.12.05	OK: 90.7 % (StAv 87.4 %)			
C17.09	17.12.06	OK: 86.3 % (StAv 81.1 %)			
C17.10	17.12.07	OK: 80.6 % (StAv 72.0 %)			
C17.11	17.12.08	OK: 78.7 % (StAv 68.3 %)			
C17.12	17.12.09	OK: 94.9 % (StAv 89.6 %)			
C17.13	17.12.10	OK: 91.0 % (StAv 85.7 %)			
C17.14	17.12.11	OK: 80.6 % (StAv 72.4 %)			
C17.15	17.12.12	OK: 78.8 % (StAv 88.9 %) (4.5 h lost)			

4 Monitoring Activities

We continued with monitoring activities:

Calibration of pressure sensor

The ground pressure sensor at the observatory is continuously monitored and compared with a “travelling” barometer in order to maintain traceability to SI. The travelling barometer was calibrated at the SMHI main office in Norrköping on 16 January 2018. The differences were ≤ 0.1 hPa in the interval 950–1050 hPa.

The comparisons between the two sensors at the observatory, carried out during the two years since the last biennial report, are shown as the differences in Figure 3, and the dynamical range is illustrated in Figure 4. A very weak systematic change of about 0.1 hPa over the two years can be seen, but we find this acceptable, because an uncertainty of 1 hPa corresponds to 2.3 mm in the zenith hydrostatic delay.

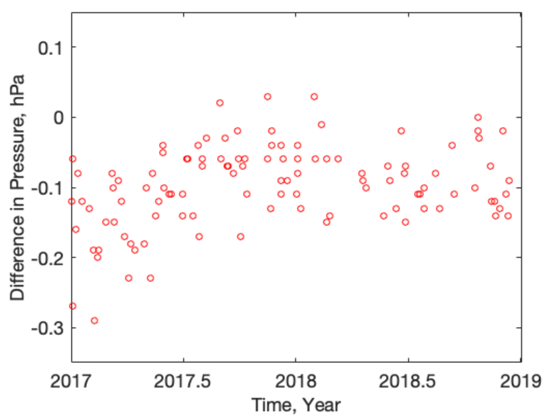

Fig. 3 Time series of pressure differences between the VLBI pressure sensor at the 20-m telescope and the calibrated pressure sensor from SMHI.

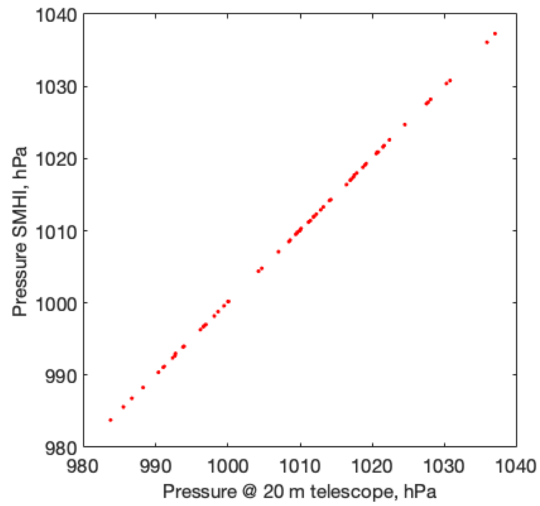

Fig. 4 The dynamical range of the comparisons during 2017–2018 between the VLBI pressure sensor at the 20-m telescope and the calibrated pressure sensor from SMHI.

Vertical changes of the 20-m telescope tower

We continued to monitor the vertical changes of the telescope tower using the invar rod system at the 20-m telescope. The measurements are available at `http://wx.oso.chalmers.se/pisa/`.

The local geodetic network

During 2018 six geodetic survey pillars were installed around the twin telescopes. The extended local geodetic network at the observatory was thereafter surveyed in the summer by colleagues from the Frankfurt University of Applied Sciences (UAS), Germany.

Gravitational deformation of the OTT

In the summer of 2018 photogrammetric measurements were performed to determine the gravitational deformation of the OTT. This work was done in collaboration with Frankfurt UAS and involved photogrammetry with a drone. A popular science video summarizing this work is available at `https://www.youtube.com/watch?v=sNnHvBaQ3_w`.

Superconducting gravimetry

The superconducting gravimeter operated continuously and produced a highly accurate record of gravity variations. Tide solutions were prepared on a weekly basis, and results are available on the SCG homepage (`http://holt.oso.chalmers.se/hgs/SCG/toe/toe.html`).

Absolute gravimetry

Lantmäteriet, the Swedish mapping, cadastral, and land registration authority, visited the observatory twice with their FG5 instrument. Measurement campaigns were performed in 2017 and 2018.

Table 3 VGOS observations at Onsala during 2017 and 2018. We participated in international VGOS test sessions (VT), European VGOS test sessions (VGT), and a few test sessions with the Japanese interpretation of VGOS (OK). The two MC sessions were “mini-CONT” VGOS test sessions for preparation for VGOS-CONT17. The filled circles indicate which VGOS system was used, ONSA13NE (ON) and/or ONSA13SW (OW).

Session	Date	h	OE	OW	Comment
VT7268	17.09.25	24	•	○	PCAL problems, weak fringes
MC7277	17.10.04	24	•	•	PCAL problems, weak fringes
MC7278	17.10.05	24	•	•	PCAL problems, weak fringes
VT7303	17.10.30	24	•	•	PCAL and ampl. problems
VT7317	17.11.13	24	•	○	PCAL and ampl. problems
VT7331	17.11.27	24	○	•	PCAL and ampl. problems
VT8039	18.02.08	24	○	•	band-A and -D problems
OK8051	18.02.20	1	○	•	fringes found
VT8060	18.03.01	24	•	○	OK, but variable amplitudes
OK8065	18.03.06	1	•	○	wrong recording, failed
VT8067	18.03.08	24	•	○	DBBC3 problems, data lost
OK8074	18.03.15	1	•	○	OK, fringes found
VT8078	18.03.19	24	•	○	DBBC3 problems, data lost
OK8086	18.03.27	19	•	○	OK
VGT095	18.04.05	4	•	○	problems with band-A Y-pol
VT8095	18.04.05	24	•	○	DBBC3 problems, data lost
VGT109	18.04.19	4	•	○	OK, but variable amplitudes
VT8109	18.04.19	24	•	○	DBBC3 problems, data lost
VT8123	18.05.03	24	•	○	DBBC3 problems, data lost
VGT134	18.05.14	4	•	○	
VT8134	18.05.14	24	•	○	DBBC3 problems, data lost
OK8138	18.05.16	1	•	○	OK
OK8141	18.05.21	20	•	○	OK
VGT149	18.05.29	4	•	○	
VT8149	18.05.29	24	•	○	DBBC3 problems, data lost
VGT162	18.06.11	24	•	○	
VT8162	18.06.11	24	•	○	DBBC3 problems, data lost
VT8249	18.09.06	24	•	○	DBBC3 problems, data lost
VGT260	18.09.17	4	•	○	
VT8260	18.09.17	24	•	○	DBBC3 problems, data lost
VGT274	18.10.01	4	•	○	
VT8274	18.10.01	24	•	○	recording problems, data lost
VGT288	18.10.15	4	•	○	
VT8288	18.10.15	24	•	○	completely correlated ?
VGT302	18.10.29	4	•	○	
VT8302	18.10.29	24	•	○	DBBC3 problems, data lost
VGT319	18.11.15	4	•	○	
VT8319	18.11.15	24	•	○	DBBC3 problems, data lost
VT8330	18.11.26	24	•	○	DBBC3 problems, lost
VT8347	18.11.26	24	•	•	OK

Seismological observations

The seismometer owned by Uppsala University and the Swedish National Seismic Network (SNSN) was operated throughout the two-year period.

Water vapor radiometry

The two radiometers Astrid and Konrad have been operated at the observatory. During 2017 Astrid was operating continuously from July through December, and Konrad was operating for $\approx$ 300 days. However, unfortunately CONT17 was only covered by Konrad observations for $\approx$ 5 days. During 2018 both radiometers were operating continuously with some data loss ($<$ 5 %). In addition to these data losses, data acquired during rain, which are not sufficiently accurate for our applications in geodesy VLBI, shall be ignored. Rain or rain clouds are typically present $\approx$ 10 % of the time.

Sea level

The inauguration of the Onsala tide gauge station was reported in the last IVS biennial report. Since then, it has been operating continuously. A status report was presented at the recent EVGA meeting [1].

The GNSS-R based tide gauge was operated continuously, and the recorded data were analyzed.

5 Future Plans

- In the coming two years we plan to participate in about 50 IVS legacy S/X sessions per year with the 20-m telescope.
- We plan to participate in as many VGOS test sessions as possible in 2019 and plan to become fully operational with the OTT by 2020.
- We will work on connecting the OTT with the 20-m telescope through interferometric measurements and also derive local tie vectors from classical observations.
- The monitoring activities reported above will be continued.

References

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Parkes Network Station Report 2017–2018

John Reynolds

Abstract This report describes observing carried out by the Parkes 64-m telescope during 2017 and 2018 and the future outlook for the telescope.

1 Observing in 2017 and 2018

The Parkes 64-m telescope did not participate in any scheduled IVS sessions over this period, owing to continued scheduling pressures. However, the Observatory continues to operate the Mark-5B recording system and concentric S/X receiver and supported two precision astrometry/geodesy programs over this period. Both programs used the software correlator at the Pawsey Supercomputing Centre in Perth, Western Australia.

Parkes participated in two 24-hour sessions aimed at improving the accuracy of the ICRF in the south by a factor of two. This program was led by Dr Oleg Titov of Geoscience Australia with collaborators from Australia, New Zealand, South Africa, and China. Three telescopes from the Russian Federation also participated. A second aim of this program is to investigate quadrupole systematic effects in positions and proper motion that could be an indication of the stochastic background gravitational waves.

A second program led by Leonid Petrov of the Astrogeo Center, USA used Parkes for another two 24-hour sessions in a program aimed at improving the VLBI positions of southerly AGN detected by ESA's Gaia mission. This program team also includes collaborators from Australia, New Zealand, South Africa, and China. The goal of these observations was to improve VLBI position accuracy to sub-milliarcsecond levels through imaging at X- and S-bands, and determining jet directions. Results from this program will form part of the Radio Fundamental Catalogue (http://astrogeo.org/rfc).

The participation of Parkes in precision astrometry and geodesy observations remains at a modest level, but it is planned to continue to support programs that require a large Southern hemisphere aperture to meet specific science goals.

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Parkes Network Station

IVS 2017+2018 Biennial Report

“Quasar” VLBI Network Stations 2017—2018 Biennial Report

Dmitry Ivanov, Alexander Ipatov

Abstract The current status as well as activities in 2017 and 2018 of the “Quasar” VLBI Network Stations are considered.

1 General Information

The “Quasar” VLBI Network is a unique Russian astronomical instrument created at the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS). The main purpose of the “Quasar” Network is to improve the celestial and terrestrial reference frames and other data products essential for understanding the Earth’s environments. The network consists of three stations, including Svetloe in the Leningrad Region, Badary in Eastern Siberia, and Zelenchukskaya in the Northern Caucasus, and the Data Processing Center in St. Petersburg. Svetloe Observatory was the first to be put into operation in 1999, then Zelenchukskaya in 2002, and finally Badary in 2005. The baselines of the radio interferometer vary from 2,000 to 4,400 km. Each station is equipped with at least three co-located instruments of different techniques: VLBI, SLR, combined GNSS receivers, and the DORIS system [1]. All observatories are linked by optical fiber lines and are equipped with identical hydrogen Time Standards, Water Vapor Radiometers, and meteorological stations which are used for all types of observations.

Institute of Applied Astronomy of RAS

“Quasar” VLBI Network Stations

IVS 2017+2018 Biennial Report

The main instrument in each of the three observatories is a 32-m radio telescope (RT-32), which provides a completely automatic process of observing the radio sources and satellites in a radiometric or a radio interferometric mode. The main technical characteristics of the antennas are presented in Table 1. Each RT-32 radio telescope is equipped with highly sensitive receivers, providing signal amplification in the Ka (22.02–22.52 GHz), X (8.18–9.08 GHz), C (4.6–5.5 GHz), S (2.15–2.5 GHz), and L (1.38–1.72 GHz) frequency bands in both circular polarizations. A cooled low-noise amplifier is used at all frequency bands in order to achieve a less than 50 K noise temperature for the radio telescope and radiometer system. We use an R1002M data acquisition system with 16 converters developed in the IAA RAS [2] and the Mark 5B recording systems. Observational data are transmitted to the ARC correlator [3] in the Data Processing Center in the IAA RAS, which is capable of processing the data in Mark 5 format received simultaneously from three stations at an average rate up to 1,024 Mbps.

In 2015 two multi-band fast rotating antennas with a mirror diameter of about 13.2-m (RT-13) were installed at the Zelenchukskaya and Badary stations [4]. The inaugural ceremony of the third RT-13 radio telescope at the Svetloe observatory was held on September 19, 2018 (Figure 1). Table 2 presents some specifications of the RT-13 Antenna System, which meet all requirements of the VGOS program. Each RT-13 radio telescope is equipped with a specially designed receiver system. The main feature of this system is the cryogenic receiver unit that includes a cooled tri-band feed and low-noise amplifier. Such a design makes it possible to achieve high sensitivity to receive weak noise signals of the cosmic origin.

The feed design allows us to receive signals in three frequency bands: S (2.2–2.6 GHz), X (7.0–9.5 GHz), and Ka (28–34 GHz) in both circular polarizations simultaneously [5]. Wideband intermediate frequency (1.024—1.536 GHz) signals from the receiver outputs are digitized by the Broadband Acquisition System (BRAS). The BRAS digitizes the input signals, performs signal processing, and packs the output data into ten Gigabit Ethernet VDIF frames [6].

Since 2016 the IAA RAS has been conducting regular observations with RT-13 radio telescopes. During the observations the dataflow generated by BRAS (up to 16 Gbps) is routed via optical fiber line to a data transfer and recording system (DTRS). DTRS then transfers the data to the Russian Academy of Sciences FX (RASFX) correlator in the Data Processing Center in St. Petersburg. The registration and transmission procedures take place simultaneously. The RASFX correlator based on a hybrid-blade HPC cluster was designed in IAA RAS in 2014 and is now used to process wideband signals of RT-13 radio telescopes [7].

Table 1 Specifications of the RT-32.

Mount	alt-azimuth
Configuration	cassegrain
Subreflector scheme	asymmetrical
Main mirror diameter	32 *m*
Subreflector diameter	4 *m*
Focal length	11.4 *m*
Azimuth speed	$1.0\,^{\circ}/sec$
Elevation speed	$0.5\,^{\circ}/sec$
Limits by Az	$\pm 265^{\circ}$
Limits by El	$0^{\circ} - 85^{\circ}$
Axis offset	$0.9 \pm 1.0\ mm$
Tracking accuracy	$\pm 10\ arcsec$
Surface accuracy (RMS)	0.5 *mm*
Frequency range	$1.4 - 22\ GHz$
Polarization	LCP + RCP

2 Current Status and Activities

During 2017–2018 the RT-32 and RT-13 radio telescopes of the “Quasar” VLBI Network participated in both the IVS and domestic VLBI observations. Activities of the observatory are presented in Table 3 and Table 4. E-VLBI mode is used for the domestic sessions data transfer. Since 2015, the RT-13 radio telescope has participated in the following geodetic sessions:

- One-hour geodetic sessions in S/X bands for UT determination (R);
- Sessions performed simultaneously with RI sessions at RT-32 antennas with the same schedule (RI-RT13);
- 24-hour geodetic sessions in S/X bands for improving the position of the RT-13 antennas (24-h);
- 30-minute geodetic sessions in S/X/Ka bands for UT determination (S/X/Ka-TEST).

Fig. 1 The RT-13 antenna at the Svetloe observatory.

Table 2 Specifications of the RT-13.

Mount	alt-azimuth
Configuration	cassegrain
Subreflector scheme	ringfocus
Main mirror diameter	13.2 *m*
Subreflector diameter	1.48 *m*
Focal length	3.7 *m*
Azimuth speed	$1.0\,^{\circ}/sec$
Elevation speed	$0.5\,^{\circ}/sec$
Limits by Az	$\pm 245^{\circ}$
Limits by El	$6^{\circ} - 109^{\circ}$
Axis offset	$-0.3 \pm 0.5\ mm$
Operation	$24h/7d$
Tracking accuracy	$\pm 15\ arcsec$
Surface accuracy (RMS)	$0.3 - 0.1\ mm$
Frequency range	$2 - 40\ GHz$
The surface efficiency	> 0.7
Polarization	LCP + RCP

Table 3 VLBI observations with the RT-32 radio telescopes.

	Sv		Zc		Bd	
Sessions	2017	2018	2017	2018	2017	2018
IVS-R4	23	19	17	16	24	21
IVS-R1			2		2	
IVS-T2	5	3	5	7	6	6
EUROPE	1	1	2	1	1	4
EURR & D		4		4		
IVS-CONT17			15		15	
AUA	3		2		1	
AOV		1		1		1
IVS-Intensive	18	18				
RuE	40	40	40	40	40	40
RI	32	35	340	340	358	349

Table 4 VLBI observations with the RT-13 radio telescopes.

	Sw		Zv		Bv	
Sessions	2017	2018	2017	2018	2017	2018
R			1298	1401	1298	1401
RI-RT13			331	355	331	355
24-h		1	8	3	8	3
S/X/Ka-TEST			256	236	256	236

3 Staff

The list of the staff members of the "Quasar" VLBI network stations in 2017+2018 is given below.

3.1 Svetloe

- Prof. Ismail Rahimov — observatory chief;
- Vladimir Tarasov — chief engineer;
- Tatiana Andreeva — engineer;
- Alexander Isaenko — engineer.

3.2 Zelenchukskaya

- Andrei Dyakov — observatory chief;
- Dmitry Dzuba — FS, pointing system control;
- Anatoly Mishurinsky — front end and receiver support.

3.3 Badary

- Valery Olifirov — observatory chief;
- Alex Maklakov — chief engineer, FS, pointing system control;
- Roman Kuptsov — engineer.

4 Future Plans

In the next two years all stations of the "Quasar" VLBI network will continue to participate in IVS and domestic VLBI observations, upgrade the existing equipment, and replace obsolete equipment.

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Shanghai Station Report for 2017–2018

Bo Xia, Qinghui Liu, Zhiqiang Shen

Abstract This report summarizes the observing activities at the Sheshan station (SESHAN25) and the Tianma station (TIANMA65) in 2017 and 2018. It includes the international VLBI observations for astrometry, geodesy, and astrophysics and domestic observations for satellite tracking. We also report on updates and development of the facilities at the two stations.

1 General Information

The Sheshan station ('SESHAN25') is located at Sheshan, 30 km west of Shanghai. It is hosted by the Shanghai Astronomical Observatory (SHAO), at the Chinese Academy of Sciences (CAS). A 25-meter radio telescope is in operation at 3.6/13, 5, 6, and 18-cm wavelengths. The Sheshan VLBI station is a member of the IVS and EVN.

The Tianma station ('TIANMA65') is located in the western suburbs of Shanghai, Sheshan town, Songjiang district. It is jointly funded by the Chinese Academy of Sciences (CAS), the Shanghai Municipality, and the Chinese Lunar Exploration Program. The telescope construction started in early 2009, and the majority of the mechanical system was completed in October 2012. On December 2, 2013, the Tianma 65 telescope passed the acceptance evaluation. By design, the Tianma telescope with a diameter of 65 meters, one of the largest steerable radio telescopes in the world, is a multifunction facility, conducting astrophysics, geodesy, and astrometry, as well as space science. By the end of 2018, ten cryogenic receiver systems (L, C, S/X, Ku, K, Ka, X/Ka, and Q), of which K-band, Ka-band, and Q-band all have two beams, had been installed on the Tianma telescope. In the future, a K-band seven-beam cryogenic receiver will be installed on the Tianma telescope, in 2020. The CDAS and DBBC2 were installed at the Tianma VLBI 65-m telescope terminal.

The SESHAN25 and TIANMA65 telescopes take part in international VLBI experiments on astrometric, geodetic, and astrophysics research. Apart from its international VLBI activities, the telescope spent a large amount of time on the Chinese Lunar Project, including the testing before the launch of the Chang'E test satellite and the tracking campaign after the launch and other single dish observing.

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2 Component Description

In 2017, SESHAN25 participated in 39 IVS sessions (including ten INT3 Intensive sessions) while TIANMA65 participated in five IVS sessions. In 2018, SESHAN25 participated in 36 IVS sessions (including 11 INT3 Intensive sessions and six INT2 Intensive sessions) while TIANMA65 participated in four IVS sessions.

Table 1 Statistics of experiments observed.

Session Name	2017 (SH)	2018 (SH)	2017 (T6)	2018 (T6)
AOV	4	4	2	3
APSG	2	2	0	0
AUS-AST	1	1	0	0
IVS-R1	19	8	0	0
IVS-T2	2	1	0	0
IVS-R&D	1	1	3	1
IVS-INT2	0	6	0	0
IVS-INT3	10	11	0	0

3 Current Status

3.1 Antenna Maintenance with SESHAN25

The Sheshan station encountered an antenna azimuth towing chain fault and suspended observations in early September 2018. Repairs were carried out. From September to December in 2018, we did some maintenance work with the antenna chain, etc.

3.2 Antenna Maintenance with TIANMA65

The Tianma radio telescope conducted mechanism maintenance in March 2018, including the greasing of the driving mechanism of azimuth and elevation, elevation bearing, the adjusting mechanism of the sub-reflector, and the rotating mechanism of the feed. We also checked the status of the central pivot. Apart from the above annual maintenance, we greased the azimuth track and elevation gear every three months. All the maintenance work assured the antenna to be in a good status. In addition, we updated the wheels of the protection cover of the azimuth track, which shows a good running state at present.

The primary reflector of the Tianma Radio Telescope (TMRT) distorts due to gravity, which dramatically reduces the aperture efficiency of high-frequency observations. In 2017–2018, we have acquired a model for the compensation of the gravitational deformation of the TMRT. After applying the model, there is a 150%–400% improvement in the aperture efficiency at low and high elevations. The model flattens the gain curve between 15%–80% elevations with an aperture efficiency of approximately 50%. The final weighted root-mean-square (RMS) error is approximately 270 m.

We also measured the thermal deformations when the back and front structures, respectively, were heated by the sun, and we then used the active surface system to correct the thermal deformations immediately to confirm the measurements. The thermal deformations when the back structure is heated are larger than those when the front structure is heated. The values of half power beam width (HPBW) are related to the illumination weighted surface RMS and can be used to check the thermal deformations. When the back structure is heated, the aperture efficiencies can remain above 90% of the maximum efficiency at 40 GHz for approximately two hours after one adjustment. While the front structure is heated, the aperture efficiencies can remain above 90% of the maximum efficiency at 40 GHz and above 95% after one adjustment in approximately three hours.

3.3 Other Upgrades

A new Fluxbuff has been installed at the Tianma 65 m in June 2018. The total capacity is 240 TB. We can work up to 2 Gbps using fila10g of the DBBC with flexbuff. At the same time, we also upgraded the FS from fs-9.11.8 to fs-9.11.19 for supporting the new devices.

4 The Staff of the Shanghai VLBI Station

Table 2 lists the group members at the Shanghai VLBI Station. The staff is involved in the VLBI program at the station with various responsibilities.

5 Future Plans

In 2019, the Sheshan radio telescope will take part in 30 IVS sessions. The Tianma radio telescope will take part in five IVS sessions. The telescopes will regularly track the Chang'E-4 satellite in its lunar orbit.

Fig. 1 The antenna chain removal, completed.

Fig. 2 The antenna maintenance of the SHESHAN 25-m telescope.

Fig. 3 The new Flexbuff hardware system at Tianma station.

Nanshan IVS Biennial Report for 2017 and 2018

Wenjun Yang, Hua Zhang, Peng Li, Guanghui Li, Ming Zhang, Lang Cui

Abstract This report briefly introduces the general information about the Nanshan 26-m Radio Telescope (NSRT) and the status of each system. The report also summarizes the IVS sessions with NSRT during 2017 and 2018.

1 General Information

The Nanshan 26-m Radio Telescope (NSRT) is situated in the Eurasia hinterland (about 70 km south of Urumqi) and operated by Xinjiang Astronomical Observatory (XAO), Chinese Academy of Sciences (CAS). Figure 1 gives a new picture of the NSRT. In 2017, there were 154 experiments conducted by the Nanshan 26-meter telescope, serving in EVN, IVS, EAVN, and CVN networks, with a total observing time of about 1,051 hours, including the lunar exploration observations. In 2018, 200 experiments were conducted, and the total observing time was about 1,500 hours.

Fig. 1 The Nanshan 26-m Radio Telescope (NSRT).

2 Antenna Systems

The Stewart platform for maneuvering the sub-reflector on the NSRT was upgraded in 2018. The incremental rotary encoder of the actuator motor has been replaced with the absolute one. So the position measurement for the actuators is now more accurate and repeatable, which is crucial for the sub-reflector to be stably repositioned during observing. The antenna roller bearings and motors were also replaced or maintained, see Figure 2.

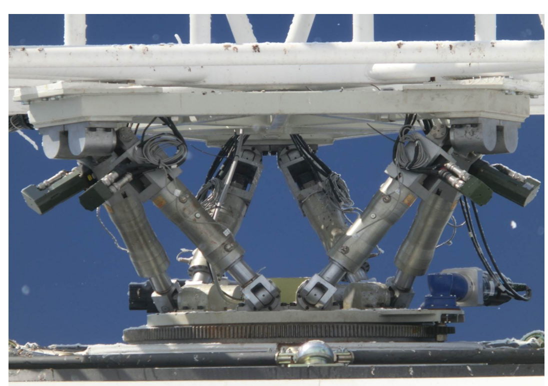

Fig. 2 The upgraded actuator motors on the Stewart platform of the NSRT.

Xinjiang Astronomical Observatory (XAO), CAS

XAO-Nanshan Network Station

IVS 2017+2018 Biennial Report

3 Receiver Systems

The Q-band (7 mm) receiver was tested and mounted in the RF cabin on the NSRT. Currently the signal was only down-converted to 4-12 GHz, and a secondary down-converting mixer is being shipped from the manufacturer to meet our digital IF backends, see Figure 3. The Q-band system is expected to operate in late 2019.

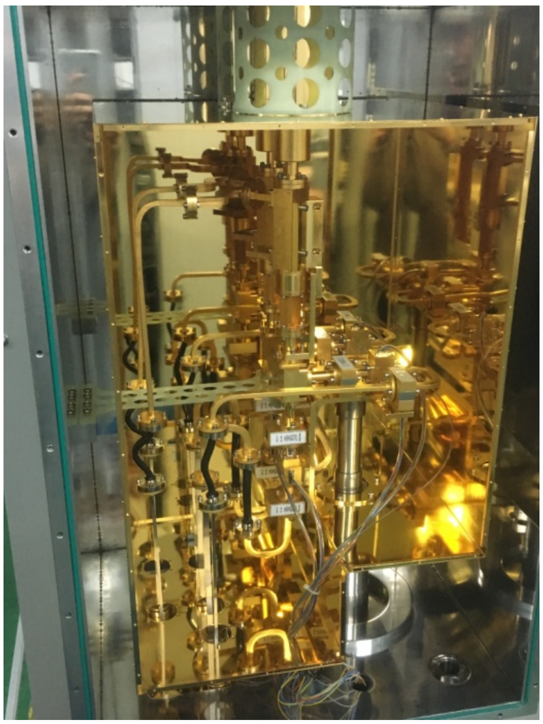

Fig. 3 The new Q-band receiver mounted on the NSRT.

4 Upgrade of VLBI Backend Systems

The installment of DBBC2 and CDAS2 and their system testing have been accomplished. They have been successfully used in the EVN, IVS, and CVN joint observing since 2017. So the VLBI backends at Nanshan station are now fully digitalized. We are now preparing a firmware upgrade on DBBC2 from V.105 to V.107 to meet the new requirement for coming EVN observations. We have ordered 12 diskpacks with 32 TB storage per pack to enhance our capacity to participate in high recording-rate EVN observations. The diskpacks will contribute to the circulation pool starting in late 2019.

5 Time-Frequency Systems

The old H-maser clock MHM2010 purchased from the U.S. has expired and stopped working in 2018. Thereupon, two new H-maser clocks made at the Shanghai Astronomical Observatory (ShAO) are now taking up the role of providing standard time-frequency service, the short-term frequency stability of which is now approaching 10^{-13}. See Figure 4.

Fig. 4 The new on-site H-maser clock made at the Shanghai Astronomical Observatory.

6 Geodetic VLBI Observations

In total, the NSRT participated in 27 24-hour regular IVS sessions during the years 2017 and 2018, as well as

EVN, Eastern Asia VLBI Network (EAVN), and Chinese VLBI Network (CVN) sessions. The detailed information about IVS sessions in which the NSRT was involved is listed in Table 1.

Table 1 IVS sessions at Nanshan Station during 2017 and 2018.

No.	Epoch	Code	Duration (hours)
1	2017-004 UT18:30	R4773	24
2	2017-016 UT16:30	Aov013	24
3	2017-080 UT17:30	Aov014	24
4	2017-082 UT18:30	R4784	24
5	2017-087 UT17:30	T2117	24
6	2017-089 UT18:30	R4785	24
7	2017-101 UT17:30	Aov015	24
8	2017-102 UT18:30	R4787	24
9	2017-110 UT18:30	R4788	24
10	2017-171 UT17:30	Aov016	24
11	2017-206 UT17:30	Apsg40	24
12	2017-208 UT18:30	R4802	24
13	2017-220 UT17:30	Aov017	24
14	2017-284 UT17:30	Apsg41	24
15	2017-318 UT17:30	T2122	24
16	2017-319 UT18:30	Aov018	24
17	2018-023 UT18:30	Aov019	24
18	2018-079 UT17:30	Aov021	24
19	2018-086 UT18:30	R4835	24
20	2018-095 UT18:30	R4836	24
21	2018-100 UT17:30	Apsg42	24
22	2018-179 UT18:30	R4848	24
23	2018-191 UT17:30	Apsg43	24
24	2018-205 UT17:30	Aov025	24
25	2018-219 UT17:30	Aov026	24
26	2018-317 UT17:30	T2128	24
27	2018-326 UT16:00	Aov029	24

Westford Antenna 2017–2018 Biennial Report

Mike Poirier, Alex Burns

Abstract Technical information is provided about the antenna and the VLBI equipment at the Westford site of the MIT Haystack Observatory and about changes to the systems since the IVS 2015—2016 Biennial Report.

1 Westford Antenna at Haystack Observatory

Since 1981, the Westford antenna has been one of the primary geodetic VLBI sites in the world. Located 70 km northwest of Boston, Massachusetts, the antenna is part of the MIT Haystack Observatory complex.

The Westford antenna was constructed in 1961 as part of the Lincoln Laboratory Project West Ford that demonstrated the feasibility of long-distance communication by bouncing radio signals off a spacecraft- deployed belt of copper dipoles at an altitude of 3,600 km. In 1981, the antenna was converted to geodetic use as one of the first two VLBI stations of the National Geodetic Survey Project POLARIS. Westford has continued to perform geodetic VLBI observations on a regular basis since 1981.

In recent years Westford has been focused on the next generation VLBI VGOS technology development and operational integration. As the first prototype VGOS station, Westford provides this valuable knowledge base to all of the new VGOS operational stations as they come on line around the world.

MIT Haystack Observatory

Westford Antenna

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Fig. 1 Aerial view of the radome and facilities of the Westford antenna. (For scale the diameter of the radome is 28 m.)

Table 1 Location and addresses of the Westford antenna.

Longitude	71.49° W
Latitude	42.61° N
Height above m.s.l.	116 m
MIT Haystack Observatory 99 Millstone Rd Westford, MA 01886-1299 U.S.A.	
`http://www.haystack.mit.edu`	

2 Technical Parameters of the Westford Antenna and Equipment

The antenna is enclosed in a 28-meter air-inflated radome constructed of a 1.2 mm thick teflon fabric (Raydel R-60) (see Figure 1). The major components of the VLBI data acquisition system at Westford include a VGOS broadband cryogenically-cooled receiver, RF-over-Fiber (RFoF) Transmission links, an RF power distributor, four Up/Down converters, four RDBEs, and a Mark 6 recorder with expansion chassis, which are all controlled by a PCFS running version 9.12.11. We also use the MCI system, which monitors and logs parameters for key components in the system. The primary frequency standard on site is the NR-4 Hydrogen maser.

Fig. 2 View of the Westford antenna inside the radome. The VLBI VGOS receiver is located at the prime focus.

Westford continues to host the WES2 GPS site of the IGS network. A Dorne-Margolin chokering antenna is located on top of a tower about 60 meters from the VLBI antenna. A Septentrio PolaRx5 Reference Station receiver completes the WES2 GPS site.

3 Westford Staff

The personnel associated with the geodetic VLBI program at Westford, and their primary responsibilities, are:

Table 2 Technical parameters of the Westford antenna for geodetic VLBI.

Parameter	*Westford*
primary reflector shape	symmetric paraboloid
primary reflector diameter	18.3 meters
primary reflector material	aluminum honeycomb
feed location	primary focus
focal length	5.5 meters
antenna mount	elevation over azimuth
antenna drives	electric (DC) motors
azimuth range	$90° - 470°$
elevation range	$4° - 87°$
azimuth slew speed	$3°\ s^{-1}$
elevation slew speed	$2°\ s^{-1}$
	Frequency range 2-14 GHz
T_{sys} at zenith	*40-70 K*
aperture efficiency	0.25-0.60
SEFD at zenith	1800-4500 Jy

- Alex Burns: Technician, Observer
- Chet Ruszczyk: VGOS Technical Manager
- Pedro Elosegui: Principal Investigator
- Colin Lonsdale: Site Director
- Glenn Millson: Observer
- Arthur Niell: VLBI Science Support
- Michael Poirier: Site Manager
- Ganesh Rajagopalan: Lead RF Engineer

4 Standard Operations

From January 1, 2017 through December 31, 2018, Westford participated in 55 VGOS sessions, including 48 VT, two Mini-CONT, and five CONT sessions. Westford also supported many short fringe tests with other worldwide stations assisting in their VGOS system configuration and operational checkout.

Use of the Westford antenna was shared with the Terrestrial Air Link (TAL) Program, but this was ended in 2017.

5 Research and Development

Presently we are running bi-weekly 24-hour sessions supporting the core VGOS stations. These sessions covered a wide range of focus from engineering testing to the standardizing of operational configuration formats supporting the expanding VGOS network.

6 Outlook

Westford expects to continue to support the VGOS operational series of 24-hour sessions, along with supporting new development, testing, and integration of VGOS operational systems around the world.

We soon will be installing four new V2.1 UDCs and four R2DBEs into our operational VGOS system. These upgrades will make Westford a fully VGOS compliant station in terms of operating frequency and 1 GHz bandwidth coverage. We expect over the next two years we will continue to upgrade our operational systems to help Westford in breaking new ground in VLBI technical development along with running stable and consistent operations.

Acknowledgements

We would like to thank Pedro Elosegui, Arthur Niell, Ganesh Rajagopalan, and Chet Ruszczyk for their contributions to this report. Funding for geodetic VLBI at Westford is provided by the NASA Space Geodesy Program.

Geodetic Observatory Wettzell – 20-m Radio Telescope and Twin Radio Telescopes

Alexander Neidhardt [1], Christian Plötz [2], Gerhard Kronschnabl [2], Torben Schüler [2]

Abstract The Geodetic Observatory at Wettzell, Germany mainly contributed very successfully to the IVS observing program and to some observations of the EVN in the years 2017 and 2018. Technical changes, developments, improvements, and upgrades had been made to increase the reliability of the entire VLBI observing system. While the 20-m Radio Telescope Wettzell (RTW, Wz) and the 13.2-m Twin radio Telescope Wettzell North (TTW1, Wn) are in regular S/X sessions, the 13.2-m Twin radio Telescope Wettzell South (TTW2, Ws) is equipped with a VGOS receiving system and participates in all test and regular international and European VGOS sessions.

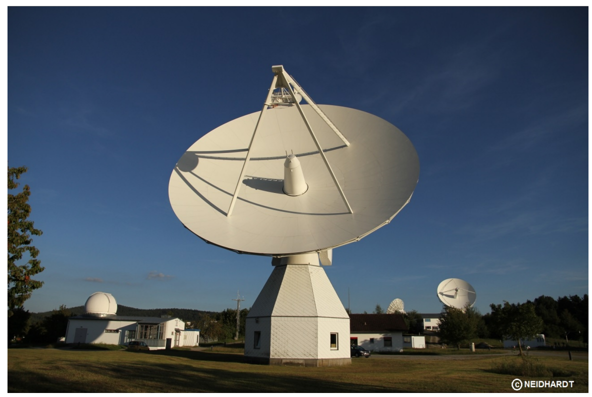

Fig. 1 The Geodetic Observatory Wettzell with the two 13.2-m TWIN radio telescope antennas in the background on the right and the 20-m Radio Telescope Wettzell in the center.

1 General Information

The Geodetic Observatory Wettzell (GOW; see Figure 1) is jointly operated by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG) and the Research Facility Satellite Geodesy (Forschungseinrichtung Satellitengeodiäsie, FESG) of the Technical University of Munich (TUM). The 20-m Radio Telescope at Wettzell (RTW) has been an essential component of the IVS since the year 1983. Meanwhile, the 13.2-m Twin radio Telescope Wettzell North (TTW1, Wn) also produces S/X-data as a regular station with up to three-fourths of the load of RTW in 2018. Doing observations with the second 13.2-m Twin radio Telescope Wettzell South (TTW2, Ws), which is the first complete VGOS antenna at Wettzell, the observatory is prepared for future requirements in the IVS.

In addition to VLBI, an ILRS laser ranging system, several IGS GNSS permanent stations, a large laser gyroscope G (ring laser) and corresponding local techniques, e.g., time and frequency, meteorology and super conducting gravity meters, are also operated. Wettzell also runs a DORIS beacon as a complete geodetic core site. Activities to monitor atmospheric parameters use a continuously growing amount of equipment, including a Nubiscope and weather balloons. Another project with external contractors has been established to improve the timing system with compensated fiber-optic transfers and a frequency comb. The developments also must meet the requirements for future operation strategies, so projects to increase automation and remote control are on-going.

1. Forschungseinrichtung Satellitengeodäsie (FESG), Technische Universität München
2. Bundesamt für Kartographie und Geodäsie (BKG)

RTW/TWIN Wettzell Network Station

IVS 2017+2018 Biennial Report

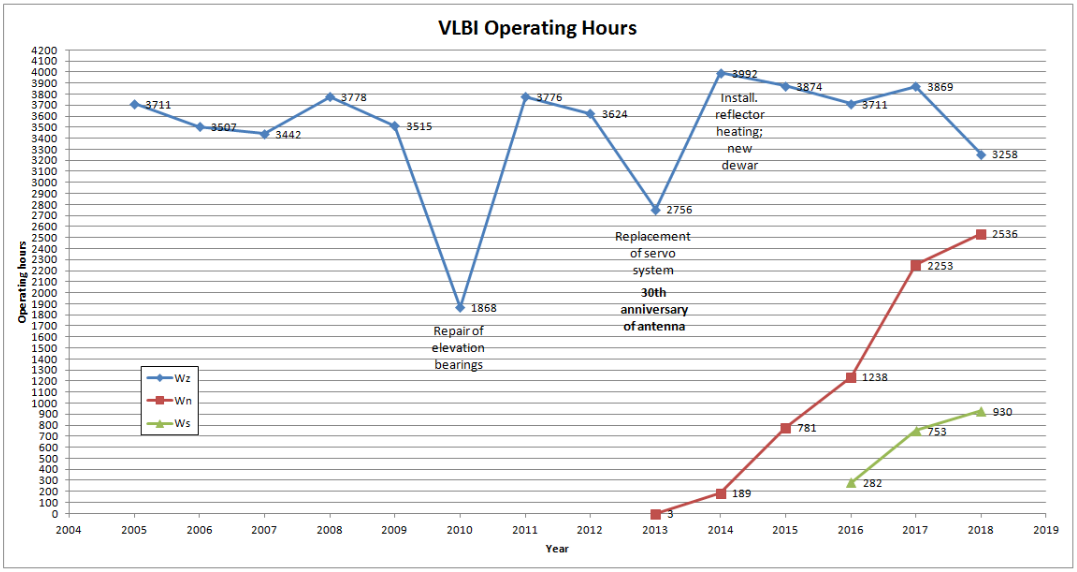

Fig. 2 Annual hours of operation of the Wettzell antennas since 2005.

The GOW is also responsible for the AGGO system in La Plata, Argentina (which is the former station TIGO in Concepción, Chile), and the German Antarctic Research Station (GARS) O'Higgins on the Antarctic Peninsula (see separate reports).

2 Staff

Table 1 Staff members of RTW.

Name	Affiliation	Function	Mainly working for
Torben Schüler	BKG	head of the GOW	GOW
Alexander Neidhardt	FESG	head of the microwave group, VLBI chief	RTW, TTW
Erhard Bauernfeind	FESG	mechanical engineer (until Dec. 2018)	RTW
Ewald Bielmeier	FESG	technician	RTW, TTW
Martin Brandl	FESG	mechatronic engineer	RTW, TTW
Gerhard Kronschnabl	BKG	electronic engineer (chief engineer TTW)	TTW, RTW
Christian Plötz	BKG	electronic engineer (chief engineer RTW)	RTW, TTW, O'Higgins
Raimund Schatz	FESG	software engineer	RTW
Walter Schwarz	BKG	electronic engineer	RTW, WVR
Armin Böer	BKG	electronic engineer	Infrastruct., RTW
Apurva Phogat	BKG	MSc	correlation
Nadine Schörghuber	FESG/ BKG	student (until Sept. 2017)	Operator VLBI

The staff of the GOW consists of over 30 members in total (plus student operators) on permanent and fixed-term contracts to do research, operations, maintenance, and repairs, or to improve and develop all GOW systems. The staff operating VLBI are summarized in Table 1.

3 20-m Radio Telescope Wettzell (RTW, Wz)

The 20-m RTW (see Figure 3) has been supporting geodetic VLBI activities of the IVS and partly other partners, such as the EVN, for over 35 years now. Operational hours in the reporting period are plotted in Figure 2 (also see Table 2). The telescope is still in a very good and stable state. The main priority was the participation in all daily one-hour Intensive sessions (INT/K) to determine UT1–UTC. Increasing the know-how, sessions can now also be scheduled, correlated, and analyzed by the Wettzell observatory's staff. Therefore, several of Wettzell's own local and global sessions were operated, including a 10-day local CONT campaign testing the stability of all Wettzell antennas at the end of 2018. Using the Field System extension for remote control, weekend Intensives were partly done remotely. The antenna supported all main IVS 24-hour sessions and is still one of the IVS' main components. Up to 94% of the operations were IVS schedules in 2017, and up to 86% in 2018. About maximum 1% of the observation load was for EVN in 2018. Local sessions increased in 2018 to over 13% of the operations. In 2017, IVS again scheduled a CONT campaign (CONT17) where a continuous operation over 15 days was supported.

Table 2 Annual participation of RTW allocated to services.

Network	Number of observations	Hours of operation	Percent of operation
2017			
IVS	510	3627	93.75 %
Local	30	198	5.12 %
Others	2	44	1.14 %
2018			
IVS	470	2797	85.85 %
EVN	3	28	0.86 %
Local	52	433	13.29 %

All VLBI data from the 20-m RTW is transferred with e-VLBI techniques to Bonn, Tsukuba, Haystack, Washington, and Socorro, using TSUNAMI or now only Jive5ab anymore on the 1 Gbit/sec connection of the Wettzell observatory. Meanwhile, the Bonn and Washington correlators fetch sessions from Flexbuff systems at the Wettzell observatory. Most of the sessions are recorded on Mark5B+ systems and later on transferred to the local Flexbuff servers. But also direct recording is possible. Mainly the weekend Intensives are directly recorded as VDIF streams on the Flexbuff systems. Additionally, 24-hour sessions were recorded with this technique to evaluate the stability in parallel to the classic recording. About 5% of all sessions at the 20-m RTW were directly recorded on Flexbuff in 2018 (0.36% in 2017).

The 20-m antenna, together with the northern twin telescope Wn, also supported the final Wettzell high-speed VLBI session (WHISP) sessions in 2017, planned by colleagues of the Bonn University. WHISP sessions schedule a large number of observations to validate turbulence models in a local application. During WHISP, common clock tests were made where all telescopes were connected to maser EFOS-60. These tests were quite interesting for finding issues in technical solutions for stable frequency transfers over hundreds of meters using classic techniques. The problems found should be obsolete after using a new optical time distribution system with active phase compensation.

Fig. 3 20-m Radio Telescope Wettzell during sunset.

Monthly maintenance days were scheduled to give enough time to maintain the systems. Additionally, service periods were necessary to finalize the cleaning and coating of the antenna tower, the back structure, and the cabins by an external contractor. Using a replacement dewar, built by IVS Centro de Desarrollos Tecnológicos de Yebes, Spain enabled short maintenance times for the cryo-systems, because the complete dewar hardware can be replaced and the repair can be done in the workshop while keeping the antenna operative. The NASA Field System is now on version 9.11.19. All DBBC2s use now firmware DDC v106 and are connected or integrate a FILA10G to stream data over 10 Gbit/s networks.

A main change was switching from the Mark4 rack to digital DBBC recording. All sessions are now recorded using DBBC2 and a Mark5B (partly Flexbuff in addition). On October 1, 2017, the conformity declaration to follow the EC Machinery Directive was signed, so that now all VLBI antennas ensure legal certainty in the sense of European right. Open issues are an oil leakage in two elevation gears, the upgrade of the IF or maybe RF distribution, and an improvement of control structure.

4 13.2-m Twin Telescope Wettzell North (TTW1, Wn)

The Twin Telescope Wettzell (Figure 4) project is Wettzell's realization of complete VGOS conformity. The northern antenna Wn is still equipped with an

S/X/Ka receiving system to support the standard S/X sessions of the IVS and of local performance tests and research questions. The northern antenna was the first available antenna supporting fast slewing modes in the IVS and uses now a DBBC2 (firmware DDC v105_1) in combination with a Mark5B+. It is used in sessions like the 20-m antenna. Its performance in operating hours can be found in Figure 2 (also Table 3). It mainly participates in IVS sessions where it also supported a separate network in the CONT17 campaign. The EVN uses about 1% of the time. Locally scheduled and analyzed sessions increased to about 18%. Missing partners for Ka sessions reduce the possibilities to demonstrate geodetic Ka observing. All recorded data is transferred with e-VLBI techniques.

Table 3 Annual participation of TTW1 allocated to services.

Network	Number of observations	Hours of operation	Percent of operation
2017			
IVS	129	1956	86.82 %
Local	39	207	9.19 %
Survey	5	46	2.04 %
Others	2	44	1.95 %
2018			
IVS	160	2017	79.53 %
EVN	3	29	1.14 %
Local	58	448	17.67 %
Survey	4	42	1.66 %

Fig. 4 The Wettzell Twin Telescope with its two 13.2-m antennas (Wn in the front) and the control building.

The Wn antenna is quite stable and reliable. It is controlled with NASA Field System version 9.11.19. Minor changes were made. It is now additionally equipped with a cable calibration system built by IVS Centro de Desarrollos Tecnológicos de Yebes, Spain.

5 13.2-m Twin Telescope Wettzell South (TTW2, Ws)

The southern antenna Ws of the twin telescopes is Wettzell's first VGOS-compliant antenna using a broadband feed (Elevenfeed). It uses a tunable up-down converter, two DBBC2s, and a Mark 6 to record four bands in both polarizations. Meanwhile, Ws is a regular part of the IVS VGOS network doing bi-weekly observations. Its performance in operating hours can be found in Figure 2 (also see Table 4). In 2017, the main part of the work was to find issues and to stabilize the system. After some tests it was able to be integrated into the Wettzell telescope array, so that all three telescopes can be used and correlated for local sessions. Data of the VGOS sessions is shipped to Haystack for correlation because of the huge data amount of about 16 or 32 Terabytes per day. Local sessions are correlated at Wettzell, and their observation takes about a quarter of the operation time.

Table 4 Annual participation of TTW2 allocated to services.

Network	Number of observations	Hours of operation	Percent of operation
2017			
IVS	21	476	63.21%
Local	15	194	25.76%
Survey	8	83	11.02%
2018			
IVS	25	590	63.44%
Local	12	263	28.28%
Survey	4	41	4.41%
Others	9	36	3.87%

The Wettzell staff does continuous upgrades, implementations, and tests of the backend system. The DBBC2 got new firmware, PFB v106. A DBBC3 was installed and will be tested. Ws now uses the same cable calibration system as Wn installed in 2018. Ws uses the NASA Field System version 9.12.7 VGOS branch.

6 Other VLBI-relevant Activities

To improve the e-VLBI capacities, three Flexbuff systems with 21 TB, 72 TB, and 102 TB were installed. The main systems behind are extendable DELL PowerVault MD3460 Storage Arrays connected to a DELL PowerEdge R730 server. All systems are accessible with Jive5ab, while the use of Tsunami will fade out.

To connect all Flexbuff, Mark 6, and FILA10G systems and to support a flexible, selectable recording, a new 10 Gbit/sec network was installed using fiber links between the telescopes and suitable network switches. The network supports a direct recording of VDIF streams from different FILA10G sources.

A cluster with ten nodes (including one head node), each with four cores, was installed for correlating local sessions at Wettzell using the software correlator DiFX and hardware from the previous Bonn correlator. The installation was supported by Bonn colleagues. Also, all necessary software for scheduling (Sked, VieVS), fringe fitting (fourfit etc.), and analysis (VieVS, nuSolve) was installed, so that staff at Wettzell can now do the whole processing chain from scheduling to analysis. The local software LEVIKA is used for planning observation times and for analyzing local sessions. To exchange the latest news about correlation with a software correlator, the 12th DiFX Users and Developers Meeting was held at Wettzell from September 3 to 7, 2018.

For a better overview of antenna parameters and for emergency detections, a monitoring system was installed as a central data archive using ZABBIX software. Data from the NASA Field System and the recording systems, but also from the antenna control unit, UPS systems, and meteorological sensors, are collected and evaluated to generate triggers showing alerts according to different severity levels. The TUM at Wettzell also joined the project “Joining up Users for Maximizing the Profile, the Innovation and Necessary Globalization of JIVE” (Jumping JIVE) to implement a monitoring infrastructure for the whole EVN network coordinated by Joint Institute for VLBI ERIC, Dwingeloo, The Netherlands. Jumping JIVE is funded by the Horizon 2020 program of the European Union. Part of the local Wettzell development and installation was a Web-based remote monitoring Web page for the NASA Field System (see Figure 5) which can be used to retrieve about 110 parameters. Additionally, data collectors and Web screens were implemented for Mark 6 systems and different other hardware. The guard of the Wettzell observatory got a monitoring tablet showing current problems and alarms as a central monitoring point.

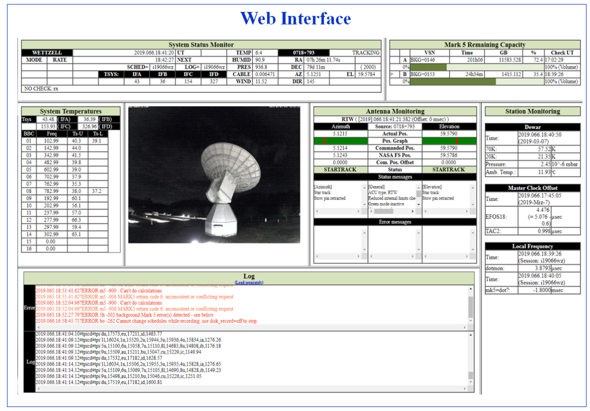

Fig. 5 Web interface of the NASA Field System for the 20-m radio telescope Wettzell.

The permanent survey of the reference point of the twin antennas was continued, using total stations on different pillars and 20 to 30 reflectors in the back structure of the antenna. With about four sessions per year, a continuous monitoring of the reference point over the year is possible.

7 Future Plans

Dedicated plans for the next reporting period are:

- Establishing automated observations
- Studying future use of the 20-m radio telescope
- Implementing VGOS compatibility for TTW1 using a QRFH feed
- Continuous improvements with the VGOS broadband system at TTW2
- Installing a DBBC3 and further Flexbuff systems
- Establishing monitoring of atmospheric parameters
- Increasing the correlation capabilities

Yebes Observatory Report

Javier González, Pablo de Vicente

Abstract We present the main activities performed by the Yebes Station during 2017 and 2018.

1 General Information

The National Geographic Institute of Spain (Instituto Geográfico Nacional, Ministerio de Fomento) has run geodetic VLBI programs at Yebes Observatory since 1995 and currently operates two radio telescopes at that site that contribute to the IVS. A 40-m radio telescope, station code "Ys", has been operating regularly since 2008. For the last couple of years, 2017–2018, the 13.2-m VGOS-type antenna inaugurated in 2014 with code "Yj" (RAEGYEB) has been observing biweekly in the VGOS Trial network. Detailed information about RAEGE is available on the Web at http://www.raege.net/. The IGN Yebes Observatory is also the reference station for the Spanish GNSS network and holds permanent facilities for gravimetry. Since 2014, the IGN Yebes Observatory has been a Technology Development Center for the IVS. Activities are described in the corresponding contribution in this Biennial Report.

2 Activities during the Past Year

During the last two years, both telescopes were involved in geodetic observing under the auspice of the IVS. Starting in 2017, the 13.2-m radio telescope was devoted to the initial VGOS Trial series, with experiment code prefix VT7, being one of the first five stations in the emerging VGOS network. In this first year, the telescope participated in 27 sessions, including five CONT17 experiments between the 3rd and 7th of December and two pre-CONT simulation tests carried out on the 4th and 5th of October.

Yebes' 40-m telescope also participated in the CONT17 campaign as a component of the Legacy network. Concerning the regular yearly agenda, Ys took part in a total of 49 experiments, with two type R1 sessions, 21 of type R4, six from the EUR program, four T2, and one experiment with the AUS network. All of this amounts to 54% of the VLBI time of the telescope (2,689 hours in 2017).

In 2018 the VGOS Trial network observed a total of 24 sessions. RAEGYEB could only take part in 14 of these because a severe failure in one of the subreflector encoders made the antenna unavailable during the months of July and August. Furthermore, sporadic failures in the servo encoders subsystem suffered in the last months of 2018 are believed to be the origin of sensitivity lost at high frequencies due to pointing errors. Those errors were detected and corrected by the end of the year with the help of the Haystack correlator.

Legacy IVS experiments were observed by the 40-m dish, with the following observational program distribution: six EUR, 22 R4, two R1, and four T2 sessions — 34 sessions in total, 42% of the VLBI-dedicated use of the telescope (1,784 hours in 2018).

By 2017 it was noticed by Arthur Niell that the CDMS might not be working properly and some extra noise was being introduced into the cable measurements. Local works were done to improve the measure-

Observatory of Yebes, IGN

Observatory of Yebes Network Station

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Table 1 VGOS Trial sessions participated by RAEGYEB

	2017	2018
VT obs	27	14

Table 2 IVS observations participated by Yebes 40 m.

YEBES40m (Ys)	2017	2018
IVS R1	2	2
IVS R4	21	22
IVS T2	4	4
EUR	6	6
AUS	1	0
CONT	15	0
TOTAL	49	34

ments by replacing the phase-cal Ground Unit with a new module with little modifications, but that did not allow the measurements to reach the required accuracy either. This was the reason to design a major upgrade to the CDMS that is now being tested on site with promising results.

In 2017 the invariant point of the 13.2-m telescope (IVP) was measured using two different techniques. The results and comparison between both methods can be consulted in the internal report IT-CDT-2017-2. Later that year it was discovered that water condensation on the azimuth encoders caused frequent errors in the ACU that could potentially ruin an observation. A small space under the azimuth cabin was conditioned to prevent condensation on these encoders (see IT-CDT-2017-7 for details). By 2017 the amount of Mark6 storage space was increased to a total of 24 modules, each of them filled with eight disks of 4 TB each to reach a net storage capacity of 768 TB. Also a 10 GB switch was installed in the backends room to route data between the backends and the recorders without needing to change fibers. This setup was demonstrated to be very convenient to prevent human errors.

In 2018 the local tie vector to both radio telescopes was successfully determined (IT-CDT-2018-20.pdf). Other activities with potential impact on VLBI observing include two RFI monitoring campaigns in 1.5 - 15 GHz (BRAND-EVN) (IT-CDT-2017-13) as well as in K-band (IT-CDT-2017-14) conducted by station RF engineers. Finally, the RT40m vertex membrane was replaced between the 18th and the 22nd of September.

3 Current Status

The station runs two active Hydrogen masers from T4-Science that provide the frequency references (5, 10, and 100 MHz and also a 1PPS TTL signal) for all the electronics involved in VLBI operations. Normally only one is “active”, while the other runs as a backup system. A monitoring system developed by Yebes staff allows monitoring and control of the master clocks, as well as fast switching between active and backup units. This scenario is also used with two GPS receivers (CNS Clock II and Symmetricom XLi).

The 40 m is equipped with a simultaneous S/X receiver, a C-band receiver, a W-band receiver, and a simultaneous K/Q-band receiver. The W- and Q-band receivers were built in Yebes labs during 2018 and commissioned on January 2019. All the receivers can record dual circular polarization except the W and Q receivers, which are linear. Continuous calibration is available in the S/X, C, and K receivers using a noise-diode driven by an 80 Hz signal generated in the backend. Q- and W- band observations can be calibrated with a hot-cold load system.

By the end of 2016, the 13.2-m VGOS-type telescope was equipped with four RDBE-G backends connected to a single Mark6 unit. The frontend signal chain consists of a cryo-temperature QRFH feed connected to Yebes’ own broadband receiver that sends the full 2 to 14 GHz band through optical fiber link to four UDCs. Each of them adapts a 512 MHz band in Nyquist zone 2 to be digitized by an RDBE-G. All the experiments since then have been observed using this configuration, and the whole signal chain has shown good reliability, being able to run for months without human intervention other than routine monitoring operations. YEBES40M is still involved in geodetic VLBI operations under the legacy network. RAEGYEB is doing biweekly observing within the emerging VGOS network.

4 Future Plans

A prototype for the new CDMS system is being tested on the 13.2-m antenna, and it is planned to be used in regular observing starting in the second quarter of 2019. Yebes engineers have also designed an upgrade to the system that will cover the full link between the H-maser and the phase-cal Antenna Unit. Currently the path between the H-maser and the phase-cal Ground Unit is not being monitored. By the end of last year, four R2DBE units were bought from Digicom. The equipment, which will allow recording of instantaneous bandwidths up to 2 GHz, has already been received and will be installed in the backends room in the next months, to start with the first testing in 2019. The Observatory also bought a DBBC3 backend to be used in high data rate astronomical observations. First fringes have already been obtained with this system, although it is not yet used in normal operations. The recording capability is also expected to increase with the purchase of a new flexbuff system. It is equipped with four 10 GbE interfaces to cope with a potential bitrate of 32 Gbps.

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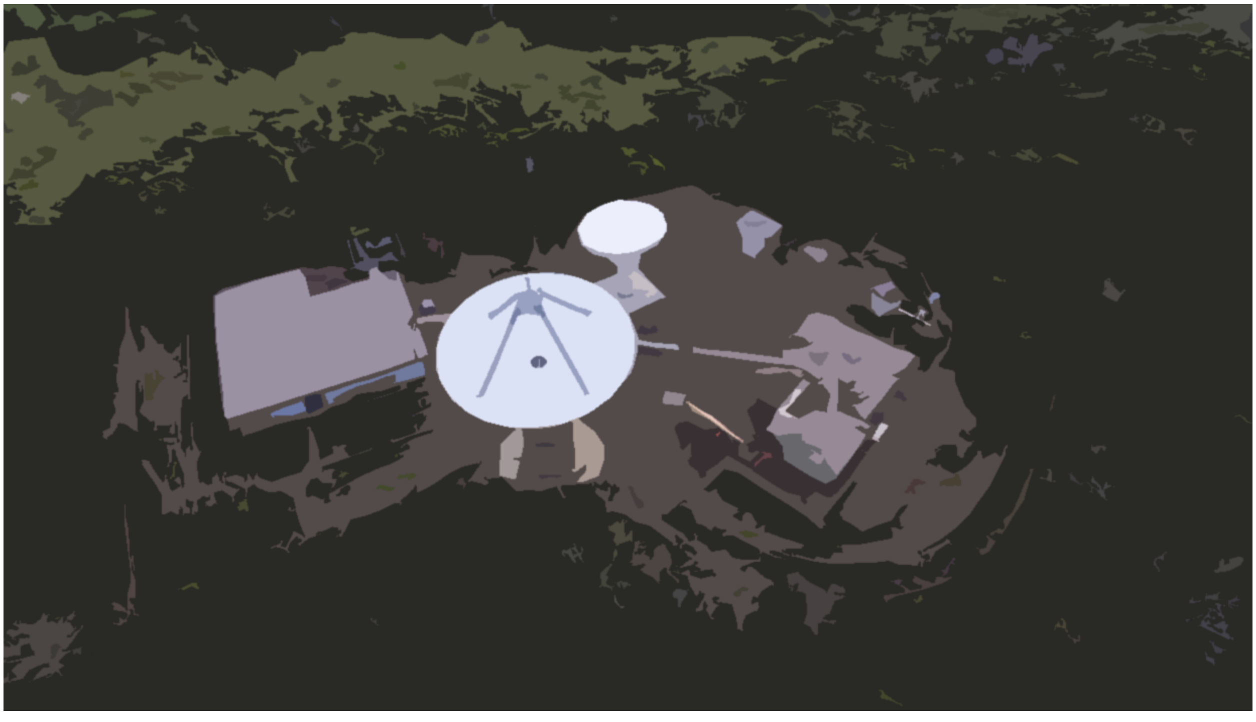
OPERATION CENTERS



Bonn Geodetic VLBI Operation Center

A. Müskens, A. Nothnagel

Abstract The IGGB Operation Center has continued to carry out its tasks of organizing and scheduling various observing sessions of the IVS-T2, IVS-OHIG, IVS-INT3, and EUROPE series. From 2020 onwards, the IGGB Operation Center will transfer its commitment to the Wettzell Geodetic Observatory of the Bundesamt für Kartographie und Geodäsie (BKG).

1 Center Activities

The IGGB VLBI Operation Center is part of the Institute of Geodesy and Geoinformation of the University of Bonn, Nußallee 17, D-53115 Bonn, Germany. It has been organizing and scheduling VLBI observing sessions for more than thirty years. The work of the Operation Center is closely related to the Bonn Correlator. For this reason, distribution of the Mark 5 disk units to the stations after correlation and the extension of the Internet connection from previously 1 Gbps to 2 Gbps in the fall of 2016 are the most costly parts of the operations. Below, we describe the activities related to individual observing programs.

- **IVS-T2 series**
  This series has been observed roughly every second month (seven sessions each in 2017 and 2018) primarily for maintenance and stabilization of the VLBI terrestrial reference frame as well as for Earth rotation monitoring as a by-product. Each station of the global geodetic VLBI network is planned to participate in the T2 sessions at least once per year. In view of the limitations in station days, priority was given to strong and robust networks with many sites over more observing sessions. Therefore, generally 15 to 24 stations have been scheduled in each session. The scheduling of these sessions has to take into account that, in view of the large variety in telescope sensitivities, a sufficient number of observations is planned for each baseline of these global networks. The recording frequency setup has always been the greatest common denominator with 16 channels, 4-MHz channel bandwidth, and 360/80 MHz spanned bandwidth at X- and S-band, respectively. Considering that the setup of IVS sessions should cover as wide a spanned bandwidth and as high a sampling rate as possible, it was decided to test which stations of the global IVS network are capable of a 720/140 MHz spanned bandwidth and 256 Mbit/s setup. So, in December 2016 we carried out a test experiment to check a higher recording mode. We observed with 256 Mbps, 16 tracks, and a bandwidth of 8 MHz/channel. Wide-band was used with 720 MHz spanned bandwidth at X-band and 140 MHz at S-band. The sky frequencies were set to

  8212.99, 8252.99, 8352.99, 8512.99,
  8732.99, 8852.99, 8912.99, 8932.99 MHz;
  2225.99, 2245.99, 2265.99, 2295.99,
  2345.99, 2365.99 MHz.

  It turned out that several stations such as KASHIM11, KOGANEI, NOTO, CRIMEA, and the DSN stations could only observe the 360 MHz spanned bandwidth at X-band. Hence, it was decided to record only the first four channels (i.e., 8212.99, 8252.99, 8352.99, 8512.99 MHz)

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still covering 300 MHz spanned bandwidth and producing a reasonable delay resolution function. The full 140 MHz spanned bandwidth at S-band was not covered in all cases either. This session was analyzed to figure out how to proceed with the T2 sessions in the future.
The results were more or less disappointing. Some stations did not realize the differences in the frequency setup, others were not able to set up the frequencies in the correct way, and others did not observe at all (see the T2115 correlation report). The conclusion was to leave the setup as it was before.

- **Measurement of Vertical Crustal Motion in Europe by VLBI (EUROPE)**
  Since the late 1980s, a series of special sessions has been scheduled regularly on the European continent for precise determination of station coordinates and for long term stability monitoring. In the past years, six observing sessions were scheduled every year. Before 2017, all sessions employed the narrow-band frequency setup of 360/80 MHz with 16 channels and 4-MHz bandwidth, identical to the setup of the IVS-T2 sessions. In 2018, we started configuring the network sessions with two different observing modes. The first set of sessions employed the old setup, while for some sessions the spanned bandwidth was increased to 720 MHz at X-band and 140 MHz at S-band with 2-bit sampling recording at 512 Mbps. The latter group of sessions were called EUR-R&D and were observed four times in 2018. The network was built with the telescopes NYALES20, BADARY, MEDICINA, MATERA, ONSALA60, SVETLOE, YEBES40M, ZELENCHK, and METSAHOVI in different configurations depending on the availability of the stations. The other two EUROPE experiments continued observing with the frequency setup of 360/80 MHz with 16 channels and 4-MHz bandwidth. In these sessions, DSS65A, NOTO, and CRIMEA were employed in addition to the EUR-R&D telescopes.
- **Southern Hemisphere and Antarctica Series (OHIG):**
  In 2017, five sesions and in 2018 six sessions of the Southern Hemisphere and Antarctica Series were organized. The purpose of these observations is the maintenance of the VLBI terrestrial reference frame (TRF) and monitoring of Earth rotation as a by-product. The recording frequency setup is 16 channels with 4-MHz channel bandwidth and a data rate of 128 Mbps spanning 360/80 MHz. Due to the fact that SYOWA is not able to deliver the recorded data for nearly one year after the observations, the correlation and the generation of the databases is always delayed considerably.
  In the OHIG sessions, the two Antarctic stations OHIGGINS (Germany) and SYOWA (Japan) were mostly scheduled with KATH12M (North Australia), YARRA12M (West Australia), HOBART12 and HOBART26 (Tasmania), WARK12M (New Zealand), HARTRAO and HART15M (South Africa), KOKEE (Hawaii, USA), and FORTLEZA (Brazil). Three sessions were observed in February 2017, two in November 2017, three in February 2018, and three in November 2018. One in November 2017 was not scheduled due to the CONT17 campaign. The next step for a higher frequency setup and up to 512 Mbps observing mode in these OHIG experiments is planned for 2020 when SYOWA should have upgraded its system.
- **UT1 determination with near-real-time processing (INT3):**
  The basic INT3 network initially consisted of NYALES20, TSUKUB32, and WETTZELL for rapid UT1 determinations on Monday morning at 7:00 a.m. UT. SESHAN25 takes part on a monthly basis. By now, ISHIOKA has replaced TSUKUB32, and WETTZ13N has joined the sessions in addition to WETTZELL. In 2017 and in 2018, more than 40 INT3 sessions were observed. In May 2017, we changed the standard frequency setup of 512 Mbps with 8 MHz/channel (16 tracks), 2-bit sampling, and 720/140 MHz spanned bandwidth to the higher 1-Gbps frequency setup, increasing the channel bandwidth to 16 MHz (32 tracks). The analysis reports document a slight improvement of around 20% in the UT1 formal errors for many of these sessions.
  The operations part of the INT3 sessions also includes rapid data transmission and correlation. The raw VLBI observation data of the sites are transferred to the Bonn Correlator by Internet connections directly after the session is completed. The transmission rate is about 300–800 Mbps from all stations. Three transfers at a time may occupy the available data lines of 2 x 1 Gbps.

In the last two years, around 98% of the sessions were correlated, and the databases delivered, within the first four hours after the end of the observations. A further 2% were completed within the next 24 hours due to difficulties with networking hardware and/or station and processor problems.

2 Staff

Table 1 Personnel at IGGB Operation Center.

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3 The Future

On December 31, 2019, the IVS Bonn Operation Center, maintained by the VLBI research group of the Institute of Geodesy and Geoinformation of the University of Bonn, will terminate its activities. Taking effect on January 1, 2020, the staff at the Wettzell Geodetic Observatory of the Bundesamt für Kartographie und Geodäsie (BKG), Germany, will take over the responsibilities for operating the sessions mentioned above. In the time until then, the two groups closely cooperate in phasing in the duties of the new center, benefitting from the long experience of the old one.

Acknowledgements

For the last three decades, two of them within the IVS, we have been operating the IVS Bonn Operation Center. This would not have been possible without the many individuals helping us to straighten out organizational difficulties and technical hurdles. There have been many steps back and forth, causing a lot of communications which went extremely well considering the widespread range of issues and global distances. We thank all of you involved for this always friendly relationship between colleagues.

CORE Operation Center 2017–2018 Biennial Report

Cynthia C. Thomas, Daniel S. MacMillan

Abstract This report gives a synopsis of the activities of the CORE Operation Center from January 2017 to December 2018. The report forecasts activities planned for the year 2019.

1 Changes to the CORE Operation Center's Program

The Earth orientation parameter goal of the IVS program is to attain precision at least as good as 3.5 μs for UT1 and 100 μas for pole position.

The IVS program, which started in 2002, used the Mark IV recording mode for each session. The IVS program began using the Mark 5 recording mode in mid-2003. By the end of 2007, all stations were upgraded to Mark 5. Due to the efficient Mark 5 correlator, the program continues to be dependent on station availability and media storage. The following are the network configurations for the sessions for which the CORE Operation Center was responsible in 2017 and 2018:

- IVS-R1 (2017): 49 sessions, scheduled weekly and mainly on Mondays, six to 13 station networks
- RV (2017): Six sessions, scheduled evenly throughout the year, 14 to 17 station networks
- IVS-R&D (2017): ten sessions, scheduled monthly, five to seven station networks
- CONT17: 35 sessions, two networks scheduled concurrent for 15 consecutive days (13 to 14 stations and 14 stations), one network scheduled for five consecutive days (six stations)
- IVS-R1 (2018): 52 sessions, scheduled weekly and mainly on Mondays, four to 13 station networks
- RV (2018): Six sessions, scheduled evenly throughout the year, 13 to 14 station networks
- IVS-R&D (2018): ten sessions, scheduled monthly, six to eight station networks

NVI, Inc./NASA Goddard Space Flight Center

CORE Operation Center

IVS 2017+2018 Biennial Report

2 IVS Sessions from January 2017 to December 2018

This section describes the purpose of the IVS sessions for which the CORE Operation Center is responsible.

- IVS-R1: During the period of January 2017 through December 2018, the IVS-R1s were scheduled weekly with six to 14 station networks. The last session of 2018 only had four stations because it ran on December 26, the day after Christmas, and most of the stations were not available. Twenty different stations participated in the IVS-R1 network and 14 stations participated in at least 26 of the 52 sessions. This was an increase since the period 2015–2016 when only seven stations participated in at least half of the scheduled sessions.
  The purpose of the IVS-R1 sessions is to provide weekly EOP results on a timely basis. These sessions provide continuity with the previous CORE series. The "R" stands for rapid turnaround because the stations, correlators, and analysts have a commitment to make the time delay from the end of data recording to the analysis results as short as possible. Participating stations are requested to ship

Table 1 Median and variability of EOP formal uncertainties for 2017 and 2018. For the IVS-R4s in 2018, two sessions had much larger formal uncertainties. The values without these sessions is given in parenthesis.

	Num	X-pole (μas)	Y-pole (μas)	UT1 (μas)	X nutation (μas)	Y nutation (μs/d)
R1	49, 52	38, 41	41, 43	2.3, 2.6	24, 27	23, 27
		12, 10	9, 7	0.6, 0.6	11, 10	9, 10
R4	50, 53 (51)	38, 44 (40)	41, 49 (44)	2.2, 2.1 (2.4)	28, 33 (30)	27, 33 (30)
		7, 21 (6)	5, 32 (5)	0.5, 1.7 (0.5)	8, 17 (8)	7, 20 (7)
RDV	6, 6	45, 52	44, 51	2.5, 3.0	27, 35	30, 33
		7, 8	4, 7	0.4, 0.6	4, 10	5, 9
CONT11	15	27	28	1.3	16	16
		0.7	0.7	0.1	1	1
CONT14	15	28	30	1.4	16	14
		0.7	0.3	0	1	1
CONT17-L1	15	34	36	1.8	17	17
		1.6	0.9	0.1	2	2
CONT17-L2	15	35	39	1.7	22	21
		1.4	1.7	0.1	2	2

Values are given for 2017 and 2018 in that order. The RMS variabilities are given in the second lines.

disks to the correlator as rapidly as possible or to transfer the data electronically to the correlator using e-VLBI. The "1" indicates that the sessions are mainly on Mondays. The time delay goal is a maximum of 15 days from the end of data recording to the end of correlation. Sixty-three percent of the IVS-R1 sessions were completed in 15 or fewer days during 2017. The remaining 37% were completed in 16 to 30 days [16 days (four), 17 days (two), 20–25 days (ten), 29 days (one), 30 days (one)]. During 2018, the precentage of R1 sessions being processed within 15 days decreased from 63% to 50%. The remaining 50% ranged from 16 to 54 days [16 days (four), 17 days (three), 18 to 25 days (15 days), 26 to 30 days (two), 31 days (one), 54 days (one)]. The largest delay in 2017 was 30 days, while in 2018 the largest delay was 54 days.

- RV: There are six bi-monthly coordinated astrometric/geodetic experiments each year that use the full ten-station VLBA plus up to seven geodetic stations.
  These sessions are coordinated by the geodetic VLBI programs of three agencies: 1) USNO performs repeated imaging and correction for source structure; 2) NASA analyzes RDV data to determine a high accuracy terrestrial reference frame; and 3) NRAO uses these sessions to provide a service to users who require high quality positions for a small number of sources. NASA (the CORE Operation Center) prepares the schedules for the RDV sessions.
- R&D: The purpose of the ten R&D sessions in 2017, as decided by the IVS Observing Program Committee (OPC), was to vet sources for the GAIA proposal (RD1703, RD1704, RD1705, RD1708, RD1709, and RD1710) and evaluate the INT1 sessions (RD1701, RD1702, RD1706, and RD1710).
  The purpose of the R&D sessions in 2018, as decided by the OPC, was to vet GAIA transfer sources. All ten R&D sessions were allocated for this purpose.

3 Current Analysis of the CORE Operation Center's IVS Sessions

Table 1 provides the median formal Earth Orientation Parameter (EOP) errors for the R1, R4, and RDV for 2017 and 2018, and for the CONT sessions. The standard deviation of the formal errors for each case is also shown to give an idea how much variation there is. For comparison, we also show the formal error statistics for the CONT11, CONT14, and the CONT17 Legacy 1 and 2 networks. The R1 session formal uncertainties were not significantly different between 2017 and 2018. R4 uncertainties were less in 2017 than 2018 by 5–10%

Table 2 Offset and WRMS differences (2017 and 2018) relative to the IGS Finals Combined Series.

		X-pole		Y-pole		LOD	
	Num	Offset (μas)	WRMS (μas)	Offset (μas)	WRMS (μas)	Offset (μs/d)	WRMS (μs/d)
R1	49, 52 (883)	59, 93 (18)	90, 59 (89)	100, 107 (130)	69, 68 (85)	1.4, 7.4 (1.2)	17, 14 (16.2)
R4	50, 53 (882)	58, 61(7)	77, 57 (112)	124, 126 (137)	67, 74 (94)	0.6, 0.6 (0.8)	18, 15 (17.2)
RDV	6, 6 (115)	27, −71 (35)	98, 88 (97)	17, 128 (134)	51, 111 (81)	−4.2, 13.7 (1.1)	19.1, 21.7 (14.6)
CONT11	15	-10	26	107	29	7.1	5.7
CONT14	15	27	19	175	30	1.9	5.3
CONT17-L1	15	34	32	57	31	4.0	9.1
CONT17-L2	15	49	55	3	49	1.7	6.3

Values are for 2017 and then 2018 and in parentheses for the entire series (since 2000) for each session type.

The RDV formal errors are comparable to the R4 uncertainties. However, RDV uncertainties were about 10% greater in 2018 than in 2017.

For comparison, we also included the formal uncertainties for the CONT11 and CONT14 campaigns. These are significantly better than for any of the other networks. Median polar motion uncertainties are at or below 30 µas and the UT1 uncertainties are only 1.3–1.4 µs (or equivalently 20–21 µas). Uncertainties for the CONT17 Legacy networks are larger than for CONT11 or CONT14 because compromises had to made to design two independent networks to observe simultaneously.

Table 2 shows EOP biases and WRMS differences with respect to the IGS Finals series for the R1, R4, RDV, and the CONT series. To do this calculation, we used the latest operational GSFC EOP series based on the GSFC 2016a quarterly solution. This solution used the ITRF2014 reference frame model, which includes earthquake site models for co-seismic offsets and post-seismic deformation. In doing this, we no longer needed to estimate post-seismic station positions for TSUKUB32 and TIGOCONC. This reduces the formal uncertainties as well as allowing these stations to contribute fully to EOP estimation. We found that this leads to better agreement between VLBI and IGS polar motion.

The WRMS differences were computed after removing a bias, but estimating rates does not affect the residual WRMS significantly. Both the R1 and R4 series have better WRMS agreement in X-pole and LOD for 2018 than for 2017. The X-pole biases (58–93 µas) and Y-pole biases (100–126 µas) of the R1 and R4 sessions relative to IGS are significant and likely due to reference frame bias. The significant biases for the CONT and RDV are also an indication of overall reference frame bias between the VLBI solution and the IGS frame.

For comparison with the 2017–2018 operational R1 and R4 sessions discussed here, we included the statistics for the CONT11 and CONT14 campaigns. These sessions clearly have the best WRMS agreement with IGS. The X-Pole agreement with IGS for CONT14 is significantly better than for CONT11; otherwise, the WRMS differences are comparable. It is likely that a single CONT17 network would have performed better than either of the CONT17 Legacy networks since compromises had to be made to design two independent networks. The performance of the Legacy 2 network was compromised by the fact that it had only one southern hemisphere station.

4 The CORE Operations Staff

Table 3 lists the key technical personnel and their responsibilities so that everyone reading this report will know whom to contact about their particular question.

5 Planned Activities during 2019

The CORE Operation Center will continue to be responsible for the following IVS sessions during 2019:

- The IVS-R1 sessions will be observed weekly and recorded in Mark 5 mode. There is a strong possibility that mixed mode will be observed and processed. Westford may be added to the network as a Mark 6 station. The correlation of the IVS-R1 sessions will be reviewed to determine how the latency

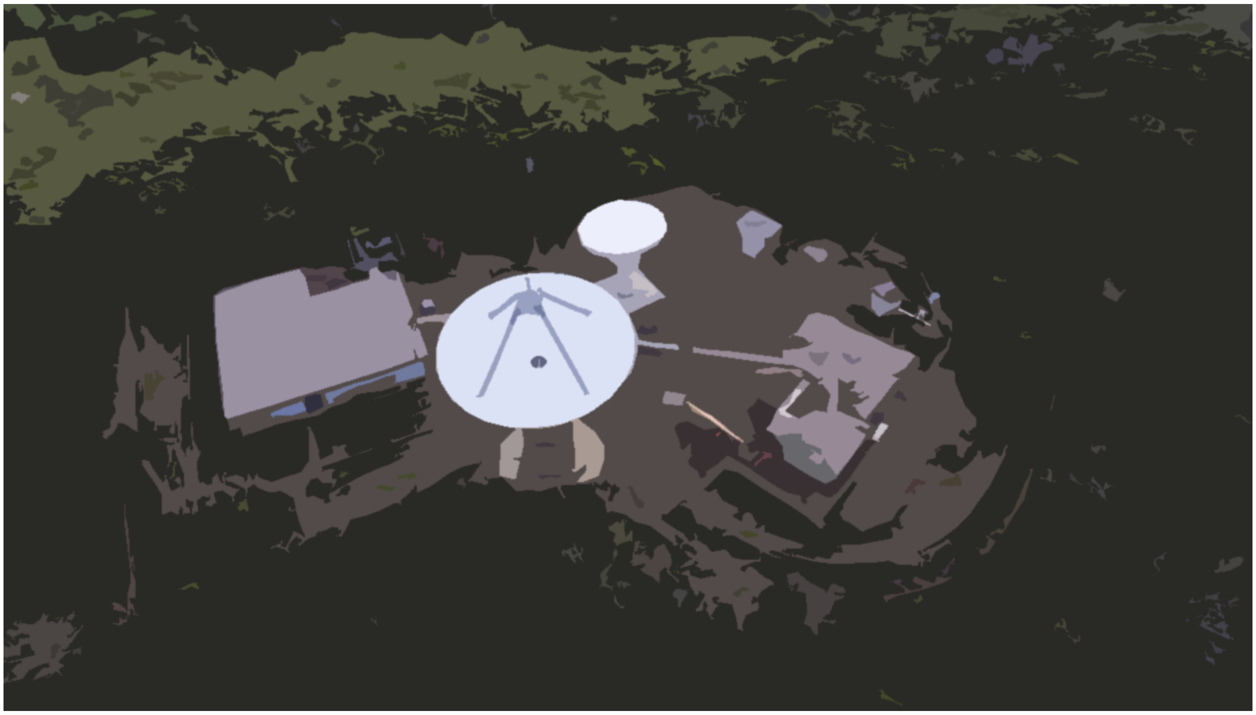
Table 3 Key technical staff of the CORE Operations Center.

Name	Responsibility	Agency
Dirk Behrend	Organizer of CORE program	NVI, Inc./GSFC
Brian Corey	Analysis	Haystack
Jay Redmond	Receiver maintenance	Peraton
John Gipson	SKED program support and development	NVI, Inc./GSFC
David Horsley	Software engineer for the Web site	NVI, Inc./GSFC
David Gordon	Analysis	NVI, Inc./GSFC
Ed Himwich	Network Coordinator	NVI, Inc./GSFC
Dan MacMillan	Analysis	NVI, Inc./GSFC
Katie Pazamickas	Maser maintenance	Peraton
Lawrence Hilliard	Procurement of materials necessary for CORE operations	NASA/GSFC
Cynthia Thomas	Coordination of master observing schedule and preparation of observing schedules	NVI, Inc./GSFC

can be decreased so that most of the sessions will be completed in less than 15 days.

- The IVS-R&D sessions will be observed ten times during the year.
- The RV sessions will be observed six times during the year.
- The CN sessions will be observed six times during the year and will run concurrent with an even 512 Mbps IVS-R1 session. The network will consist of all ten VLBA stations.

CORRELATORS



The Bonn Correlation Center

Laura La Porta [1,2], Walter Alef [3], Simone Bernhart [1,2], Mikhail Lisakov [3], A. Müskens [4], Y. Pidopryhora [3], Helge Rottmann [3], A. Roy [3], Torben Schüler [2], Jan Wagner [3]

Abstract We present a status report of the Bonn Correlator for the years 2017 and 2018. After discussing some technical aspects concerning the cluster and its performance, we will introduce the people working at the correlator, as well as the ongoing activities, focusing on aspects relevant for geodesy.

1 General Information

The Bonn Correlator is operated jointly by the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn and by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG), with the support of the Institute of Geodesy and Geoinformation (IGG) of the Bonn University. The MPIfR hosts the correlator facility and shares with the BKG the costs of the cluster, of most of the staff, and of the Internet connectivity. The IGG contributes to the connectivity of the cluster and pays one member of the geodetic staff. Since January 2017 the personnel responsible for the correlation of geodetic sessions is employed by the BKG via a private contractor, the Reichert GmbH.

1. Reichert GmbH
2. Bundesamt für Kartographie und Geodäsie
3. Max-Planck-Institut für Radioastronomie
4. Institut für Geodäsie und Geoinformation der Rheinischen Friedrich-Wilhelms Universität Bonn

Bonn Correlator

IVS 2017+2018 Biennial Report

2 Correlator Capabilities

Several versions of the Distributed FX software correlator (Deller et al. 2011) are available at the Bonn correlator, and in particular, a branch version developed by J. Anderson specifically for RadioAstron experiments (Bruni et al. 2014). For geodetic production we use the latest stable DiFX release, and before switching to a newer DiFX version we perform a comparison of the resulting observables. During 2017 and 2018 we have been using DiFX 2.5.2. The correlator is running on a High Performance Computing (HPC) cluster, which was renewed in 2015 to match both VGOS and mm-VLBI requirements and nowadays consists of:

- 68 nodes with 20 compute cores each, for a total of 1,360 cores, which provide a computing power about ten times larger than that available with the old cluster;
- three head nodes which allow to execute several correlations in parallel (up to three parallel correlations were tested and no reduction in speed was observed);
- 56 Gbps Infiniband interconnect between all nodes;
- 1.5 PB of disk space organized in RAID units (each with redundancy) and combined in a BeeGFS parallel cluster file system;
- 15 Mark 5 playback units; and
- nine Mark 6 playback units each with four bays.

The raw data are recorded at the stations on Mark 5 or Mark 6 modules, or on Flexbuff fixed disk arrays. For geodetic experiments the data are mostly e-transferred to the HPC cluster, connected to the Internet through two 1-Gbit lines, one of which belongs to the Bonn University. Various data formats were already correlated in Bonn: Mk4, Mk5, DVP, and various components of VDIF.

The correlated data can be exported to FITS and HOPS (MK4) format. For post-processing the following software packages are available: AIPS, PIMA, and HOPS, the latter of which is the standard tool for geodesy. The correlator outputs and other important files (e.g., vex and v2d files) are backed-up daily on the HPC cluster. The final products are archived on the MPIfR archive server, where they will be kept for at least ten years.

The EXPAD and COMEDIA tools are used for bookkeeping of experiments correlated in Bonn. They are the frontends to a local data-base into which all relevant information (observation date, participating stations, modules, and the status of the experiment) is collected.

3 Staff at the Bonn Correlator

The **MPIfR staff at the Bonn correlator** is a subgroup of the VLBI Technical Department, headed by W. Alef. Its members are:

W. Alef - head of the VLBI technical department, computer systems and cluster administration, manager of the BRoad bAND (BRAND) receiver project, VLBI expert, and consultant to the EU-VGOS project.

A. Roy - project manager for VLBI at the Atacama Pathfinder EXperiment (APEX), for DBBC3 commissioning, and head of the polarization conversion effort for Atacama Large Millimeter/submillimeter Array (ALMA) VLBI.

H. Rottmann - responsible for the beamforming software of ALMA, cluster administrator, DiFX developer.

G. Tuccari - guest scientist from INAF, leader of the Digital Base Band Converters (DBBCs) and the Fila10G development, as well as project engineer of the BRAND receiver.

J. Wagner - developer of DiFX, Mark 5 and Mark 6 software, responsible for correlation of EHT VLBI experiments, support scientist with instrumentation and observing-related work in mm-VLBI (EHT and GMVA).

Y. Pidopryhora - organizes, conducts, correlates and performs the post-processing of Global MM VLBI Array (GMVA) sessions and of various soft/hardware related tests.

M. Lisakov - joined the team in June 2018 to take care of the correlation and post-processing of the RadioAstron imaging observations. He also participates in the DiFX software correlator improvement for the needs of space VLBI.

S. Dornbusch - developer of firmware and software for the DBBC3 backend, responsible for manteinance of software for the DBBC2 backend, test and verification of the DBBC2 and DBBC3, support for stations that use a DBBC2 or a DBBC3.

The **geodesy group at the Bonn correlator** has 2.3 FTEs.

A. Müskens - scheduler of various IVS sessions, namely of INT3, EURO, T2, and OHIG, which he generates with the SKED software.

S. Bernhart and **L. La Porta** - coordinate the data logistics, prepare and supervise the correlation, carry out the post-processing and deliver the resulting observables to the IVS repository in form of databases. Besides these standard duties, they provide the stations with a feedback on their performance and support tests of the VLBI systems, in particular for the Wettzell Observatory.

The group is responsible for keeping the cluster software up to date, for hardware maintenance and repair, as well as for IT support and software correlator improvements. The group members are involved in several astronomical projects, which are focused on very high resolution imaging especially with the Event Horizon Telescope (EHT).

As a final remark, the Bonn Correlator is a natural test-bench for the DiFX software and for the e-transfer protocols, so that all its personnel contributes to the debugging of those tools.

4 Activities during the Past Two Years

IVS regular sessions: During 2017 and 2018, we correlated 97 R1, 12 EURO, 13 T2, 93 INT3, ten OHIG, and five days of CONT17. Since May 2018, the databases are produced solely via the vgosDBmake software in VGOS format.

CONT17: The Legacy-1 S/X network of the IVS CONTinous VLBI campaign 2017 was correlated in Bonn. Standard activities were stopped a couple of weeks before CONT17 to prepare storage space and organize the logistics of data transfers. We stored about 500 TB, which were mostly e-transferred to Bonn (only three stations sent modules).

The cluster BeeGFS failed at the beginning of the campaign, so that we could rely solely on three RAIDs for storing and correlating the Rapid-like sessions (C1701-R1, C1703-R4, C1707-R4, and C1714-R1). As a consequence the correlation ran much slower (by a factor three) w.r.t. normal, and we had to pause e-transfers until the beginning of January, when the cluster BeeGFS was completely restored.

Nevertheless, we managed to submit the databases of the Rapid-like sessions within the usual 2–3 weeks latency time. The final correlation of CONT17 was completed during February, but we did not resume standard activities until the beginning of May, due to some long-lasting discussions concerning the global set of clock parameters.

The effective processing time of the CONT17 campaign was enormously reduced with respect to CONT14, thanks to the capabilities of the new cluster. The computing time for 24 hours of data was about a factor of three higher for CONT14, also due to the larger number of modules involved in the correlation (Mk5 units had to be reset often).

Tests of Distributed Correlation: A possible way to deal with the huge workload foreseen for VGOS could be to share it among several correlators by dividing the sessions into time blocks. Each correlator would receive only part of the raw data for a given session.

Upon request of the IVS Directing Board, we organized testing of such an approach, together with five other correlators (Onsala, Warkworth, Hobart, Seshan, and Vienna). We agreed on a common DiFX and HOPS version and performed the test for a regular IVS-R1 session, i.e., R1.840.

Bonn acted as main correlator, therefore we prepared and sent to our colleagues the vex and v2d files to be used for correlation, as well as the control file for fringe-fitting the data. We then collected the DiFX and Fourfit outputs of the branch correlators to compare them with ours. No differences were found between the products of the various correlators, as was to be expected. We generated a new database for R1.840 by combining the output of the main and the branch correlators.

R. Haas performed a geodetic analysis of that database and compared the outcome with that of the original database, which contains only the outputs of the Bonn Correlator. Also this test was positive.

As a remark, the main downside of a distributed correlation is that the data logistics becomes more complicated. The raw data should be distributed to the various correlation centers, which should later upload their products to the main correlator for producing the final database.

EU-VGOS Project: In March 2018—on initiative of W. Alef of the Bonn Correlator Center—started a collaboration with the three European stations of Wettzell, Onsala and Yebes, equipped with both standard S/X and VGOS systems, to carry out a VGOS Proof-of-Concept study. The aim of the project is to verify the processing chain for VGOS experiments end-to-end, from the scheduling to the geodetic analysis of the derived observables.

All parties are learning about the various aspects of the project, from the more technical ones, as system settings and data recording at the station, to data decoding and correlation, and finally to the post-processing of the data, i.e., to the fringe-fitting.

This is desired by all partners in light of the forthcoming IVS-VGOS sessions. In particular, most of the European stations have different back-end systems w.r.t. the American sites; therefore, the European stations must rely mostly on their own resources to debug their systems together with the correlator and the DBBC team in Bonn.

For example, these test sessions revealed that the VDIF multi-threaded files generated via VGOS broadband systems sometimes show anomalies. Namely, the threads are not correctly interleaved in time: for each time tag there should be all threads present in the file, whereas some threads appear with a certain delay w.r.t. the others. As a result, the DiFX's decoding buffers can overflow, thus leading to data loss. The percentage of correlated data decreased by 70% in the worst cases we experienced. The problem can be circumvented by reordering the threads in the raw data file and merging them into a single-thread via a DiFX utility called *vmux*.

RadioAstron: Approximately five experiments were correlated in Bonn in the second half of 2018. Those sessions involve up to 38 antennas and baseline lengths of several Earth diameters. The H-maser onboard the satellite stopped working in September 2017. Since then, there were two modes employed: a

Closed-loop mode (a.k.a. Coherent mode) as default and a Rubidium clock mode.

Global Millimeter VLBI Array (GMVA): Four sessions with up to 21 antennas were correlated in Bonn during the past two years. The recorded data rate is 16 Gbps for ALMA and 2 Gbps for the other telescopes, so that the amount of stored data can be as large as 700 TB.

As ALMA uses a different sampling rate, correlation requires intense use of so-called zoom bands, which allow to cut the non-matching observing subbands into pieces. These pieces are then stitched together so that the correct sub-bands can be reconstructed. Starting from Spring 2018, the GMVA network includes also the brand new Greenland telescope (GLT).

Event Horizon Telescope (EHT): The Bonn cluster is used also to correlate one half of EHT mm-VLBI experiments. The other half of the data is correlated at the MIT Haystack Observatory. The observing campaign of April 2017 lead to the first image of a Black Hole (The EHT Collaboration 2019).

The EHT campaigns in April 2017 and in April 2018 were carried out for five days using the phased ALMA and SMA, and up to seven single mm-VLBI antennas. The frequency setup consisted of multiple 2,048-MHz-wide IFs sampled by R2DBE backends. Each IF was recorded in dual polarization on separate Mark 6 units.

The April 2017 session had two IFs (2×2048 MHz dual polarization) and was recorded on two Mark 6 and eight modules at a total data rate of 32 Gbps. The April 2018 session had four IFs (16 GHz) and was recorded on four Mark 6 and 16 modules at 64 Gbps total. Aggregate rates are reaching 0.5 Tbps, with total storage requirements of around 5–10 PB for raw recordings, and 5 TB for the correlated and final polarization converted visibility data.

Correlation is limited by the available playback units; 32 Mark 6 with 32 expansion chassis would be required for a full 4-IF correlation assuming that eight stations participated in the observations. Hence, the correlation load is shared between the MIT Haystack and the Bonn MPIfR/BKG correlators. The full 230 GHz (1.3 mm) session is split by IF such that the Mark 6 modules of one IF subset are processed in Bonn and the other at MIT Haystack. Playback rate alone via fuseMk6 from a 2×2-module group is slightly above real-time and averages 2.4 GB/s total (18 Gbps).

The correlation of one hour of data for eight antennas in 1-IF takes about 3.5 hours. Format conversion, polarization conversion, fringe-fitting, and deliverables packaging via the pipeline of the EHTC Correlation WG need about the same amount of time.

Upon feedback from EHTC Calibration & Error Analysis WG a number of fine-tuned recorrelations have been necessary. For four IFs that led to a correlation and post-processing time of well over 20 weeks shared by the Haystack and Bonn correlators.

Digital Backends: Noteworthy results from 2017 and 2018 (Tuccari et al. 2018): acceptance and use of the DBBC3 in DDC mode for VGOS observations and in OCT mode for EHT observations; further improvement of DBBC2 capabilities in terms of sampled bandwidth and performance.

BRAND: During the past two years the main tasks have been: a) a survey of the specifications which would enable the installation of a BRAND receiver at the EVN antennas; b) definition of the receiver frontend with the primary focus feed including filters for RFI suppression; c) selection of suitable chips for the sampling board of the backend; d) development of a high data rate processing board with FPGA processors. This board has an input data rate of almost 1 Tbps and up to 512 Gbps as output and is the most powerful data processors available in radio astronomy at present.

5 Current Status and Future Plans

All activities described above are ongoing and some more have been started in 2019.

- M. Lisakov and J. Wagner will implement a closed-loop mode correlation in DiFX to be able to deal with the RadioAstron sessions observed after September 2017. On 10 Jan 2019 the satellite stopped to receive commands at all. Since then, no observations were performed, except for GG085F, which was observed in spring 2019 solely with the Global VLBI. Thirteen experiments await correlation to complete the project.
- Recently the upgraded NOrthern Extended Millimeter Array (NOEMA), the next generation of

IRAM'S Plateau de Bure instrument, joined the GMVA network. A first fringe test was successful.
- During the GMVA session carried out in Spring 2019 the VLBA recorded for the first time on Mark 6 units so that the recording data-rate for the GMVA can be increased now to 4 Gbps.
- Lately, some preliminary tests have successfully been performed at Pico Veleta by using DBBC3s.
- J. Wagner is working on DiFX outputbands feature for DiFX 2.7. The feature is based on earlier standalone de-zooming 'difx2difx' he developed to recover and correlate GMVA+ALMA 2017 (Issaoun et al. 2019). It will enable correlation of VLBI experiments that have inconvenient sky-frequency IF placements and bandwidth mixtures of (non-)overlapping 32/58/62.5/64/128/2048 MHz wide bands.
- He is also working on a Mark 6 reading layer in DiFX together with FUSE layer fuseMk6, as well as improvements towards multi-datastream handling in DiFX native Mark 6 support. He implemented some improvements for playback of lossy or "clumpy" multi-threaded VDIF recordings affecting some VGOS stations and for the PolConverter conversion flow.
- A. Müskens started testing the VieVS (Madzak et al. 2013) scheduling program in collaboration with the Vienna group. In 2019 several INT3 sessions were scheduled with the VieVS software with good results. In early 2020 A. Müskens will retire, thus ending the IVS scheduling activity in Bonn.
- In September 2019, W. Alef will retire and his role as group leader will be taken over by H. Rottmann.
- In August 2019, L. La Porta will also leave her job at the correlator. In April a new scientist was employed by the Reichert GmbH to take care of geodetic correlation with S. Bernhart: Y. Choi.

The Bonn correlator is technically ready for the VGOS era, as has been demonstrated by the successfull correlation of astronomical experiments with comparable data rates (e.g., the EHT).

The real challenge for VGOS will not be the computing power, but rather the data logistics. It is unlikely that stations and correlators will have at their disposal adequate Internet connections and data storage for e-transferring the amount of raw data generated in a VGOS session. Stations will likely have to ship their modules to the correlators, which is rather expensive. Furthermore, the foreseen duty cycle (24 hours per day on consecutive days) will require a rich media pool to provide stations with enough modules to keep observing while part of the raw data is being sent to the correlators.

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MIT Haystack Observatory VLBI Correlator: Biennial Report

Mike Titus, John Barrett, Roger Cappallo, Brian Corey, Pedro Elosegui, Arthur Niell, Chester Ruszczyk, Jason SooHoo

Abstract This report summarizes the activities of the VLBI correlator at the Massachusetts Institute of Technology (MIT) Haystack Observatory during the period 2017–2018.

1 Introduction

The distributed FX-type (DiFX) VLBI software correlator (Deller et al., 2011) of the MIT Haystack Observatory, located in Westford, Massachusetts, is supported by the NASA Space Geodesy Program (SGP) and the National Science Foundation (NSF). It is dedicated approximately equally to the geodetic pursuits for the International VLBI Service (IVS) and to radio astronomy imaging for the Event Horizon Telescope (EHT) project. The MIT Haystack correlator serves as a development system for testing new correlation modes, such as those needed for observations with the next-generation VLBI system — the so-called VLBI Global Observing System (VGOS) — and for recorder developments, such as the Mark6 system. Software support is also provided to similar DiFX installations at the U.S. Naval Observatory (USNO) and the Max Planck Institut für Radioastronomy in Bonn (MPIfR), Germany, and to the general IVS community for processing of VLBI experiments.

MIT Haystack Observatory

MIT Haystack Correlator

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2 Summary of Activities

2.1 General VGOS Activities

The last two years have seen a significant expansion and ramping up of regular VGOS observations. Progress has mostly moved beyond a period of basic debugging of fundamental problems, as described in the last report, to observing a regular series of VGOS experiments once every two weeks with six stations.

During this period the VGOS stations at Wettzell, Yebes, and ("northeast") Onsala have joined the US stations (i.e., Westford, GGAO, and KPGO) on a regular basis. Occasionally, ("southwest") Onsala and Ishioka have also joined the group, making for a VGOS network of eight stations. There is still a moderate level of problem diagnosis and repair embedded in the process, but in general all the participating stations fairly routinely generate data worthy of inclusion in a database for further data processing and analysis.

In addition, a VGOS network of six stations successfully participated in the Continuous VLBI Campaign 2017 (CONT17) for five continuous days, 4–8 December 2017. The broadband VGOS network ran simultaneously with two legacy VLBI networks, which only observed with the traditional dual-frequency (S/X) bands for a period of 15 days, from 28 November to 12 December 2017.

As a measure of the maturing of the VGOS network, databases from the regular, bi-weekly VGOS observations are now being publicly distributed.

2.2 CONT17 Campaign

Significant effort went into preparatory observations, execution, and post-processing of the CONT17 campaign. A pilot pre-CONT17 campaign spanning two consecutive days was conducted in preparation. There was much preparatory work in station problem diagnosis and repair and in post-processing problem discovery, diagnosis, and mitigation. For example, correct VGOS-specific clock and sampler delay setting techniques became a major issue in VGOS processing, but, ultimately, results from VGOS and the legacy network were well aligned.

2.3 Tool Development for VGOS Processing Automation

We have developed software tools and an accompanying users manual to describe and facilitate the correlation and post-processing steps of VGOS observing (Barrett et al., 2019), as this process is significantly different from traditional S/X observing. This effort is a significant knowledge-transfer exercise of VGOS processing capabilities to other correlators and to the IVS.

2.4 VGOS Equipment Verification and Validation

The MIT broadband signal chain for the new VGOS station at McDonald Observatory (MGO; Merkowitz et al., 2018) has undergone comprehensive testing. This includes parallel-rack testing whereby two VGOS backend systems, the Westford and MGO backends, ran in zero-baseline mode at the Westford station during regularly scheduled VGOS sessions. Both systems were correlated at MIT Haystack for verification and validation of the MGO signal chain.

2.5 Digital Backend Testing

Tests of non-standard modes of observing with RDBEs, such as full 512 MHz bandwidth with 16 Gb/sec recording using all RDBE channels and testing a proposed new frequency sequence (B. Petrachenko, private communications), have been conducted and are being analyzed. Tests of VGOS-compliant (1024 MHz bandwidth) R2DBEs have been performed during this period, validating their use for VGOS observations at the Westford site.

2.6 Mixed-mode Observations

Results from a mixed-mode (using both legacy and VGOS antennas) test session have been obtained, and two more mixed-mode sessions were observed since the last report. The RD1606 mixed-mode experiment with Westford tagging along was shown to fully validate the technique and was released to the IVS. Since that time, two more mixed-mode sessions have been observed, first with Westford and GGAO recording simultaneously in mixed mode in RD1804, and then with KPGO joining in for RD1810. These experiments are in post-production and production, respectively.

Parallel development of the MIT Haystack Observatory Post-processing System (HOPS) software package has continued apace in order to accommodate this highly non-standard mode which is incompatible with current norms. Most changes have been directed at simplifying the data processing pipeline. This is necessary as the current pipeline is not sustainable for bulk production.

2.7 Cluster Upgrade

A major expansion of the correlator cluster was implemented in 2017 under the auspices of the EHT project. Thirty-eight new compute servers were purchased and installed. Together they host 2x10 core (Intel Xeon) CPUs, three 100 Gb/sec Ethernet backbone switches, and (Mellinox) network cards supporting a Gb/sec Ethernet fabric with supporting racks and power distribution. The upgrade has greatly increased the bandwidth and computational power of the correlation backbone infrastructure. Additionally, four new Mark6 playback units have been added, increasing the total number of available playback units to eleven. Approximately 38 TB of storage space has also been added for data.

In parallel, global IT management tools were implemented in order to make configuration and control of this new large cluster of machines manageable. Since the last report, all of the equipment from the geodetic and EHT clusters has been combined into one uniform cluster. The geodetic (Infiniband) fabric was retired in favor of the Gb Ethernet fabric. As a result, the geodetic projects that include VGOS antennas have benefited from the upgrade in having access to this hardware for their correlation tasks.

2.8 Clock-summit Meetings

A teleconference series has been conducted on a regular basis to incorporate a consistent and uniform "ensemble method" of adjusting correlator clock offsets at all IVS correlators to improve the accuracy of UT1-UTC estimates using VLBI. Much progress has been made in having the three major correlators (i.e., MIT, USNO, and MPIfR) use these methods. These teleconferences have tangentially improved VGOS clock-setting methods through the exposure of inconsistencies in the method of application of sampler delays.

2.9 DiFX Software Support

Support for the community continues for difx2mark4, fourfit, and HOPS. This support includes addition of features requested by users, other enhancements, and bug fixes.

3 e-VLBI

Non-real-time electronic transfers of VLBI data have continued during this period. Data from 11 stations from 20 VLBI sessions (10 R&D sessions from each of the IVS and VLBA networks) were transferred to MIT Haystack during the past two years for in-house correlation or for conversion to Mark5 media prior to shipping for off-site correlation.

4 Experiments Correlated

A total of 96 geodetic VLBI sessions have been processed, at least in part. These include 18 R&D, eight T2, 42 VGOS Trial (VT), five CONT17, two mini-CONT, and 21 VGOS-related sessions that were either broadband, mixed mode, or tests of other types. This count does not include smaller tests because they were too small to warrant individual experiment numbers.

5 Existing Correlator Capabilities

The "old" geodetic DiFX cluster, consisting of six PCs (each with a dual hex core 2.66 GHz Intel Xeon processor), was merged and integrated with the existing 16 EHT cluster PCs (each with single deca core 2.8 GHz Intel Xeon processors controlled by two equivalent master nodes) and the 38 newly purchased PCs (each with dual deca core Intel Xeon CPUs). The merged monolithic (but easily subdivided) "super cluster" has over 1,152 cores.

Connecting, providing data to, and supporting this computing infrastructure are a Gb Ethernet fabric with three 100 Gb Ethernet switches, 197 TB of new data storage space, and three file storage servers that can also act as DiFX compute nodes providing >200 TB of file storage. The 40 Gb/sec (Infiniband) network fabric using a Qlogic switch and 40 Gb Ethernet network fabric from the EHT cluster mentioned in the last report were retired in this process. A total of 11 Mark6 playback units with DiFX fully installed are connected to the Gigabit Ethernet fabric. In addition, new racks and uninterruptible power supplies condition and stabilize power provided from a new 208-volt power distribution fabric.

The integrated cluster (Figure 1) is used to correlate data from EHT, VGOS, and legacy S/X observing sessions.

6 Staff

The following staff have participated in various aspects of correlation, post-processing Mark6, and e-VLBI development and operations.

Fig. 1 (Left) Cluster correlator and (right) Mark6 playback units at the MIT Haystack Observatory.

6.1 Correlator Software Development

- John Barrett - software development and support
- Roger Cappallo - HOPS software development
- Geoff Crew - DiFX, HOPS, and Mark6
- Kevin Dudevoir - Mark6, e-VLBI, computer system support and development, and DiFX
- Tim Morin - cluster IT, hardware/software support
- Jon Rose - cluster IT, hardware/software support
- Jason SooHoo - cluster IT, Mark6, and e-VLBI
- Chester Ruszczyk - Mark6 and e-VLBI

6.2 Correlator Operations

- Peter Bolis - correlator maintenance
- Alex Burns - Mark6 and general technical support
- Brian Corey - correlation oversight, station evaluation, and technique development
- Glenn Millson - correlator operations
- Arthur Niell - technique development
- Don Sousa - media management and shipping
- Mike Titus - correlator operations setup, oversight, and hardware/software testing
- Ken Wilson - correlator and Mark6 maintenance

7 Conclusions and Outlook

Building, commissioning, and expansion of the VGOS network will continue. Standardization and automation of procedures to export VGOS processing to other correlators will proceed. Mixed-mode observation and correlation methods will be developed and exported. Routine geodetic processing will continue.

Acknowledgements

In memory of Kevin Dudevoir, for his contributions to the MIT Haystack VLBI correlator.

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IAA Correlator Center Biennial Report 2017+2018

Igor Surkis, Voytsekh Ken, Yana Kurdubova, Alexey Melnikov, Vladimir Mishin, Nadezhda Mishina, Violetta Shantyr, Vladimir Zimovsky

Abstract The IAA Correlation Center activities in 2017 and 2018 are described. All regular observations of the Russian geodetic VLBI programs were transferred to the IAA in e-VLBI mode and correlated using the ARC, RASFX, and DiFX correlators.

1 General Information

The IAA Correlator Center is located at St. Petersburg, Russia and maintained by the Institute of Applied Astronomy. The main goal of the IAA Correlator Center is processing geodetic, astrometric, and astrophysical observations made with the Russian VLBI network Quasar. At present three correlators are involved in this processing: ARC, RASFX, and DiFX.

The ARC (Astrometric Radio Interferometric Correlator) is a six-station 15-baseline hardware correlator. The ARC was designed and built by the IAA RAS in 2007–2009. The correlator is the XF-type and based on FPGA technology. The ARC maximum data rate is 1 Gbps for each station, 6 Gbps total.

In 2014 the Russian Academy of Sciences FX (RASFX) six-station near-real time GPU-based VGOS correlator was developed [1]. The correlator software is installed on an HPC cluster, which contains 40 servers, each equipped with two Intel CPUs and two Nvidia GPUs. Due to high GPU performance, the RASFX correlator is able to process up to 96 Gbps input data rate. Since 2015, the DiFX software correlator has been up and running on the HPC cluster.

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2 Activities during the Past Years

ARC commonly operates with data obtained from 32-m telescopes RT-32 “Svetloe”, “Badary”, and “Zelenchukskaya”. ARC processes daily Intensive single hour sessions for UT determination and weekly 24-hour sessions for EOP determination in the standard legacy IVS geodetic setup (1-bit, 16 frequency channels of 8 MHz bandwidth). More than 800 sessions were processed in 2017–2018.

During 2017–2018, two new VGOS-compatible 13-m telescopes RT-13 located in Badary and Zelenchukskaya carried out observations on a regular basis with a 2 Gbps data transfer rate from the stations to the Correlation Center. Up to five single hour S/X and one half hour S/X/Ka sessions are performed daily with the following setup: four frequency channels with 512 MHz bandwidth and two-bit sampling (8 Gbps per station), which forms a total data rate of nearly 4 TB per hour. The RASFX and DiFX correlators are used for these sessions' data processing.

The five-station (three RT-32 and two RT-13) 23-hour session was performed to clarify the 13-m antennas' positions. The S/X observations were recorded with 512 MHz bandwidth frequency channels at the RT-13 stations and with 32 MHz bandwidth frequency channels at the RT-32 stations. This session was processed using the DiFX correlator.

Experiments for Intensive GLONASS satellite observations were made during 2017. Satellite signals were obtained using the three RT-32 stations, and data processing was performed using the RASFX correlator. High precision VLBI delays were calculated.

The new 13-m VGOS-compatible telescope in Svetloe was constructed in 2017–2018. The first three-station VLBI observations were made in S/X on September 2018. Fringes were obtained by the RASFX and DiFX correlators.

The experiments of the mobile VLBI station project were carried out. A small 4-m antenna in Svetloe was used as a mobile prototype. The observations in X-band with 512 MHz bandwidth 2-bit sampling frequency channels were performed with RT-13 Badary and Zelenchukskaya. The correlation fringes were also calculated by the RASFX and DiFX correlators.

The Correlation Center also processed calibration and equipment test observations for the Quasar VLBI network. A zero-baseline radio interferometer model was created at IAA RAS in 2017 in order to analyze VLBI radio interferometer characteristics in laboratory conditions. The model consists of the radio telescope RT-13 tri-band and ultra-wideband receivers (UWB) [2] heterodyne type receivers, broadband data acquisition system, and RASFX correlator. The radio interferometric sessions were carried out in S/X/Ka-bands with 512 MHz channel bandwidth and 2-bit sampling. The session duration was varied from single 5 to 20 minute “scans” to a single hour that consisted of 120 10-second “scans”. To simulate cosmic radio sources, the noise generator signal was injected into the receivers. We performed more than 200 such sessions. Correlator fringe characteristics obtained with RASFX were analyzed: signal-to-noise ratio (SNR), group delay, group delay rate, fringe phase, and their standard deviations [3].

The comparison of group delays obtained by the RASFX and DiFX correlators using PIMA post-processing software was made. It was found that the differences between the group delays from both correlators are mainly due to the different mathematical implementations of the correlation and post-processing algorithms. The data converter software has been developed, which allows the use of the PIMA post-processing routine on RASFX correlator data instead of the native RASFX post-processing software WOPS. The calculated group delays from WOPS and PIMA software are in good agreement and differ by 0.9 ps or less [4].

In 2017–2018 the following types of sessions were performed:

- a one-hour geodetic program in S/X band for UT determination (“RI”, two or three 32-m stations), daily
- a 24-hour geodetic program in S/X band for EOP determination (“RU-E”, three 32-m stations), weekly
- a one-hour geodetic program in S/X band for UT determination (“R”, two VGOS 13-m stations), five per day, RASFX and DiFX processing
- 0.5-hour test programs in S/X/Ka bands (“RX”, two VGOS 13-m stations), RASFX and DiFX processing.

The set of test observations (“Ru-TEST”) included:

- a 23-hour test geodetic program in S/X band to improve positions for 13-m antennas (two 13-m and three 32-m radio telescopes), DiFX processing
- a GLONASS observation test program, (three 32-m radio telescopes), RASFX processing
- New 13-m antenna “Svetloe” tests, RASFX and DiFX processing
- 4-m mobile antenna prototype “Svetloe” tests, RASFX and DiFX processing
- Miscellaneous test sessions, including international cooperation (“Ru-TEST”).

More than 4,000 sessions were carried out during 2017–2018.

3 Staff

The list of the staff members of the IAA Correlator Center in 2017–2018 is given below.

- Igor Surkis — lead researcher, software developer;
- Voytsekh Ken — GPU software developer, data processing;
- Alexey Melnikov — DiFX processing, scheduler;
- Vladimir Mishin — software developer, data processing;
- Nadezhda Mishina — software developer, data processing;
- Yana Kurdubova — software developer, data processing;
- Violetta Shantyr — software developer;
- Vladimir Zimovsky — data processing lead;
- Ekaterina Medvedeva — data processing;
- Alexander Salnikov — e-VLBI data transfer lead;

- Ilya Bezrukov — e-VLBI data transfer;
- Vladislav Yakovlev — e-VLBI data transfer.

4 Future Plans

In 2019 and 2020, the IAA Correlator Center activities will be focused on the following aspects:

- Routine processing of the geodetic observations,
- Clarifying station positions with VLBI techniques,
- Developing new features for the RASFX correlator.

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NICT Correlation Center 2017–2018 Biennial Report

Mamoru Sekido, Kazuhiro Takefuji, Masanori Tsutsumi

Abstract This report describes the NICT Correlation center and its activities.

1 General Information

The VLBI Correlation Center of NICT is operated by Space-Time Standards Laboratory of NICT/Applied Electromagnetic Research Institute and is located in the Kashima Space Technology Center. The development of broadband VLBI technology for the application to precise frequency comparison between atomic clocks is the primary mission of our group. VLBI experiments for this project were conducted and were processed.

2 Component Description

The VLBI system 'GALA-V' is a broadband VLBI system composed of two small diameter antennas and the Kashima 34-m diameter VLBI station. The upgrading of the receiver system [1] and development of wideband bandwidth synthesis techniques [2] have been performed by using these stations. Small (2.4-m) diameter stations were installed at the headquarters (HQ) of NICT in Tokyo and the National Metrology Institute of Japan (NMIJ) in Tsukuba, respectively. Both institutes are in charge of keeping time series UTC (NICT) and UTC (NMIJ); thus, the time difference with respect to UTC is regularly monitored by using GPS-link. This environment was suitable for frequency-link evaluation by VLBI.

Kashima Space Technology Center, National Institute of Information and Communications Technology

Fig. 1 The cluster computer of the correlator system using the GICO3 Software correlator at NICT/Kashima.

A series of VLBI experiments for clock comparison were conducted in 2017 and 2018 [3]. In March 2018, the VLBI station at NMIJ was moved to Kashima. Then it was exported to Medicina in Italy for intercontinental VLBI experiments. Installation of the small VLBI station at the Medicina observatory was made at the end of July 2018. After initial testing, a series of VLBI experiments was conducted from October 2018.

Data acquisition has been made by the RF-Direct sampler K6/GALAS [4] and the K6 recording system. The observation mode was 2,048-Msps/1-bit/4-ch. The total data rate is 8,192-Mbps per station. Correlation processing of the Kashima–Koganei, Kashima–Tsukuba, or Kashima–Medicina baselines is performed with the GICO3 software correlator [5]. Figure 1 shows the cluster computer for correlation processing with the GICO3 software correlator.

Table 1 Specifications of cluster computers for correlation processing.

Machine	CPU	Memory	RAID
A	Intel i7-3960x v2 6-Core 3.3GHz	64 GB	
B	Xeon E5-2680 v2 20Core 2.8GHz (Dual CPU)	64 GB	Areca ARC-1882ix-24
C	Xeon E5-2680 v2 20Core 2.8GHz (Dual CPU)	64 GB	Areca ARC-1883ix-24
D	Xeon E5-2687 v2 16Core 3.4GHz (Dual CPU)	64 GB	Areca ARC-1882ix-24

Specifications of the cluster computers for correlation processing are summarized in Table 1.

About 30 TB of data is acquired per day per station. One session of the GALA-V experiment continues for two to three days.

Observed data at NMIJ was collected by the physical transportation of a disk set. In the case of VLBI experiments with the Medicina–Kashima baseline, observed data was transferred over high speed network. VLBI stations between Medicina, NICT/Kashima, and Koganei are connected by 10-Gbps network. The available data transfer rate is around 5 Gbps from Medicina to Kashima. This is realized by the support of the high-speed research network of GARR in Italy, GEANT in Europe, Internet2 and TransPAC in USA, and JGN in Japan. The data processing takes one to two times the data acquisition rate. Thus, it takes about four days for correlation processing, totaling 150-200 TB of observation data.

3 Staff

Members who are contributing to the Correlation Center of NICT are listed below (in alphabetical order):

- KONDO Tetsuro: Development of wideband bandwidth synthesis software.
- SEKIDO Mamoru: Coordinating of VLBI observations and making data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Performing correlation processing for broadband data.
- TSUTSUMI Masanori: Maintaining the computer servers of the K6 VLBI recording system and cluster computers for the correlation process.

Acknowledgement

A high speed network environment is provided by the high speed R&D network testbed JGN[1]. Especially, we appreciate Takatoshi Ikeda of JGN, Kunitaka Namba of the Information System Section of NICT, and Yoshihiro Okamoto, also of the Information System Section of NICT, for supporting this project.

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Shanghai VLBI Correlator 2017–2018 Biennial Report

Fengchun Shu [1,2], Weimin Zheng [1,2], Xuan He [1], Yidan Huang [1], Zhong Chen [1,2], Juan Zhang [1], Tetsuro Kondo [1]

Abstract This report summarizes the activities of the Shanghai VLBI Correlator during 2017 and 2018. Highlights include the peculiar clock offset compensation, CVN and K5 correlators comparison, 4-Gbps data e-transfer, VLBI Ecliptic Plane Survey, 2-Gbps experiments at S/X, K-band fringe tests for Tianma65, and RadioAstron space VLBI fringe test.

1 Introduction

The Shanghai VLBI Correlator is hosted and operated by the Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences (CAS). It is located at the Sheshan campus, about 40 kilometers from the Xujiahui headquarters of SHAO. The Shanghai correlator has been used in the data processing of the Chinese VLBI Network (CVN), including the CMONOC project for monitoring the Chinese regional crustal movement, and the Chinese deep space exploration project for spacecraft tracking.

As shown in Figure 1, Shanghai (including Seshan25 and Tianma65), Kunming, and Urumqi participate in international and domestic VLBI sessions, while the Beijing station is mainly used for spacecraft data downlink and VLBI tracking.

The Shanghai correlator was accepted as an IVS correlator in March 2012. It began to correlate IVS data using the DiFX software correlator in 2015. In the long run, our goal is to correlate a weekly IVS observing session on a regular basis.

Fig. 1 Distribution of the VLBI stations in China.

2 Component Description

We are operating two types of correlators. The CVN correlator developed by SHAO has been operational since 2006. It is mainly used for spacecraft VLBI tracking in the Chang'E lunar exploration project by producing differential VLBI observables. The data latency is less than one minute in real-time mode, and the typical accuracy is better than 1 ns. It was used to correlate a few tens of Chinese domestic geodetic sessions before 2014. The other one is the DiFX software correlator,

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Shanghai Correlator

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which is dedicated to astrophysical and geodetic data correlation.

The DiFX software was installed on a powerful hardware platform in December 2014, with a 420 core cluster system and a 400-TB storage space. The disk array was expanded to 800 TB in 2018 to meet the requirement of increased data volume. Three Mark 6 units were installed and are under testing. The suite version is Mark6_1.3c with dplane as 1.22 and cplane as 1.0.26. Features of the DiFX cluster system are listed as follows:

- DiFX 2.52, HOPS 3.18, nuSolve 0.6.4
- Head nodes: DELL R820 (E5-4610 CPU, 2.4 GHz, 2*6 cores), 64 GB Memory, DELL R730 (E5-2623 CPU, 3.0 GHz, 2*4 cores), 64 GB Memory.
- Computing nodes: 20 DELL R630 nodes, two socket Intel E5-2660 CPU (2.6 GHz, ten cores), 64 GB Memory, 400 cores in total
- I/O nodes: RAID6, 800 TB raw storage capacity
- Data playback units: three Mark 5A, three Mark 5B, and three Mark 6.
- 56 G Infiniband for internal computing network connection
- 1/10 G Ethernet for internal and external network connection

3 Staff

The people involved in the operation, development of the correlator, and VLBI digital backend are listed below.

3.1 Operations Team

- Fengchun Shu: group leader, scheduler, experiment oversight
- Zhong Chen: e-transfer support, cluster administration
- Zhanghu Chu: media library
- Shaoguang Guo: Mark 6 maintenance
- Xuan He: DiFX operation
- Yidan Huang: DiFX operation, post-correlation technique development
- Tianyu Jiang: data playback, DiFX operation
- Wu Jiang: DiFX operation
- Xiuzhong Zhang: VLBI terminal and correlation technique development

Wu Jiang is no longer involved in regular geodetic VLBI data correlation from 2018 onward. He will put emphasis on some pilot fringe tests and astronomical data correlation.

3.2 Technique Development Team

- Weimin Zheng: group leader, software correlator, and VLBI terminal development
- Jiangying Gan: FPGA programming
- Tetsuro Kondo: wideband bandwidth synthesis and correlators comparison
- Lei Liu: software correlator development
- Xiaochuan Qu: CDAS development
- Ping Rui: visualization programming and operation for CVN correlator
- Fengxian Tong: VLBI scheduling and modeling
- Li Tong: VLBI raw data simulation
- Yajun Wu: CDAS development
- Zhijun Xu: FPGA programming and hardware correlator development
- Juan Zhang: software correlator development and maintenance
- Renjie Zhu: CDAS development

Tetsuro Kondo from NICT joined the group in mid-2017 as a distinguished scientist, offered by the CAS President's International Fellowship.

4 Summary of Activities

4.1 DiFX Correlation

We use the latest stable version of DiFX and HOPS software for regular IVS data correlation. The DBedit software was replaced by vgosDBmake to generate database files in 2018. The vgosDB files are available at our ftp site[1]. We also produce FITS-IDI files which can be downloaded by the request of users.

[1] http://202.127.29.4/vgosDB/

For a few IVS schedule files (e.g., CRDS93) generated in VEX format, there was no source flux density information available. In order to provide baseline SNR statistics in the correlation report, we need to convert the schedule file to SKED format by adding source flux density information.

We introduced peculiar clock offsets to compensate instrumental delays of reference stations during the correlation procedure in early 2018. As shown in Figure 2, we analyzed all 98 correlated sessions, and derived clock biases of the Shanghai correlator, i.e., compensation errors with respect to the peculiar clock offset table maintained by Ed Himwich and used by the Washington correlator. In most of cases, the clock bias is less than 3 μs. Only two sessions (AOV006 and AUG020) have clock biases greater than 5 μs. We are trying to keep the correlator clock bias within 0.1 μs.

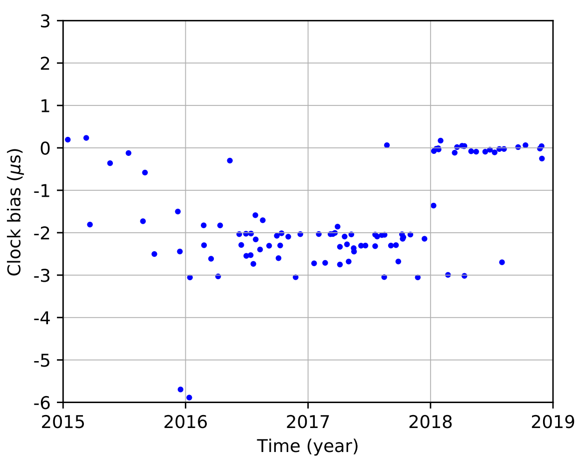

Fig. 2 Clock bias of Shanghai correlator over 98 sessions.

4.2 Development of the CVN Software Correlator

The CVN software correlator has implemented two new features: VDIF format decoding support and real-time fringe monitoring. It has been used to process single-band VDIF data acquired from VGOS stations in the Sheshan area. Good fringes were obtained.

To support the future space VLBI project, we have implemented the calculation of space-ground delay model compatible with the new data format RDF. With the help of ASC, we have processed a set of RasioAstron space-ground VLBI data and successfully obtained good fringes.

We are developing and testing a GPU-version correlator. The processing data rate is 1 Gbps/station for ten stations totally. The GPU cluster includes four GPU-nodes. Features of each GPU-node are as follows:

- Node: 36 Intel Xeon CPU E5-2697 v4 @2.3GHz, 4* NVIDIA K80;
- 56 G Infiniband for internal computing network connection.

4.3 CVN and K5 Correlators Comparison

We used the VLBI experiment K14349 observed on 2014/349 07h-08h UT to perform a comparison of the CVN and K5 correlators. Four stations, such as Nyales20, Seshan25, Tsukub32, and Wettzell, participated in the experiment.

Results obtained by the CVN software correlator have been compared with those obtained by the K5 software correlator. Earth-centered epoch correction and X clock offset correction were applied to K5 results. As a result, K5 and CVN show a good agreement with each other on observed values, such as fine (multi-band) delay, delay rate, and fringe amplitude. The average of the standard deviation of the differences between X-band fine delays is 7.6 ps. As for the delay rate, the average of the differences at X-band is 0.00±0.09 ps/s. As for the fringe amplitude at X-band, the average ratio (CVN/K5) is 0.98±0.11.

4.4 Chang'E 4 Tracking

China's Chang'E 4 spacecraft is the first probe to make a soft landing on the far side of the moon. Tianma65, Beijing, Kunming, and Urumqi stations participated in intensive VLBI tracking sessions from its launch on 8 December 2018 to its soft landing on 3 January 2019. We observed 22 tracking sessions in total. During the same time period, we also observed Chang'E 4 data relay satellite Queqiao which means "bridge of magpies" in 19 tracking sessions.

4.5 e-VLBI

The network link to Seshan25 and Tianma65 is 10 Gbps. The network link to the Urumqi, Kunming, and Beijing stations is 200 Mbps for spacecraft e-VLBI observations. In the Chang'E 4 lunar mission, we made real-time data transfers at a data rate of 128 Mbps for each station. However, for regular geodetic observations, the Chinese stations always ship modules to the Shanghai correlator.

In order to process IVS global sessions, we have established a network link to most of the IVS stations and correlators. The maximum data rate could be up to 4 Gbps. An example is shown in Figure 3.

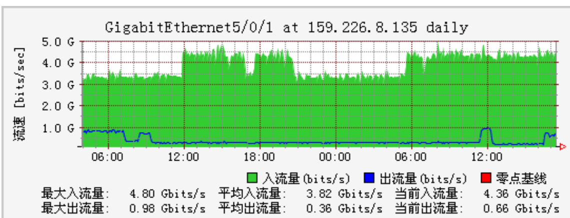

Fig. 3 A screenshot of e-VLBI data rate daily monitoring, where the output data rate is shown in blue and the input data rate is in green.

Except for Kokee and Matera, all other international stations e-transfer data to Shanghai. Since May 2018, we had module shipment issues due to customs clearance. Thus, Kokee data were shipped to Haystack and then e-transferred to Shanghai.

4.6 Experiments Correlated

Within the framework of the IVS, we correlated 33 sessions in 2017 and 26 sessions in 2018. Most of them are focused on VLBI absolute astrometry. There are no stringent requirements on data latency. More details can be found in Table 1.

It is worth noting that APSG sessions and some AOV sessions were scheduled by SHAO. So far we have correlated 98 IVS sessions with 33 participating stations distributed over the globe. The cumulative data volume is approximately 2.5 PB, collected from more than 600 station days. The top five stations with most observing days are Katherine, Yarragadee, Hobart26, Warkworth, and Kunming.

Table 1 Statistics of experiments correlated.

Session Name	2017	2018
AOV	3	7
APSG	2	2
AUS-AST	14	6
IVS-CRF	6	5
IVS-CRDS	3	1
IVS-R&D	5	5

In addition, we correlated some domestic VLBI experiments for geodesy or astronomy.

4.7 VEPS

We completed the first circle of the VLBI Ecliptic Plane Survey (VEPS) in 17 sessions by the end of 2017. Seshan25, Kunming, and Urumqi were core participating stations, while a few international stations, such as Kashim34, Hobart26, and Sejong, took part in the observations on an ad-hoc basis. The raw data from the stations is more than 900 TB in total. We detected 662 calibrator candidates from more than 4,000 observed sources.

4.8 2 Gbps at S/X

We performed the first international 2 Gbps experiments at S/X dual band on 24 January 2018 (EPA001) and 10 February 2018 (EPA002). The participating stations were Chinese and Russian stations. Kashim34 joined in EPA002. Due to strong RFI at S-band, there were unusable channels and decreased sensitivity. Therefore, the results are not as good as what we expected.

4.9 K-band Test for Tianma65

We conducted a K-band fringe test with participation of Tianma65 and HartRAO on 18 April 2017. The observations were performed at a 2,048 Mbps data rate, with 16 IF channels (8 USB and 8 LSB) and 2-bit sampling. Only RCP was used. Each IF channel has 32 MHz wide. Good fringes were detected as shown in Figure 4.

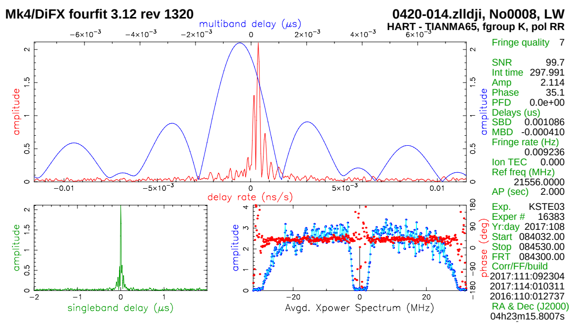

Fig. 4 K-band fringes on the baseline Tianma65–HartRAO.

5 Future Plans

As the data correlation of AUA sessions is in transit to Vienna VLBI group, the number of IVS observing sessions correlated at Shanghai will be decreased. Currently, only 20 are scheduled in 2019. However, most of them will be observed at a 1-Gbps data rate.

The CVN correlator will be expanded into a general purpose correlator, and its performance will be updated by GPU acceleration. It will continue to support China's follow-up series of lunar and deep space missions, as well as the space VLBI project.

Two VGOS antennas have been deployed in Sheshan area. We are ready to make test correlation of VGOS data. Hopefully they will soon join in international VGOS experiments.

Acknowledgements

We acknowledge the support of National Natural Science Foundation of China (Grant No. 11573056 and 11573057), and Fundamental Science Data Sharing Platform (DKA2017-12-02-09).

Tsukuba VLBI Correlator

Takahiro Wakasugi [1], Michiko Umei [1], Tetsuya Hara [1,2]

Abstract This report summarizes the activities of the Tsukuba VLBI Correlator during 2017 and 2018. The correlator was regularly involved in the weekend IVS Intensive (INT-2) sessions as well as the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) sessions using the K5/VSSP correlation software.

1 Introduction

The Tsukuba VLBI Correlator, located in Tsukuba, Japan, is operated by the Geospatial Information Authority of Japan (GSI). It is fully devoted to processing geodetic VLBI observations of the International VLBI Service for Geodesy and Astrometry (IVS). All of the weekend IVS Intensive (INT-2) sessions for UT1-UTC (= dUT1) estimation and half of the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) sessions, which began as regular IVS sessions in 2015, were processed at the correlator. The K5/VSSP correlation software developed by the National Institute of Information and Communications Technology (NICT) is used for all processing.

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co., Ltd.

Tsukuba VLBI Correlator

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2 Component Description

2.1 e-VLBI

The Tsukuba VLBI Correlator has been connected to a broadband network, and all of the observed VLBI data are delivered via the network basically. The correlator has a 10 Gbps dedicated link to the *SINET5* operated by the National Institute of Informatics (NII), which is connected to several research networks in the world such as *Internet2* in the U.S., *GÉANT2* in Europe, and *TEIN4* at Singapore. It enabled us to transfer a massive amount of data between the correlator and overseas IVS components. The Ishioka VLBI station has also been connected to the correlator and *SINET5* with a 10 Gbps dedicated cable since 2014.

2.2 K5/VSSP Correlation Software

The K5/VSSP correlation software, which was developed and has been maintained by NICT, is adopted at the correlator. The software consists of several programs for the calculation of a priori values of delay and delay rate (*apri_calc*), for the correlation processing for all observations (*fx_cor_new or cor_new*), and for monitoring the results of the correlation processing by performing a so-called "coarse search" (*sdelay*), followed by several utilities such as *komb* for the bandwidth synthesis [1]. The software can handle not only K5 format data but also Mark 5B or VDIF format data without format conversion in the latest version.

Table 1 Correlator hardware capabilities.

	Main system	Backup System
Number of servers	16 - 14 for correlation processing - 2 for controlling correlation processing	5 - 2 for correlation processing - 2 for controlling correlation processing - 1 for data storage
Operating System	Red Hat Enterprise Linux 6.3	CentOS version 6.9 and 7.4
CPU	Intel Xeon X5687 @3.60GHz 4 cores x 2	Intel Xeon X3360 @2.83 GHz 4 cores Intel Xeon Gold6130 @2.10 GHz 16 cores x 2 Intel Xeon E5-2609v4 @1.70 GHz 8 cores x 2
Total storage capacity	513 Tbytes	273 Tbytes
Network	10 Gbps dedicated line connected to SINET5 by NII	

2.3 Correlation Procedure

The following are typical correlation processes at the correlator and programs used in each process.

1. Transferring data from network stations to the correlator (*tsunami and tsunamid*, or *jive5ab*).
2. Preparation of a priori parameter files (*apri_calc*).
3. Fringe search to find a clock offset at each pair of stations (*fx_cor_new or cor_new*).
4. Running correlation processing for all observations (*fx_cor_new or cor_new*).
5. Coarse search for estimating residual delay and delay rate, and plotting them on a 3-D diagram (*sdelay*).
6. Bandwidth synthesis to derive a multi-band delay (*komb*).
7. Database creation to be submitted to IVS Data Centers (*vgosDbMake* for vgosDb format or *MK3TOOLS* for Mark III format).

The correlation and analysis management programs developed by GSI can run the above processes consecutively and automatically. The program for the management of data transfer *rapid_transfer* accesses a data server in an observing station, executes *tsunamid* there, and then executes *tsunami* to transfer data automatically at the correlator side concurrently with the start of the session as needed. *Rapid_cor* is a program to search for a fringe for each baseline based on the clock information of each station written in the FS log, as well as the station positions and source coordinates described in the schedule file and external a priori earth orientation parameters. Once the fringe is detected, the main correlation processing runs one after another with the clock offset and rate information derived from the fringe search process until the last observation. *Rapid_komb* executes *komb* on the stream of correlation outputs for bandwidth synthesis process. For the weekend Intensive sessions, *rapid_c5pp*, which gives an interface to VLBI analysis software *c5++*, executes analysis automatically as the bandwidth synthesis process finishes and delivers the result to the community (refer to the report "Tsukuba VLBI Analysis Center" in this volume for more details). The database creation is carried out manually with *vgosDbMake* for the vgosDb format or with *MK3TOOLS* for the Mark III format to be submitted to IVS Data Centers [2] [3].

2.4 Correlator Hardware Capabilities

The hardware supporting the activities of the correlator is summarized in Table 1. All these pieces of equipment are general purpose and commercially available products. It means that no dedicated hardware is required in the K5 correlation processing. The main system consists of 16 IBM X3650 servers and a Data Direct Networks storage system with a capacity of 513 TB (Figure 1). In 2018, the backup system consisting of five servers and 273 TB RAID data storage was installed and has been utilized for some test purposes.

3 Staff

The technical staff members at the correlator are:

- **Takahiro Wakasugi** — correlator/analysis chief, management.
- **Michiko Umei** — correlator/analysis operator, coordination.

Fig. 1 View of the main system (data processing servers and storage) at the Tsukuba VLBI Correlator.

- **Tetsuya Hara** (AES) — correlator/analysis operator, software development.

4 Correlator Operations

4.1 IVS Intensive for UT1-UTC

All of the weekend Intensive series (INT-2) were processed at the correlator automatically in near real time using the *rapid_* programs (see Section 2.3). The number of sessions processed in 2017 and 2018 is listed in Table 2. Ishioka in Japan and Wettzell 20 m in Germany have participated in INT-2 sessions usually. On the other hand, some telescopes such as Kokee Park in Hawaii, U.S., Sheshan in China, or Kashima 34 m in Japan were involved when Ishioka was not available during the VGOS test period for a few months a year. The 13.2-m Wettzell North Telescope also filled in during the absence of Wettzell 20 m sometimes. In addition, a few INT-3 sessions on Monday were correlated on behalf of the Bonn Correlator. Please refer to the report "Tsukuba VLBI Analysis Center" in this volume for results and more details.

Table 2 Intensive sessions processed at the Tsukuba Correlator.

2017	Baseline	Period	# of sessions
Intensive 2	IsWz	Jan 08 – Dec 31	79
	IsWn	Aug 05 – Aug 06	2
	KkWz	Jun 03 – Dec 10	8
	ShWz	Nov 04 – Nov 12	4
	KbWz	Dec 16	1
Intensive 3	IsNyWnWz	Oct 30	1
Total			95
2018	**Baseline**	**Period**	**# of sessions**
Intensive 2	IsWz	Jan 07 – Dec 29	59
	IsWn	Mar 17 – Mar 18	2
	KkWz	Jun 09 – Sep 30	18
	KkWn	Aug 11	1
	ShWz	Jul 28 – Aug 26	4
	ShWn	Aug 05	1
	KbWz	Mar 10 – Mar 11	2
Intensive 3	IsWnWz	Dec 24	1
Total			88

4.2 IVS AOV sessions

The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) is a regional subgroup of the IVS established in 2014 to foster and encourage closer collaboration in VLBI in the Asia-Oceania region. The dedicated VLBI experiments started in 2015 regularly once every two months, and the number of sessions has increased to 12 sessions in a year since 2018. Correlation tasks are shared by the Tsukuba VLBI Correlator and the Shanghai Correlator operated by Shanghai Astronomical Observatory (SHAO). The number of sessions processed at the Tsukuba VLBI Correlator in 2017 and 2018 is listed in Table 3. Most of the data were transferred via the broadband network from not only Japan, but also China, Korea, Australia, and New Zealand, while the data of Syowa in Antarctica were only shipped to Japan. In addition, the correlator works on the intensification of giving feedback to stations and schedulers based on the correlation results in order to improve the data quality of the AOV sessions through the dedicated mailing list for the AOV operation.

Table 3 AOV sessions processed at the Tsukuba Correlator.

Year	Name	Date	Stations	Data Rate
2017	AOV013	Jan 16	HbK1KeKgKmKvSyUrVmYg	128 Mbps
	AOV016	Apr 11	HbIsKeKmKvShUrVmYg	1 Gbps
	AOV018	Nov 15	KbKeKmKvShUrWwYg	1 Gbps
2018	AOV020	Feb 27	IsK1KeKgSyWwYg	128 Mbps
	AOV023	May 21	HoIsK1KgVmWwYg	1 Gbps
	AOV024	Jun 19	HoK1KeKvSyWwYg	128 Mbps
	AOV028	Oct 16	HoIsKbKeKvVmWwYg	1 Gbps
	AOV030	Dec 11	HoIsKeKvWwYg	1 Gbps

4.3 Procedure Updates

There were several major updates to the correlation procedure during this period.

- **Station Clock Update**

The handling of station clocks has direct consequences for the values of the UT1 estimation [4]. The station clock information was updated properly following instructions of the IVS.

- **Transition to vgosDb Format**

The database creation procedure was modified in response to the transition of database format from Mark III style to vgosDb style. The database creation software *vgosDbMake*, which can handle the *Komb* output directly, was installed and incorporated into the ordinary procedure. The Mark III format databases are also created based on requests from a few Analysis Centers.

- **Capability of Dealing with VDIF and Mark 5B Format**

The latest version of the K5/VSSP correlation software can handle not only K5 format but also Mark 5B and VDIF format without format conversion. The correlation and analysis management programs developed by GSI obtained the ability to deal with Mark 5B and VDIF format by slight modification of programs and have been adopted for the operational INT-2 processing since Q18335 in December 2018. This modification contributes to saving effort and reducing the amount of data generated by the data format conversion.

5 Outlook

We will continue to process the IVS Intensive sessions and AOV sessions. For more stable operation of especially near real time processing, we will make further improvements to the *rapid_* programs and maintain the hardware and network. Furthermore, we will introduce the DiFX correlation software for the correlation of VGOS data.

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Vienna Correlation Center Annual Report 2017/2018

Jakob Gruber [1], Johannes Böhm [1], Jamie McCallum [2]

Abstract In September 2018, Technische Universität Wien (TU Wien) was approved as an IVS Correlation Center. The main contribution to the IVS is with the correlation of sessions observed by the AUSTRAL network dedicated to southern hemisphere astrometry. For the correlation, we use the Vienna Scientific Cluster (VSC-3), which is a supercomputer located in Vienna. In this report, we provide details about our supercomputing infrastructure in terms of software and hardware. We highlight our main activities related to IVS VLBI correlation and other scientific developments. Furthermore, we report about our future plans and a new correlation infrastructure which is currently under development.

1 General Information

At TU Wien, we correlate VLBI sessions on the Vienna Scientific Cluster (VSC-3) which is a collaboration of several Austrian universities that provides supercomputer resources and corresponding services to their users. The VSC is located at the Arsenal building of TU Wien and is operated by the VSC Research Center and the Information Technology Solutions (TU.it) of TU Wien. Our main contribution to the IVS is by correlating sessions of the AUSTRAL VLBI network. These sessions are usually scheduled once per month and are part of southern hemisphere astrometry projects. One of these projects is the SOuthern Astrometry Program (SOAP). The scientific goal of SOAP is to improve positions of compact extragalactic sources with declinations $< -45°$. We take also part in distributed correlation experiments to evaluate a correlation strategy in the VGOS era.

1. TU Wien
2. University of Tasmania

TU Wien VLBI Correlator Center

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2 Correlation Capabilities of the VSC-3

One of the most important elements in the processing infrastructure of a VLBI correlation center is a High-Performance Computing (HPC) cluster. At TU Wien, we use the supercomputer infrastructure of the VSC-3 for this purpose (see Figure 1). The hardware capabilities which are intended for processing a large amount of data and for intensive i/o workloads make the VSC-3 an appropriate multiprocessor computing

Fig. 1 Picture of the room where the 2020 nodes with liquid submersion cooling of the VSC-3 are stored. Picture was taken at VSC Arsenal TU Wien building ©Claudia Blaas-Schenner.

environment for the correlation of the large amount of VLBI data. The VSC-3 consists in total of 2020 nodes, each equipped with two processors. A detailed description of the configuration of such a compute node and further relevant technical aspects can be found in Table 1. Usually, we request 10 nodes of this type to carry out our correlation tasks. The high-performance BeeGFS parallel filesystem intended for intensive i/o workloads provides our data storage facility on the VSC-3. For more information see [3]. A summary of the key values of the most important capabilities of the VSC-3 for both hardware and software can be found in Table 2. This table also shows the capabilities of the VSC-4, which will be a new member of the Vienna Scientific Cluster family. It will be used for VLBI correlation as soon as the installation is finished in 2019.

In terms of software we use the jive5ab software package[1] for data transfer tasks, the Distributed FX software correlator (DiFX [2]) for the actual correlation tasks, and the Haystack Observatory Post-processing Software (HOPS[2]) for fringe-fitting. To create the final VGOS database for submission to the IVS we use the vgosDbMake program of the nuSolve release.

Table 1 Configuration table of the compute nodes of the VSC-3.

Motherboard	Supermicro X9DRD-iF Intel Patsburg Chipset QuickPathInterconnect (QPI) 8.0GT/s Dual Xeon Sandybridge (E5 Series) Up to 256GB DDR3 1600/1333/1066/800MHz Slots: 1 (x16) PCI-E 3.0 and 4 (x8) PCI-E 3.0 Intel® 350 Dual-Port Gigabit Ethernet Controller 8x SATA2 and 2x SATA3 ports Integrated IPMI 2.0 with Dedicated LAN Supermicro RSC-RR1U-E8 1U PCI-E Riser Rad
Chassis	SNK-P0047P passive 1U heat sink X9 Generation Motherboard Indium Foil replaces heatsink paste 1U PowerSupply 350W
CPU	2 x Intel Xeon IvyBridge-EP E5-2650v2 2.60GHz 8 Core - 20MB Cache Intel HT Technology 95W TDP (Thermal Design Power)
Memory	8 x 8192MB DDRIII1866 ECC Registered

[1] http://www.jive.nl/~verkout/evlbi/

[2] https://www.haystack.mit.edu/tech/vlbi/hops.html

Table 2 Summary of the key values of the most important capabilities of the VSC-3/4.

	VSC-3	VSC-4
# cores	160 (on request)	480 (private)
disk space	230 TB	1 PB
e-transfer rate	several Gbps	
max. data throughput*	36 Gbps	to be verified
e-transfer software	jive5ab	
correlation software	DiFX	
fringe-fitting software	HOPS, PIMA	
geodetic analysis software	nuSolve, VieVS	

* max. data throughput during DiFX correlation (more description in [4])

3 Activities during the Past Two Years

The correlation activities at TU Wien go back to 2016 with the installation of correlation software at the VSC-3. In the last two years, we started correlating VLBI sessions on a more routine basis and implemented the full VLBI processing chain of data transfer, correlation, fringe-fitting, post-correlation processing, and geodetic parameter estimation in our working environment at TU Wien. We developed third-party tools to support the correlation procedure to enable a more automated correlation and fringe-fitting process. This proved to be very helpful, and it is becoming more economical with respect to operational tasks. For more efficient processing of the correlation tasks, we investigated the processing performance of the software packages within our supercomputing infrastructure on the VSC-3. We developed a tool to convert the fringe-fitting output of fourfit and PIMA into vgosDB. With this, it is possible to directly access the fringe-fitting output with our in-house software VieVS [1]. In 2018, we developed a digital simulator to generate VLBI baseband data which is designed and written in Matlab. This program contains also a VLBI Data Interchange Format (VDIF) formatter to pipe the simulated data into common correlation software packages and test their functionality.

In 2017 and 2018, we correlated twelve IVS sessions in total. One of these sessions, called CRDS94, was used to compare our correlation results against the Washington Correlator (WACO) to become an official IVS correlation center. The other sessions are dedicated to SOAP. The milestones reached with respect to correlation at TU Wien are listed in Table 3, including the period 2017/18.

Table 3 Milestones reached at the TU Wien correlation center, including the period of 2017 and 2018.

2014	Installation of the VSC-3
2016	Installation of DiFX and HOPS on the VSC-3 Correlation of first session AUG032 Correlation of first satellite observation APOD2 Correlation of McWz
2017	Correlation of ds317 Correlation of first official IVS session AUA025
2018	Correlation of European Intensive Session Correlation of CRDS94, verified by WACO Correlation of AUA028, AUA032, ... Correlation of SBL500 Approval as IVS correlation center

3.1 Automated Correlation of IVS Sessions

At TU Wien, we aim for a more automated correlation of VLBI sessions to reduce the manual interactions. This is helpful overall for IVS sessions dedicated to certain projects because within these projects the observing modes and correlation configuration usually stay the same for several sessions. We developed a program which takes over supporting correlation calculations and deals with exception handling and quality control. This program connects routines from DiFX, HOPS, and nuSolve in a processing chain to decrease manual interactions. These algorithms have been trained with the AUSTRAL network and SOAP schedules and make heavy use of the cluster management language SLURM, which is installed on the VSC-3. A log file parser has also been developed to obtain antenna status information more automatically.

3.2 Performance Tests and Correlation Efficiency on the VSC-3

Performance tests within high-performance computing systems play an important role in evaluating the most efficient processing configuration for correlation of raw VLBI data. We evaluated the scalability of DiFX and verified the user workload on the VSC-3. Furthermore, we applied a parallel scan processing strategy, realized with the SLURM job array. With this, an increased total data throughput up to 36 Gbps can be achieved.

3.3 Post-correlation Processing Toolbox in VieVS

We developed a software package which converts the fringe-fitting output of fourfit and PIMA into the vgosDb format. The software is written mainly in Matlab and can read fourfit Mark4 files (type-1,2,3,4) and also PIMA ASCII fringe-fitting output files. It consists also of a tool to parse station log files to extract cable delay and meteorological data and store them in the vgosDB files. With this, we can directly access and analyze the correlation results with our in-house software VieVS. Besides analyzing group delays, VieVS is also capable of processing single band and multiband delays.

3.4 Digital Baseband Data Simulator

A digital baseband data simulator has been developed in the period of 2017 until 2018. It is a software program to generate synthetic VLBI baseband data. The simulator is implemented in Matlab and contains a telescope model which is based on the parametrization of real antenna key characteristics. Moreover, source characteristics such as the signal structure of satellites and spatial velocities of source and receiver are taken into account in the model creation. Advanced digital signal processing (DSP) algorithms of Matlab are applied to model the antenna system. The software consists also of a VDIF formatter, which makes it possible to pipe the simulated raw VLBI data into common correlation software (e.g., DiFX) and test the simulated observations in the real VLBI process chain.

3.5 Correlation of Other Sessions

Besides official IVS sessions, we are also correlating other sessions with various scientific backgrounds.

One project is dedicated to an ESA project, “Independent Generation of Earth Orientation Parameters”, which uses the Wettzell antennas and the new antenna in Santa Maria. Furthermore, we are correlating short baseline sessions at HartRAO and K-band observations. In the past two years, we also successfully correlated VLBI observations to the APOD satellite.

4 Staff

Three persons are involved in the work at the TU Wien IVS VLBI correlator center. Their names and most important responsibilities are listed here:

- Jakob Gruber (jakob.franz.gruber@tuwien.ac.at):
  - Ph.D. student in the field of VLBI raw data processing
  - maintenance of data transfer
  - correlation, fringe-fitting of AUSTRAL sessions and database submission to IVS
  - development of third party software to support correlation and fringe-fitting and correlation of various other special VLBI sessions
- Johannes Böhm (johannes.boehm@geo.tuwien.ac.at):
  - head of the VLBI group at TU Wien
  - backup for Jakob Gruber for data transfer, correlation, fringe-fitting of AUSTRAL sessions
- Jamie McCallum (jamie.mccallum@utas.edu.au):
  - station array manager of the AuScope VLBI array
  - supporting role for VLBI correlation activities at TU Wien

5 Current Status and Future Plans

As in the past two years, there will be an ongoing correlation of AUSTRAL sessions in 2019. In total there are twelve IVS sessions scheduled for 2019, one per month, with Vienna as the responsible correlator. In parallel with the correlation of IVS sessions, we will keep on correlating various other special VLBI sessions and improve and refine a more automated correlation pipeline. The new supercomputer VSC-4 is currently under development and should be ready to work in 2019. Once the installation is finished, we will move our complete VLBI correlation software repository to the VSC-4, and it will represent our new correlation working environment. We will gain access to 1-PB disk storage and 480 private processing cores on the VSC-4. In view of the increased data volume produced by telescopes in the VGOS era, this will be very useful to take up some of the correlation load. Finally, we are in the process of spreading all the correlation knowledge to more members of the TU Wien VLBI group.

Acknowledgements

The computational results presented have been achieved using the Vienna Scientific Cluster (VSC).

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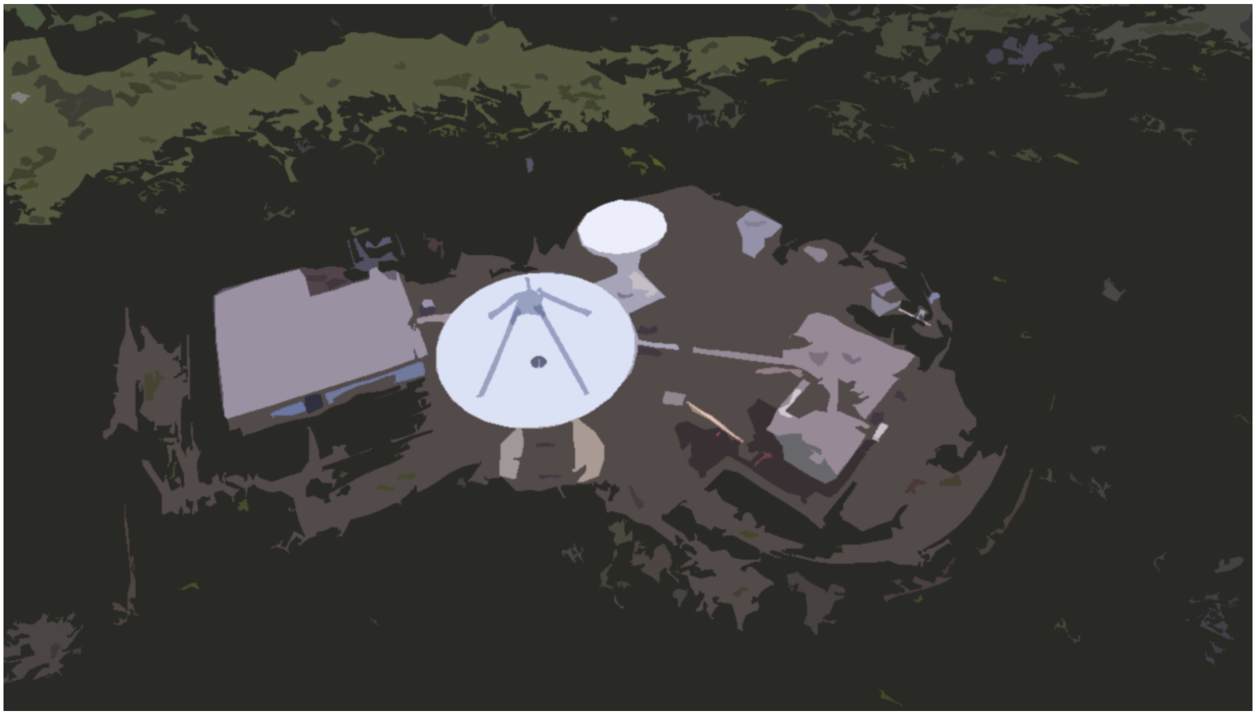
DATA CENTERS



BKG Data Center

Reiner Wojdziak, Volkmar Thorandt

Abstract This report summarizes the activities and background information of the IVS Data Center for 2017 and 2018. Included are information about functions, structure, technical equipment, and staff members of the BKG Data Center.

1 BKG Data Center Functions

The BKG (Federal Agency for Cartography and Geodesy) Data Center is one of the three IVS Primary Data Centers. It archives VLBI-related data of IVS components and provides public access for the community. The BKG Data Center is connected to the OPAR and GSFC CDDIS Data Centers by mirroring the OPAR and the CDDIS file stocks several times per day. The sketch in Figure 1 shows the principle of mirroring.

The IVS community can choose the Data Centers to put their data into the IVS archives by using its incoming area, which each Data Center has at its disposal. The BKG incoming area is protected, and users need to obtain a username and password to get access.

An incoming script monitors the incoming area and checks the syntax of the files sent by the IVS community. If it is okay, the script moves the files into the Data Center directories. Otherwise the files will be sent to a badfile area. Furthermore, the incoming script informs the responsible staff at the Data Center by sending e-mails about its activities. The incoming script is part of the technological unit which is responsible for managing the IVS and the Operational Data Center and for carrying out the first analysis steps in an automatic manner. All activities are monitored to guarantee data consistency and to control all analysis steps from data arrival to delivery of analysis products to IVS.

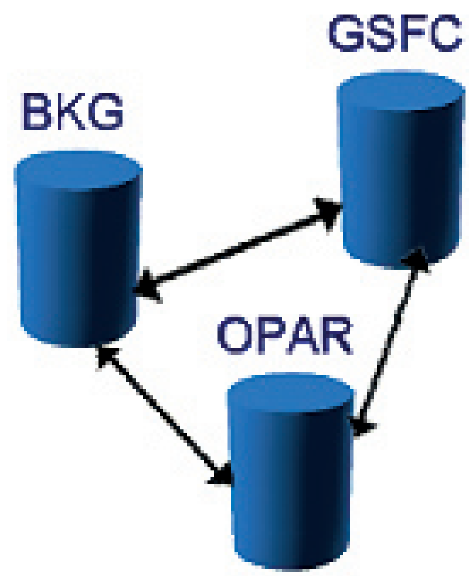


Fig. 1 Principle of mirroring.

Public access to the BKG Data Center is available through FTP and HTTP:

`ftp://ivs.bkg.bund.de/pub/vlbi/`

`http://ivs.bkg.bund.de/vlbi/`

BKG

BKG Data Center

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Structure of BKG IVS Data Center:

```
ivscontrol/     : controlfiles for the data center
ivsdata/        : VLBI observation files
ivsdocuments/   : IVS documents
ivsproducts/    : analysis products
   crf/         : celestial frames
   trf/         : terrestrial frames
   eops/        : earth orientation (24h sessions)
   eopi/        : earth orientation (Intensive sessions)
   daily_sinex/ : daily sinex files (24h sessions)
   int_sinex/   : daily sinex files (Intensive sessions)
   trop/        : troposphere
ITRF2014/       : daily sinex files for IRF2014
RECENT          : mirror IVS incoming
bonnDB_IVS      : mirrored vgos data bases (experimental)
lincDB_IVS      : mirrored vgos data bases (experimental)
usnoDB_IVS      : mirrored vgos data bases (experimental)
vgosDB_IVS      : mirrored vgos data bases (experimental)
wienDB_IVS      : mirrored vgos data bases (experimental)
```

2 Technical Equipment

The BKG IVS Data Center is based on a system of Linux servers with disk space of 1000 GBytes (Raid system), and a backup system operated by an automatic library.

3 Future Plans

It is planned that the IVS Data Center of the BKG will be extended to also process the IVS session data submitted in the vgosDB format.

4 Staff Members

- Reiner Wojdziak (Data Center coordination, Web design, reiner.wojdziak@bkg.bund.de)
- Volkmar Thorandt, until November 30, 2018 (data analysis, Data Center, volkmar.thorandt@bkg.bund.de)
- Gerald Engelhardt (data analysis, Data Center, gerald.engelhardt@ bkg.bund.de)
- Anastasiia Girdiuk, since June 15, 2018 (data analysis, Data Center, anastasiia.girdiuk@bkg.bund.de)
- Dieter Ullrich (data analysis, Data Center, dieter.ullrich@bkg.bund.de)

CDDIS Data Center Summary for the IVS 2017–2018 Biennial Report

Carey Noll, Patrick Michael

Abstract This report summarizes activities during the years 2017 through 2018 and the future plans of the Crustal Dynamics Data Information System (CDDIS) with respect to the International VLBI Service for Geodesy and Astrometry (IVS). Included in this report are background information about the CDDIS, the computer architecture, archive contents, and future plans for the CDDIS within the IVS.

1 General Information

The Crustal Dynamics Data Information System (CDDIS) has supported the archiving and distribution of Very Long Baseline Interferometry (VLBI) data since its inception in 1982. The CDDIS is a central facility that provides users access to data and derived products to facilitate scientific investigations. The full CDDIS archive of GNSS (GPS, GLONASS, Galileo, etc.), laser ranging, VLBI, and DORIS data is available online for remote access. Information about the system is available via the web at the URL https://cddis.nasa.gov. In addition to the IVS, the CDDIS actively supports other IAG services, including the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), and the International DORIS Service (IDS), as well as the International Earth Rotation and Reference Systems Service (IERS) and the IAG's observing system, the Global Geodetic Observing System (GGOS). The current and future plans for the CDDIS support of the IVS are discussed below.

The CDDIS is one of NASA's Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs) (see https://earthdata.nasa.gov); EOSDIS Data Centers serve a diverse user community and are tasked to provide facilities to search and access science data and products. The CDDIS is also a regular member of the International Council for Science (ICSU) World Data System (WDS, https://www.icsu-wds.org) and the Earth Science Information Partners (ESIP, https://www.esipfed.org).

NASA Goddard Space Flight Center

CDDIS Data Center

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2 System Description

The CDDIS archive of VLBI data and products is accessible to the public through anonymous ftp (ftp://cddis.nasa.gov) and https (https://cddis.nasa.gov/archive).

2.1 Computer Architecture

The CDDIS is operational on a dedicated server, cddis.nasa.gov, located at NASA GSFC. The system is accessible to the international user community 24 hours per day, seven days per week. By the end of 2018, over 325 Gbytes of storage was devoted to VLBI-related data, derived products, and information.

The CDDIS computer facility is fully redundant with primary and secondary/failover systems utilizing a virtual machine (VM) based system, configured with

100 Tbytes of unified storage operating within the EOSDIS computer facility and network infrastructure. This system configuration provides a reliable environment (power, HVAC, 24-hour on-site emergency personnel, etc.) and network connectivity; a disaster recovery system is installed in a different location on the GSFC campus for rapid failover if required. Multiple, redundant network switches are available to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming files along with dedicated network connections between its primary operations and its backup operations. The use of the virtual machine technology provides multiple instance services for a load balancing configuration and allows for VM instances to be increased or decreased due to demand. Furthermore, the VM technology allows for system maintenance (patching, upgrades, etc.) to proceed without any downtime or interruption to user access. The large, unified storage system will easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites. The entire archive is also mirrored to traditional storage arrays for additional complete copies of the archive. This system architecture has allowed the CDDIS to achieve an uptime figure of over 99.9% in recent years; a few brief interruptions occurred in 2018 which were outside CDDIS control, due to issues with EOSDIS and NASA infrastructure.

As shown in Figure 1, the providers of files for the CDDIS archive push their files (data, derived products, etc.) to the CDDIS ingest server, utilizing the Earthdata Login system for validating access. Incoming files are then handled by the processing system which performs file/content validation, quality control, and metrics extraction. Metadata and metrics (ingest/archive and distribution) information is pushed to the EOSDIS Common Metadata Repository (CMR) system. Content metadata, describing collections and granules, are available for access by a broad user community through the CMR. Valid files are then moved to the CDDIS archive for public access through the CDDIS ftp and web servers.

2.2 File Submissions

The CDDIS utilizes an https-based protocol method for delivery of files from suppliers of data and products. The validation is performed through the EOSDIS Earthdata Login system, the same system used for access to the CDDIS real-time caster. The file uploads can be performed through a webpage interface or a command line application that can perform an http “post” operation, which is more commonly used for scripting. This process allows data suppliers to authenticate through the Earthdata Login system and provide their files through https to CDDIS for ingest into the archive. More information on the CDDIS file upload system, including an FAQ, is available at URL: https://cddis.nasa.gov/About/CDDIS_File_Upload_Documentation.html

2.3 File Ingest Processing

New file ingest processing software was implemented at CDDIS in 2016 for incoming GNSS files; over the next year, the software was updated to process incoming SLR and DORIS files. This new software suite incorporated numerous disparate programs developed over the years into a single, easily maintained software base which incorporates all the CDDIS requirements for data ingest while also allowing additional flexibility in meeting future metadata requirements. This file ingest processing system allows staff to check for errors in a more consistent fashion, regardless of data type or file provider; the automated system allows the staff to identify several error types, such as problems with file naming, compression, and content. The software then moves validated incoming files to the appropriate directory based on the filename.

Starting in 2018, the CDDIS has worked with the GSFC VLBI staff to transition code for processing incoming VLBI-related files into this new, common file ingest software. This effort was more complicated because the process for archiving VLBI files had always been unique and actually developed by the GSFC VLBI staff. The transition to the common ingest processing is not yet complete, but work continues.

3 Archive Contents

The CDDIS has supported GSFC VLBI and IVS archiving requirements since 1979 and 1999, respectively.

The IVS Data Center content and structure is shown in Table 1 (a figure illustrating the flow of information, data, and products between the various IVS components was presented in the CDDIS submission to the IVS 2000 Annual Report). As described above, the CDDIS has established a file upload system for providing IVS data, product, and information files to the archive. Using specified filenames, Operation and Analysis Centers upload files to this system. Automated archiving routines peruse the directories and move any new data to the appropriate public disk area. These routines migrate the data based on the filename to the appropriate directory as described in Table 1. "Mirroring" software on the CDDIS host computer, as well as all other IVS Data Centers, facilitates equalization of data and product holdings among these Data Centers. At this time, mirroring is performed between the IVS Data Centers located at the CDDIS, the Bundesamt für Kartographie und Geodäsie in Leipzig, and the Observatoire de Paris.

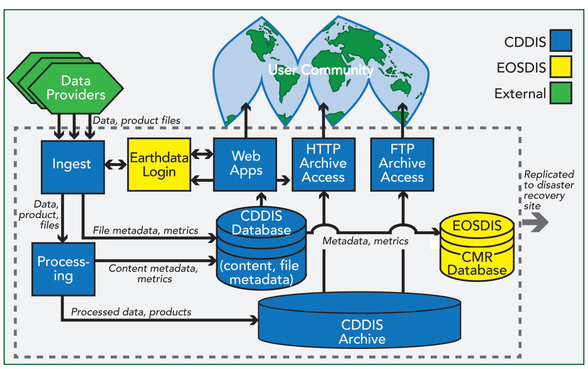

Fig. 1 System architecture overview diagram for the CDDIS facility installation within the EOSDIS infrastructure.

4 Accessing the CDDIS Archive

The CDDIS has a large international user community; over 243K unique hosts accessed the system in 2018. Today, users access the CDDIS archive through anonymous ftp and https. The ftp protocol allows users to easily automate file downloads but has problems from a system/security standpoint. As per U.S. Government and NASA directives, the CDDIS has begun to move users away from reliance on anonymous ftp. Despite this requirement, the CDDIS staff is committed to ensuring continued, easy, and open access to its archive.

The CDDIS has configured servers to utilize protocols that allow two new methods for system access: https (browser and command line) and ftp-ssl (command line). The https protocol is as efficient as ftp transfer without ftp firewall/router issues. The access to the CDDIS archive through both methods continues to present the same structure as that provided through anonymous ftp. For the near-term, access to data in the CDDIS archive will continue through ftp, but users are strongly encouraged to explore the https and ftp-ssl (address: gdc.cddis.eosdis.nasa.gov) capabilities as soon as possible. The major reasons for changing the archive access methods at CDDIS are system security and data integrity.

Archive access through the https protocol utilizes the same NASA single sign-on system, the EOSDIS Earthdata Login utility, as is used for the file upload and real-time caster user authentication. Before using the https protocol to access the CDDIS archive, new users must initially access the webpage, https://cddis.nasa.gov/archive, to establish an account and authorize access; this page will then redirect the user to the Earthdata Login page. Earthdata Login allows users to easily search and access the full breadth of all twelve EOSDIS DAAC archives. Earthdata Login also allows CDDIS staff to know our users better, which will then allow us to improve CDDIS capabilities. Once an account is established, the user has all permissions required to access the CDDIS archive using the https protocol, via a web browser or via a command line interface (e.g., through cURL or Wget) to script and automate file retrieval.

In addition, ftp-ssl access, an extension of ftp using TLS (transport layer security), can be used for scripting downloads from the CDDIS archive. The ftp-ssl is the option most similar to standard anonymous ftp. As with https, ftp-ssl will satisfy U.S. Government/NASA requirements for encryption.

Examples on using these protocols, including help with the cURL and Wget commands, are available on the CDDIS website; users are encour-

Table 1 IVS data and product directory structure.

Directory	Description
Data Directories	
vlbi/ivsdata/db/yyyy	VLBI database files for year yyyy
vlbi/ivsdata/ngs/yyyy	VLBI data files in NGS card image format for year yyyy
vlbi/ivsdata/vgosdb/yyyy	VLBI data files in vgosDB format for year yyyy
vlbi/ivsdata/aux/yyyy/ssssss	Auxiliary files for year yyyy and session ssssss
	these files include: log files, wx files, cable files, schedule files, correlator notes
Product Directories	
vlbi/ivsproducts/crf	CRF solutions
vlbi/ivsproducts/eopi	EOP-I solutions
vlbi/ivsproducts/eops	EOP-S solutions
vlbi/ivsproducts/daily sinex	Daily SINEX solutions
vlbi/ivsproducts/int sinex	Intensive SINEX solutions
vlbi/ivsproducts/trf	TRF solutions
vlbi/ivsproducts/trop	Troposphere solutions
Project Directories	
vlbi/ITRF2013	IVS contributions to the ITRF 2013 efforts
vlbi/ITRF2014	IVS contributions to the ITRF 2014 solution
vlbi/ivs-pilotbl	IVS Analysis Center pilot project (baseline)
Other Directories	
vlbi/ivscontrol	IVS control files (Master Schedule, etc.)
vlbi/ivsdocuments	IVS document files (solution descriptions, etc.)
vlbi/raw	Raw VLBI data
vlbi/dserver	dserver software and incoming files

aged to consult the available documentation at: https://cddis.nasa.gov/About/CDDIS_File_Download_Documentation.html as well as various presentations on these updates to the CDDIS archive access (see Section 5 below and https://cddis.nasa.gov/Publications/Presentations.html).

5 System Usage

During the 2017-2018 time period, nearly 2,500 distinct hosts accessed the CDDIS to retrieve VLBI related files. These users, which include other IVS Data Centers, downloaded over 1.8 Tbytes (13.6 M files) of VLBI related files from the CDDIS in this two year period.

Future Plans

The CDDIS staff will continue to work closely with the IVS Coordinating Center staff to ensure that our system is an active and successful participant in the IVS archiving effort. A major area of focus will be the completion of the modifications to the CDDIS ingest processing software to accommodate all incoming VLBI-related files.

As discussed above, in the near future, the CDDIS will no longer support non-encrypted anonymous ftp access to its archive; access to the archive through https and ftp-ssl have already been implemented. The staff is also testing providing a WebDAV (Web Distributed Authoring and Versioning) interface to provide another method for accessing CDDIS archive. If feasible for CDDIS, this interface method would allow users to securely connect to the CDDIS archive as if it were a local drive on their computer.

The CDDIS has established Digital Object Identifiers (DOIs) for several of its collections of GNSS, SLR, and DORIS data and products; website landing pages were established, linking to these published DOIs. DOIs for additional items, including VLBI data and products, are under development and review prior to registering and implementation.

The CDDIS has received funding to procure a refresh of its system servers, storage, and network hardware. Staff members have begun the engineering design for this next system; plans are to have the upgraded system installed by the end of 2019. The server and network hardware will remain within the same physical infrastructure as today's system, thus providing a reliable hosting environment with fully redundant networking paths and backup sites.

Italy INAF Data Center Report

Monia Negusini

Abstract This report summarizes the activities of the Italian INAF VLBI Data Center. Our Data Center is located in Bologna, Italy and belongs to the Institute of Radioastronomy, which is part of the National Institute of Astrophysics.

1 Introduction

The main analysis activity and storage is concentrated in Bologna, where we store and analyze single databases, using CALC/SOLVE and the newer νSolve software.

The IRA started to store geodetic VLBI databases in 1989; at the very beginning the databases archived in Bologna mostly contained data including European antennas from 1987 onward. In particular most of the databases available here had VLBI data with at least three European stations. Additionally we stored all the databases with the Ny-Ålesund antenna observations. In 2002 we decided to store the complete set of databases available on the IVS Data Centers, although we limited the time span to the observations performed from 1999 onwards. All the databases were processed and saved with the best selection of parameters for the final arc solutions. In order to perform global solutions, we have computed and stored the superfiles for all the databases. In some cases we have introduced GPS-derived wet delays into the European databases (1998 and 1999 EUROPE experiments, for the time being), as if they were produced by a WVR. These databases are available and stored with a different code from the original databases. In order to produce these databases, we have modified DBCAL, and this new version is available to external users.

Moreover, a few Italian VLBI (VITA) experiments were performed in the last years, and the relevant databases are available.

Istituto di Radioastronomia INAF, Bologna

INAF Data Center

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2 Computer Availability and Routing Access

To date, we have two Linux workstations where all VLBI data was migrated. One computer, on which the latest release of the Mark 5 Calc/Solve is installed, has the internet address geovlbi.ira.inaf.it. The νSolve software is installed on a more recent Linux workstation, and its internet address is antartide.ira.inaf.it. Since 2016, a new server with a storage capacity of 11 TB has been available, and, therefore, all experiments performed in the previous years were downloaded and archived, thus completing the catalog. The older experiments will be analyzed in order to perform global long term analysis. At present, the databases are stored in the following directories:

1 = /iranet/geo/dbase1
2 = /iranet/geo/dbase2
3 = /iranet/geo/dbase
4 = /iranet/geo/dbase3
5 = /iranet/geo/dbase4

The superfiles are stored in: /iranet/geo/super_c11.
The list of superfiles is stored in the file /iranet/geo/solve/mk5/save_files/SUPCAT.

The username for accessing the databases is geo. The password may be requested by sending an e-mail to negusini@ira.inaf.it.

NICT Data Center Biennial Report for 2017–2018

Mamoru Sekido

Abstract The Data Center at the National Institute of Information and Communications Technology (NICT) archives and releases the databases and analysis results processed at NICT. Regular VLBI sessions of the Key Stone Project VLBI Network were the primary objective of the Data Center. These regular sessions continued until the end of November 2001. In addition to the Key Stone Project VLBI sessions, NICT has been conducting geodetic VLBI sessions for various purposes, and these data are also archived by the Data Center.

1 General Information

The IVS Data Center at National Institute of Information and Communications Technology (NICT) archives and releases the databases and analysis results processed at NICT. Major parts of the data are from the Key Stone Project (KSP) VLBI sessions [1], but other regional and international VLBI sessions conducted by NICT are also archived. Since routine observations of the KSP network terminated at the end of November 2001, there have been no additional data from the KSP regular sessions since 2002. Table 1 lists the Web server locations maintained by the NICT Data Center.

National Institute of Information and Communications Technology (NICT)

NICT Data Center

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2 Activities during the Past Years

2.1 KSP VLBI Sessions

The KSP sessions had been performed with four VLBI Stations at Kashima, Koganei, Miura, and Tateyama. After regular tape-based routine observing since 1995, 24-hour real-time VLBI using a high-speed ATM (Asynchronous Transfer Mode) network became the standard operation mode of the KSP project [2, 3]. After May 1999, the ATM network line to the Miura station became unavailable. Thereafter, the daily real-time VLBI sessions were performed with the three other stations. Once every six days (every third session), the observed data were recorded with the K4 data recorders at three stations, and the Miura station participated in the sessions with the tape-based VLBI technique. In this case, the observed data at the three stations other than the Miura station were processed in real-time, and the analysis results were released promptly after the observations. A day later, the observed tapes were transported from the Kashima, Miura, and Tateyama stations to the correlation center at Koganei for tape-based correlation processing with all six baselines. Once the tape-based correlation processing was completed, the data set produced with the real-time VLBI data processing was replaced by the new data set.

In July 2000, an unusual site motion of the Tateyama station was detected from the KSP VLBI data series, and the frequency of the sessions was increased from every other day to daily on July 22. The daily sessions were continued until November 11, 2000, and the site motions of the Tateyama and Miura stations were monitored in detail. During the period,

Table 1 URLs of the Web server systems. Note that there have been minor changes to the URLs.

Service	URL
KSP Web pages	`http://ksp.nict.go.jp/`
Database files	`http://www2.nict.go.jp/sts/stmg/www3/database/`
e-VLBI UT1 Exp.	`http://www2.nict.go.jp/sts/stmg/research/e-VLBI/UT1/`

it was found that the Tateyama station moved about 5 cm in the northeast direction. The Miura station also moved about 3 cm to the north. The unusual site motions of these two stations gradually settled, and the current site velocities seem to be almost the same as those before June 2000. By investigating the time series of the site positions, the unusual site motion started sometime between the end of June 2000 and the beginning of July 2000. At the same time, volcanic and seismic activities near the Miyakejima and Kozushima Islands began. These activities were finally found to be the cause of the regional crustal deformation in the area.

2.2 UT1 e-VLBI Sessions

In the period from 2007 to 2008, experimental e-VLBI sessions for rapid UT1 determination were conducted in collaboration with the VLBI stations at NICT, GSI, Onsala Space Observatory, and Metsähovi. The observed VLBI data were transferred to Kashima (NICT) or Tsukuba (GSI) via a high-speed Internet network. Then correlation and bandwidth synthesis were performed successively to obtain quick estimates of UT1–UTC. The data of these experiments were saved in Mk3 database format and are available from the NICT data center.

3 Current Status

The VLBI project mission of our group is the development of a broadband system and its application to frequency transfer. Two sets of small-diameter VLBI stations are placed at NICT Headquarters in Tokyo and the National Metrology Institute of Japan (NMIJ) in Tsukuba, respectively. The receiver system of the Kashima 34-m VLBI station was upgraded to enable broadband observations. We conducted domestic broadband VLBI experiments [4] for the evaluation of the system until March 2018. The broadband VLBI data were stored in MK3 database format and analyzed by Calc/Solve developed by NASA/GSFC. The small VLBI station at NMIJ was moved to Italy in 2018 for an intercontinental atomic clock comparison using broadband VLBI. These experiments will be continued until the transportable VLBI station will be returned to Japan in 2020.

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4. Mamoru Sekido, "NICT VLBI Analysis Center Report for 2017–2018", International VLBI Service for Geodesy and Astrometry 2017+2018 Biennial Report, edited by K. L. Armstrong, D. Behrend, and K. D. Baver, this volume.

Paris Observatory (OPAR) Data Center

Christophe Barache [1], Teddy Carlucci [1], Sebastien Lambert [1]

Abstract This report summarizes the OPAR Data Center activities in 2017–2018. Included is information about functions, architecture, status, future plans, and staff members of OPAR Data Center.

1 General Information

The Paris Observatory (OPAR) has provided a Data Center for the International VLBI Service for Geodesy and Astrometry (IVS) since 1999. The OPAR, together with CDDIS and BKG, is one of the three IVS Primary Data Centers. Their activities are done in close collaboration for collecting files (data and analysis files) and making them available to the community as soon as they are submitted. The three Data Centers (see Figure 1) have a common protocol and each of them:

- has the same directory structure (with the same control file),
- has the same script,
- is able to receive all IVS files (auxilliary, database, products, and documents),
- mirrors the other ones every three hours,
- gives free FTP access to the files.

This protocol gives the IVS community a transparent access to a Data Center through the same directory and continued access to files in case of a Data Center breakdown.

SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 av de l'Observatoire, 75014 Paris, France

Paris Observatory (OPAR) Data Center

IVS 2017+2018 Biennial Report

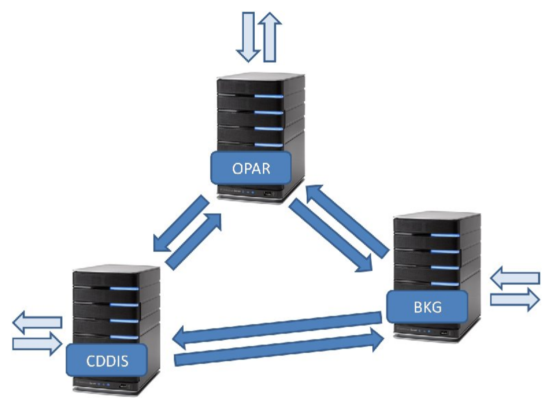


Fig. 1 The three IVS Data Centers.

2 Architecture

To be able to put a file in a Data Center, operational and Analysis Centers have to be registered by the IVS Coordinating Center. The file names have to conform to the name conventions. A script checks the file and puts it in the right directory. The script undergoes permanent improvement and takes into account the IVS components' requests. The structure of the IVS Data Centers is:
RECENT\
used for the new mirror method
ivscontrol\
provides the control files needed by the Data Center (session code, station code, solution code...)

ivsdocuments\
provides documents about IVS products
ivsdata\
provides files related to the observations
ivsdata\aux\
auxilliary files (schedule, log...)
ivsdata\db\
observation files in MkIII database CALC format
ivsdata\ngs\
observation files in NGS format
ivsdata\sinex\
observation files in SINEX format
ivsproducts\
provides results from Analysis Centers
ivsproducts\eopi\
Earth Orientation Parameters, Intensive sessions
ivsproducts\eops\
Earth Orientation Parameters, 24-hour sessions
ivsproducts\crf\
Celestial Reference Frame
ivsproducts\trf\
Terrestrial Reference Frame
ivsproducts\daily_sinex\
Time series solutions in SINEX format of Earth orientation and site positions
ivsproducts\int_sinex\
Daily Intensive solution in SINEX format, mainly designed for combination
ivsproducts\trop\
Tropospheric time series (starting July 2003)

3 Current Status

The OPAR Data Center is operated on a PC Server (PowerEdge 2800 - Xeron 3.0 GHz) located at Paris Observatory, running the Fedora Linux operating system.

To make all IVS products available online, the disk storage capacity was significantly increased and the server is equipped now with RAID 3-TB disk extensible up to 4.7 TB.

The OPAR server is accessible 24 hours per day, seven days per week through Internet connection with 2 Mbit/s rate. Users can get the IVS products by using the FTP protocol. Access to this server is free for users.

FTP access:
ivsopar.obspm.fr
username : anonymous
password : your e-mail
cd vlbi (IVS directory)

4 Activities during the Past Year

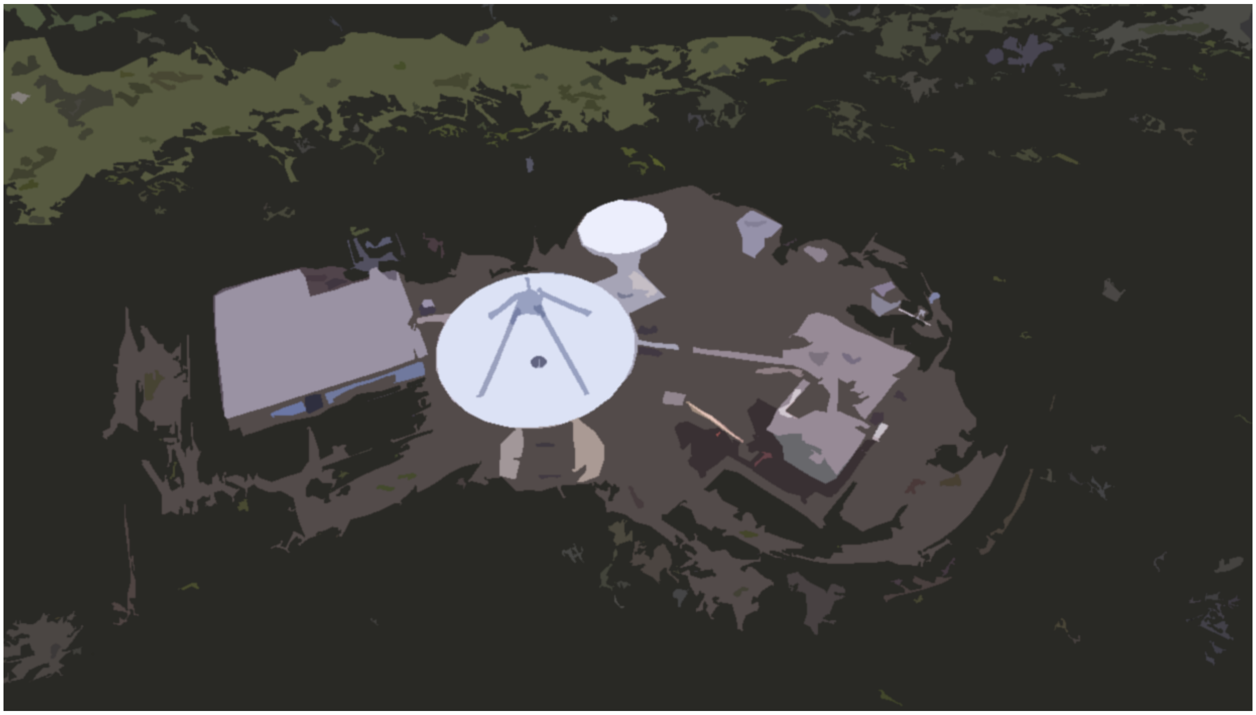
During 2017–2018, there were 2,411 unique visitors. The bandwidth was 4.2 Go.

5 Future Plans

The OPAR Data Center was moved to a new server in March 2017 with Linux Debian 8.6.

To obtain information about the OPAR Data Center please contact: ivs.opa@obspm.fr.

ANALYSIS CENTERS



Analysis Center of Saint Petersburg University

Dmitriy Trofimov, Sergey Petrov

Abstract This report briefly summarizes the activities of the Analysis Center of Saint Petersburg University during 2017 and 2018. The current status, as well as our future plans, are described.

1 General Information

The Analysis Center of Saint Petersburg University (SPU AC) was established at the Sobolev Astronomical Institute of the SPb University in 1998. The main activity of the SPU AC for the International VLBI Service before 2007 consisted of routine processing of 24-hour and one-hour observational sessions for obtaining Earth Orientation Parameters (EOP) and rapid UT1-UTC values, respectively. In 2008 we began submitting the results of 24-hour session processing.

2 Component Description

Currently we support two series of the Earth Orientation Parameters, spu00004.eops and spu2015a.eops.

- All parameters were adjusted using the Kalman filter technique. For all stations (except the reference station), the wet delay, clock offsets, clock rates, and troposphere gradients were estimated. Troposphere wet delay and clock offsets were modeled as a stochastic process such as a random walk. The clock rates and the troposphere gradients were considered to be the constant parameters.
- The main details of the preparation of the EOP time series spu00004.eops and spu2015a.eops are summarized below:
  - Data span: 1989.01–2018.08
  - CRF: fixed to ICRF-Ext.2
  - TRF: VTRF2005 was used as an a priori TRF
  - Estimated parameters:
    1. EOP: x, y, UT1–UTC, $d\psi$, $d\varepsilon$;
    2. Troposphere: troposphere gradients were estimated as constant parameters, and wet troposphere delays were modeled as a random walk process;
    3. Station clocks were treated as follows: offset as a random walk process, rate as a constant.
  - nutation model: IAU 1980 (spu00004.eops), IAU 2000 (spu2015a.eops)
  - mapping function: VMF1
  - technique: Kalman filter
  - software: OCCAM v.6_2

Sobolev Astronomical Institute of Saint Petersburg University

AI SPbU Analysis Center

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3 Staff

The assistant professor of Saint Petersburg University, Dmitriy Trofimov, was in charge of the routine processing of the VLBI observations. General coordination and support for the activities of the SPU AC at the Astronomical Institute were performed by Professor Veniamin Vityazev. After his death in the summer of 2018, the general management and support is performed by the head of the chair of astronomy Sergey Petrov.

4 Current Status and Activities

- In 2017, the routine estimation of the five Earth Orientation Parameters was performed. The OCCAM software package (version 6_2) was used for current processing of VLBI data [1]. The time series is named spu00004.eops. It includes data obtained by the IRIS-A, NEOS-A, R1, R4, RDV, and R&D observing programs, and it covers 28 years of observations (from January 2, 1989 until August 2018). The total number of experiments processed at the SPU AC is about 2,350, of which about 120 VLBI sessions were processed in 2017–2018.
- The new series of the Earth Orientation Parameters launched in 2015 was also continued. The total number of points in spu2015a.eops is about 2,350, of which about 120 VLBI sessions were processed in 2017–2018.
- Our experience and the equipment of the Analysis Center was used for giving lectures and practical work on the basics of radio interferometry to university students. We use our original manual on the training in modern astrometry and in particular VLBI [2]. In 2018 a student term paper has been performed on the center equipment. During the period 2017–2018, we processed only observations in NGS format.

5 Future Plans

In 2019, we plan to begin processing data in vgosDB format. Also we are planning to start processing a series based on new reference catalogs of antenna positions and radio sources. Lectures and practical exercises for students in a special course on radio astrometry will continue. This course is part of the curriculum of astronomical education at St. Petersburg State University.

6 Acknowledgements

In 2017 the work of the SPU AC was performed within the project “Determination of the Earth Orientation Parameters required for launching missiles to asteroids” (SPU grant 6.37.343.2015).

References

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Geoscience Australia Analysis Center 2017–2018 Annual Report

Oleg Titov

Abstract This report gives an overview of the activities of the Geoscience Australia IVS Analysis Center during 2017–2018.

1 General Information

The Geoscience Australia (GA) IVS Analysis Center is located in Canberra within the National Geodesy Section, National Positioning Infrastructure Branch, Positioning and Community Safety Division (PCSD).

2 Activities during the Years 2017–2018

Several celestial reference frame (CRF) solutions have been prepared using the OCCAM 6.3 software. The latest solution (aus2018a.crf) was released in October 2018. VLBI data comprising more than 5,000 daily sessions from January 1980 to August 2018 have been used to compute this solution. This includes 9,433,411 observational delays from 4,267 radio sources having three or more observations.

Station coordinates were also estimated using No-Net-Rotation (NNR) and No-Net-Translation (NNT) constraints. The long-term time series of the station coordinates has been used to estimate the corresponding velocities for each station. The tectonic motion for the Gilcreek VLBI site after the Denali earthquake was modeled using an exponential function typical of post-seismic deformation.

The adjustment was made by least-squares collocation, which considers the clock offsets, wet troposphere delays, and tropospheric gradients as stochastic parameters with a priori covariance functions. The gradient covariance functions were estimated from GPS hourly values.

A dedicated VLBI experiment was organized in collaboration with many institutes to estimate the post-Newtonial relativistic parameter γ from a single 24-hour geodetic VLBI session. Seven radio telescopes participated in this experiment (AUA020) on 1 May 2017 (Hobart26, Svetloe, Zelenchukskaya, Badary, HartRAO, Seshan25, and Sejong). The parameter γ was estimated with an accuracy of 9×10^{-5} that is known to be the best accuracy achieved with the geodetic VLBI technique [1].

Geoscience Australia

GA Analysis Center

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Acknowledgements

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Report for 2017–2018 from the Bordeaux IVS Analysis Center

Patrick Charlot, Antoine Bellanger, Géraldine Bourda, Arnaud Collioud, César Gattano

Abstract This report summarizes the activities of the Bordeaux IVS Analysis Center during 2017 and 2018. In this period, analysis activities using the GINS software package were pursued further, together with the systematic VLBI imaging of the RDV sessions. A major achievement was the implementation of a modernized version of the Bordeaux VLBI Image Database, where RDV images and related information (e.g., structure indices, compactness values) are stored. Another highlight was the involvement in the IAU Working Group on the next ICRF (International Celestial Reference Frame) realization, chaired by one member of the Bordeaux group, which culminated with the realization of the ICRF3 and its adoption by the IAU in August 2018. Analysis of the time series of source positions, which revealed that astrometric instabilities often occur along one or two preferred directions on the sky, is another significant accomplishment during this period.

1 General Information

The *Laboratoire d'Astrophysique de Bordeaux (LAB)* is a research center funded by the University of Bordeaux and the *Centre National de la Recherche Scientifique (CNRS)*. It is part of a bigger organization, the *Observatoire Aquitain des Sciences de l'Univers (OASU)*, formerly Bordeaux Observatory. The OASU has a wider scope, covering environmental sciences besides historic activities in astronomy and astrophysics. A specific role of the observatory is to provide support for acquiring, analyzing, and archiving observations of various types in these fields, including the participation in national and international services, such as the IVS.

VLBI activities at the LAB are carried out within the M2A (*Métrologie de l'espace, Astrodynamique, Astrophysique*) team. Contribution to IVS has been mostly concerned with the maintenance, extension, and improvement of the International Celestial Reference Frame (ICRF). This includes regular imaging of the ICRF sources and evaluation of their astrometric suitability, as well as developing specific VLBI observing programs for enhancing the celestial frame. In addition, the group conducts VLBI analyses with the GINS software package, a multi-technique software developed by the CNES (*Centre National d'Etudes Spatiales*) which has the ability to process data from most space geodetic techniques, including GNSS, VLBI, DORIS, SLR, LLR, satellite altimetry, and other space missions [1]. Those analyses are primarily targeted to estimating Earth Orientation Parameters (EOP).

2 Description of Analysis Center

The Bordeaux IVS group is engaged in analyzing the IVS-R1 and IVS-R4 sessions with the GINS software package. From these sessions, EOP estimates with six-hour resolution were produced. The focus of such work is placed upon developing a state-of-the-art operational VLBI solution with the goal of contributing to the IVS primary EOP combination in the future.

The group is also engaged in imaging ICRF sources on a regular basis. This is achieved by systematic anal-

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ysis of the data from the RDV sessions (conducted six times a year). This analysis is carried out with the AIPS and DIFMAP software packages. The aim of such regular imaging is to assess the astrometric suitability of the sources based on the so-called "structure index". Characterization of the source positional instabilities and comparison of those instabilities with their structural evolution is an additional direction of work. Such studies are essential for identifying sources of high astrometric quality, which is required to optimally define the celestial frame.

3 Scientific Staff

During 2017 and 2018, five individuals contributed to one or more of our IVS analysis and research activities. A description of what each person worked on, along with an estimate of the time spent on it, is given below. In the fall of 2017, the group was joined by César Gattano, a post-doc who got his PhD from Paris Observatory a year earlier. Apart from this arrival, there were no other changes in the IVS staff over the period.

- Patrick Charlot (50%): researcher with overall responsibility for Analysis Center work. His interests include the ICRF densification, extension, and link to the Gaia frame, studies of radio source structure and its impact on astrometric VLBI, and astrophysical interpretation. He was also chair of the ICRF3 Working Group in the period 2015–2018.
- Antoine Bellanger (100%): engineer with a background in statistics and computer science. He is tasked to process VLBI data with GINS and to develop procedures and analysis tools to automate such processing with prospects of implementing an operational VLBI analysis in the future.
- Géraldine Bourda (30%): astronomer in charge of developing the VLBI part of GINS and overseeing the analysis results derived from GINS. She also developed a VLBI observational program for linking the ICRF and the Gaia optical frame and was a member of the ICRF3 Working Group.
- Arnaud Collioud (70%): engineer with a background in astronomy and interferometry. His tasks are to image the sources in the RDV sessions using AIPS and DIFMAP, to develop the Bordeaux VLBI Image Database and *IVS Live* tools, and to conduct simulations for the next-generation VLBI system.
- César Gattano (50%): post-doctoral fellow funded by the CNES. His interest is in the celestial frame, in particular in the characterization of the time series of source positions and the connection of the observed instabilities with the source astrophysics.

4 Current Status

As noted above, one of our goals for the future is to implement an operational analysis of the IVS-R1 and IVS-R4 sessions for the EOP determination using the GINS software package. To reach this goal, a prerequisite is to assess the quality of the results derived with GINS and to validate these against similar determinations obtained with other VLBI software packages, since the VLBI capability of GINS is not widely used. In particular, we wish to compare the individual components of the VLBI delay model in GINS with the same components as derived from other software packages. For various reasons, progress towards this goal has been slow and such comparisons, along with the relevant assessment, still remain to be done.

Another major part of our activity consists in systematic imaging of the sources observed during the RDV sessions. During 2017 and 2018, seven such sessions were processed (from RDV112 to RDV124), resulting in 1,088 VLBI images at either X- or S-band for 386 different sources. The imaging work load has been shared with USNO since 2007 (starting with RDV61); the USNO group processes the odd-numbered RDV sessions while the Bordeaux group processes the even-numbered ones. The VLBI images are used in a second stage to derive structure correction maps and visibility maps along with values for structure indices and source compactness (see [2, 3] for a definition of these quantities) in order to assess astrometric source quality. All such information is made available through the Bordeaux VLBI Image Database (BVID)[1]. At present, the BVID comprises a total of 6,117 VLBI images for 1344 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO) along with 12,892 structure

[1] The Bordeaux VLBI Image Database can be accessed at http://bvid.astrophy.u-bordeaux.fr.

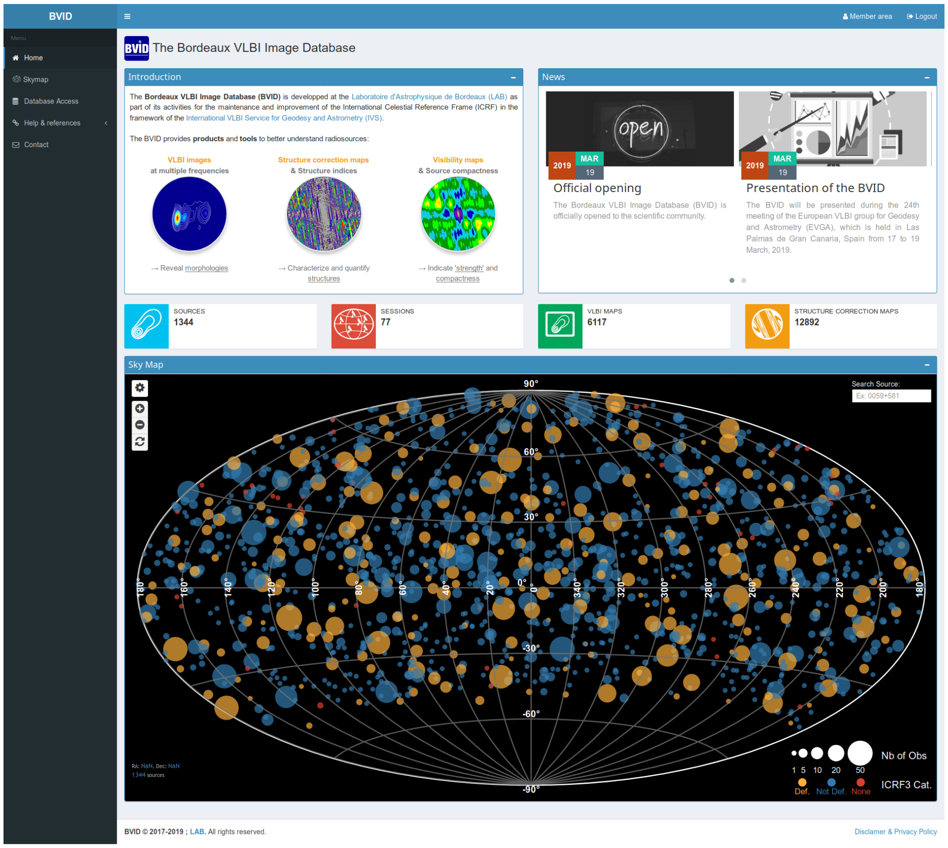

Fig. 1 View of the home page of the second version of the BVID. The interface presents the latest news, some statistics related to the BVID content, and the sky distribution of all the sources included in the BVID, color-coded according to their ICRF3 category.

correction maps and as many visibility maps. These originate from 77 sessions spanning a total of 22 years.

5 Achievements

A major achievement during the period 2017–2018 was the design and implementation of a new, modernized version of the BVID, in replacement of the initial version, built in 2008. This second version has a clean and modern user interface (Figure 1), offers additional tools, and delivers new data and information. Sky maps, interactive charts, and tables permit to navigate easily through the BVID data. Additionally, a multi-criteria form that allows users to refine queries (e.g., based on flux density, structure index) was implemented to supplement already-existing queries from source name, sky coordinates, session name, and date. The new data incorporated into BVID comprise FITS images, source models (CLEAN components), and some associated plots. Furthermore, the second version of BVID is flexible enough to host VLBI images from the community (with full credit to the authors) in addition to those produced in Bordeaux.

Another highlight of the past two years was the realization of ICRF3, which culminated with its adoption by the IAU on 30 August 2018, during the XXXth IAU General Assembly in Vienna. Two members of the group (Géraldine Bourda and Patrick Charlot) were members of the IAU Working Group on the next ICRF realization and as such contributed to the effort towards ICRF3. Their contribution had to do with (i) the assessment of astrometric source quality, a primary criterion to select defining sources, (ii) the actual selection of ICRF3 defining sources, and (iii) the identification of common sources between the ICRF3 three-frequency (S/X, K, and X/Ka bands) frame and the Gaia CRF2

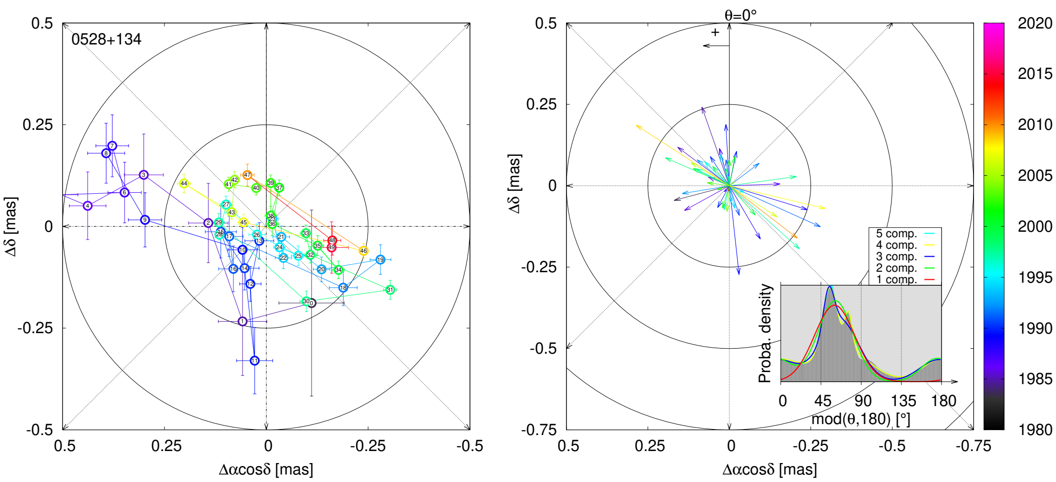

Fig. 2 *Left:* Sky trajectory drawn from the averaged VLBI positions measured over the period 1980–2018 for the source 0528+134. *Right:* Equivalent set of vectors connecting each pair of successive positions. The PDF built from these set of vectors is given as the upper edge of the shaded area in the inset box. Colored lines show fits to the PDF when 1–5 components (directions) are extracted.

optical frame [4]. Patrick Charlot, Chair of the Working Group, also led the overall work. In all, two face-to-face meetings of the Working Group were organized in the period (Bologna, Italy, 13–14 October 2017; Bordeaux, France, 22–23 February 2018) along with fourteen teleconferences, all of which were attended by at least one member from Bordeaux. An open meeting of the ICRF3 Working Group was further held during the IAU General Assembly on 29 August 2018. On the way to ICRF3, an essential element was the preparation of the IAU resolution on ICRF3 and the interaction with the IAU resolution committee on that matter. As Chair of the Working Group, Patrick Charlot also gave presentations on (progress towards) ICRF3 (either invited or contributed) at a number of international conferences to advertise about ICRF3. These include the 23rd EVGA Working Meeting (Gothenburg, Sweden, 15–17 May 2017), EWASS 2017 (Prague, Czech Republic, 26–30 June 2017), IAG–IASPEI Joint Scientific Assembly (Kobe, Japan, 30 July–4 August 2017), Journées des Systèmes de Référence et de la Rotation Terrestre 2017 (Alicante, Spain, 25–27 September 2017), 10th IVS General Meeting (Longyearbyen, Svalbard, 3–9 June 2018), and 14th EVN Symposium (Granada, Spain, 8–11 October 2018). ICRF3 was also presented at two national conferences that took place in Paris (4–7 July 2017) and Besançon (14–15 June 2018). Of course, the most important presentation was that at the IAU General Assembly on 27 August 2018, prior to the voting by the IAU members and the adoption of ICRF3 by the astronomical community.

On the research side, a specific effort was dedicated to the analysis of source coordinate time series in order to characterize astrometric instabilities. Using the Allan standard deviation for such characterization, it was found that the majority of the most observed sources in the geodetic and astrometric VLBI pool since 1979 are unstable [5]. An additional step was taken to determine whether those instabilities occur randomly or along preferred directions on the sky. The method devised to this end is based on the calculation of source trajectory (from averaged sky positions, see left panel in Figure 2) and the identification of any systematic pattern in this trajectory. In practice, each pair of successive positions is transformed into a vector which defines a direction of variation (Figure 2, right panel). A probability density function (PDF) is then built from the distribution of those directions, from which one or several preferred directions are extracted. Applying this scheme to the 215 sources observed more than 200 times at the time of the study, we found that 60% of the sources in this sample show one preferred direction while another 30% show two preferred directions. The overall homogeneous distribution of the directions on the sky (except for a small excess along the declination direction, likely due to the network geometry) is an indication that the origin of those variations is probably intrinsic to the sources, and hence due to astrophysical phenomena, a perspective that we are exploring.

6 Dissemination and outreach

The *IVS Live* Web site[2], a specific tool developed by the Bordeaux group, provides "Live" information about ongoing IVS sessions, including VLBI images of the observed sources [6]. The Web site is updated automatically based on the IVS master schedule. It now incorporates 9,174 IVS sessions, involving 81 stations and featuring 2,588 sources. Tracing the connections indicates that there were 1,685 visits (from 54 countries) in 2017 and 2018. The statistics of access to the BVID, 1,025 visits (from 42 countries) over that period, are about the same. In terms of outreach, a specific text to popularize ICRF3 or to serve as a basis for press releases, was written and distributed following the adoption of ICRF3 by the IAU. As for dissemination, Patrick Charlot taught various aspects of VLBI at two training schools, the April 2018 African VLBI Network training school held in Hartebeesthoek (South Africa) and the 9th summer school of the GRGS (*Groupe de Recherche de Géodésie Spatiale*), that took place in Oléron (France) on 3–7 September 2018.

7 Future Plans

Our plans for the next two years will be focused at first on implementing an operational analysis of the IVS-R1 and IVS-R4 sessions with the GINS software package. This implies validating the quality of the results derived with GINS, hence requiring further comparisons with other VLBI software packages, and demonstrating that we can sustain such operations on the long term. Imaging the RDV sessions and evaluating the astrometric suitability of the sources, a specificity of the Bordeaux group, will be continued along the same lines. Taking advantage of data from the second version of the BVID, we plan to explore further the connection between astrometric instabilities and source astrophysics, while also reactivating our long-standing work on source structure modeling in geodetic and astrometric VLBI. A new post-doctoral fellow, Maria Eugenia Gomez, just joined us in the framework of the EU-funded JUMPING JIVE project. Her work has to do with the implementation of full geodetic capabilities at the European VLBI Network software correlator at the Joint Institute for VLBI-ERIC (JIVE). Although not directly connected to IVS, this project, nevertheless, may have an impact at some point since it will make the JIVE correlator able to process IVS-type data.

[2] The IVS Live Web site can be accessed at http://ivslive.astrophy.u-bordeaux.fr.

Acknowledgements

We would like to thank the OASU for continued support of the Bordeaux IVS Analysis Center. In particular, the development of the second version of the BVID would not have been possible without such support. We are also grateful to the *Programme National GRAM (Gravitation, Références, Astronomie, Métrologie)* of CNRS-INSU with INP and IN2P3 co-funded by CNES for supporting ICRF3 activities all along.

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BKG/DGFI-TUM Combination Center Biennial Report 2017+2018

Sabine Bachmann [1], Mathis Bloßfeld [2], Matthias Glomsda [2], Daniela Thaller [1]

Abstract This report summarizes the activities of the BKG/DGFI-TUM Combination Center in 2017 and 2018 and outlines the activities planned for 2019 and 2020. The main focus in 2017 and 2018 was to generate operationally combined session-wise rapid solutions as well as long-term quarterly solutions. Furthermore, we tested and included additional Analysis Centers into the combined solution. We investigated the impact of different ITRS realizations on combined Earth Orientation Parameter (EOP) and scale and developed a combination strategy for IVS Intensive sessions. In 2019 and 2020, we intend to continue testing new AC contributions, to include source positions operationally in the routine combination products, and to establish a product of combined Intensive sessions. Additionally, we will provide the IVS combined contribution to the next ITRF.

1 General Information

The BKG/DGFI-TUM Combination Center was established in October 2008 as a joint effort of the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie [BKG]) and the Deutsches Geodätisches Forschungsinstitut at the Technical University of Munich (DGFI-TUM), which is responsible for the development and the maintenance of the combination software. The participating institutions as well as the tasks and the structure of the IVS Combination Center are described in [11]. The tasks comprise quality control and a timely combination of the session-based intermediate results of the IVS Analysis Centers (ACs) into a final combination product (e.g., Earth orientation parameters). In cooperation with the IVS Analysis Coordinator, the combination results are released as official IVS products. The Combination Center is also expected to contribute to the generation of the official IVS input to any ITRF activities.

The BKG/DGFI-TUM Combination Center performs an operational session-based combination of contributions from the IVS ACs. The strategy for the combination is based on the combination of normal equations and was adapted from the combination process as developed and performed by the IVS Analysis Coordinator (cf. [9, 10]).

At BKG, the following tasks are performed:

- Quality control of the AC contributions: checking the format of the contributions and their suitability for combination, identification, and reduction of outliers, inter-comparison of the Analysis Centers' results, and comparison of the results with external time series provided by IERS, IGS, and ILRS.
- Feedback to the Analysis Centers: quality control results are available at the BKG IVS Combination Center Web pages [7].
- Generation of high-quality combination products and timely archiving and distribution: combination products are created by using the combination part DOGS-CS of DGFI-TUM's software package DOGS (DGFI orbit and geodetic parameter estimation software) [6].
- Submission of official IVS combination products to the IERS: the products are submitted to the responsible IERS components to be used for IERS prod-

1. Federal Agency for Cartography and Geodesy (BKG)
2. Technische Universität München, Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)

BKG/DGFI-TUM Combination Center

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uct generation (e.g., for EOP rapid products and the EOP series IERS C04).
- Generation of the official IVS input to the ITRF: the combined session products (from 1984 to present) are submitted for ITRF computation in the form of normal equations in SINEX format. This work is also supported by the staff of the IERS Central Bureau hosted by BKG.
- Final results are archived in the BKG Data Center and mirrored to the IVS Data Centers at Observatoire de Paris (OPAR) and Goddard Space Flight Center (GSFC). This work is assisted by the staff of the BKG Data Center in Leipzig.

DGFI-TUM is in charge of the following Combination Center functions:

- DGFI is developing state-of-the-art combination procedures.
- The software DOGS-CS is updated by implementing and documenting the developed state-of-the-art combination procedures.
- Adhering to IERS Conventions: the DGFI-TUM DOGS software package is continuously updated to be in accordance with the IERS Conventions.

2 Activities During the Past Years

At BKG, the following activities were performed in 2017 and 2018:

- Generation of a combined solution for IVS 24-h rapid sessions twice a week.
- Generation of a combined long-term solution of IVS 24-h sessions every three months.
- Ensuring that the combination process is in agreement with the IERS2010 Conventions.
- Inclusion of new ACs: Norwegian Mapping Authority (NMA), Norway was added to the routine rapid combination.
- Performing combination tests for individual contributions from IGE (Spain), BEV (Austria), and ESA (Germany).
- Investigations into the impact of different ITRS realizations on VLBI-based EOP and scale.
- Refinements of the combination procedure and implementation of source position combination.
- Development of a combination strategy for IVS Intensive sessions.

2.1 Impact of Different ITRS Realizations

For our investigations into the impact of different ITRS realizations (DTRF2014 [12], ITRF2014 [2], and JTRF2014 [1]) on combined EOP and scale, we used them as a priori station information for the combination process. We found TRF-induced variations in station coordinates, such as slight offsets and seasonal variations originating from different handling of non-tidal atmospheric loading corrections (see Figure 1, left side). Furthermore, Helmert transformation parameters between the three ITRS realizations and the respective combined solution were calculated. The results show offsets in the magnitude of -0.01 ppb w.r.t. DTRF2014, -0.38 ppb w.r.t. ITRF2014, and $+0.19$ ppb w.r.t. JTRF2014. The scale parameter time series (smoothed) are shown in Figure 1 (right side).

The EOPs resulting from the test series vary very little, except for dUT1. dUT1 variations calculated using DTRF2014, ITRF2014, JTRF2014, and VTRF2015q2 as a priori station coordinates with fixed datum stations are shown in Figure 2. The left panel illustrates the dUT1 comparison with respect to the IERS 14C04 series [5] showing different offsets for the three ITRS realizations and a scatter around zero for the comparison using VTRF2015q2. A different situation is given when comparing to the (previous) IERS 08C04 series, showing a discontinuity around the year 2000. A detailed description of the impact of ITRS realizations on combined EOP and scale is given in [3].

2.2 Development of a Combination Procedure for Intensives

Routinely, we generate combined EOP products using IVS 24-h sessions. Starting in 2018, we developed a combination routine for IVS 1-h Intensive sessions. These sessions are dedicated to determining dUT1 on a daily basis. Combining IVS Intensives requires a different combination approach than 24-h sessions due to the reduced set of parameters and the associated adapted datum definition and weighting strategy. Overall we tested the Intensives combination procedure using one year of Intensive sessions and a set of four AC contributions in the form of datum-free normal equa-

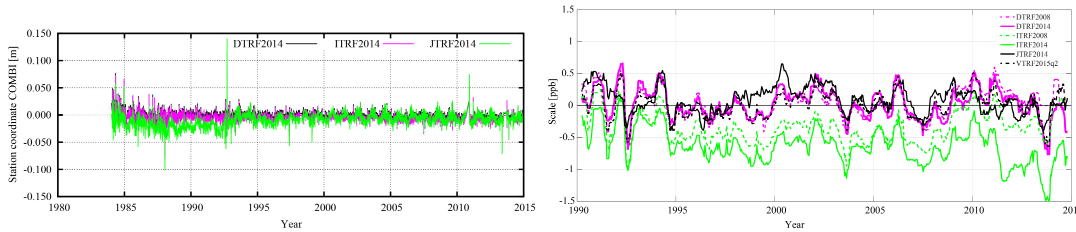

Fig. 1: Left: Station height of Wettzell (Germany) when using different TRFs as a prioris. Right: 90 day median-smoothed scale between the different ITRS realizations and the session-wise VLBI combined solution: DTRF2008 (light blue), DTRF2014 (dark blue), ITRF2008 (light red), ITRF2014 (dark red), JTRF2014 (black), and VTRF2015q2 (ocher).

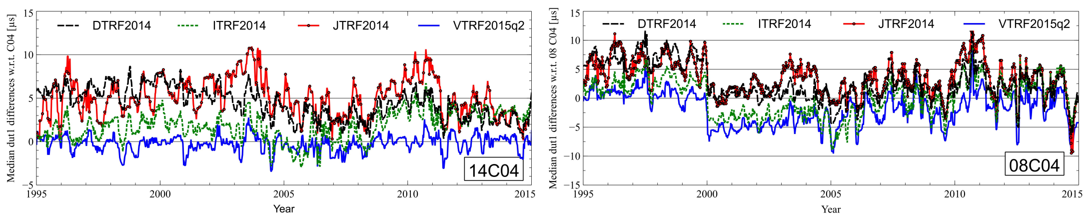

Fig. 2: dUT1 differences between the solutions based on the different TRFs and IERS 14C04 (left) and IERS 08C04 (right). 90 day median smoothed values are shown.

tions provided in SINEX files. A more detailed description of the Intensives combination procedure and the test results is published in [4]. The results of dUT1 for the individual and the combined solutions in comparison to the IERS 14C04 series are shown in Figure 3.

The results show a good agreement between the individual contributions and the combined solution, with a reduced RMS of the combined solution compared to the individual solutions: the RMS of the combined solution is 32.0 µs, while the RMS values of the individual solutions range between 38.6 µs and 33.4 µs (as can be seen in Table 1). We are optimistic that also IVS Intensives can benefit from a combined product in terms of improved repeatability, as combined 24-h sessions have already proved. In order to move forward in this respect and work on establishing an IVS combined product also for the Intensives, all ACs are encouraged to analyze Intensive sessions and provide SINEX files with datum-free NEQs containing station coordinates and all five EOPs, for instance, similar to the 24-h sessions.

Table 1: RMS and offset for dUT1 w.r.t. the IERS 14C04 series using 258 Intensive sessions from 2017 (only sessions available for all ACs are taken into account).

AC	RMS [µs]	Offset [µs]
BKG	36.9	5.1
SHAO	37.3	7.7
USNO	38.6	10.9
VIE	33.4	1.9
COMBI	32.0	5.6

2.3 Other Activities

Concerning the operational rapid combination, contributions of one additional AC were added: NMA using software “Where” was introduced in the combination routine. This increases the number of regularly contributing ACs to nine.

In late 2018, we implemented a new strategy for our server providing the IVS Combination Center’s Web site at https://ccivs.bkg.bund.de. The changes include

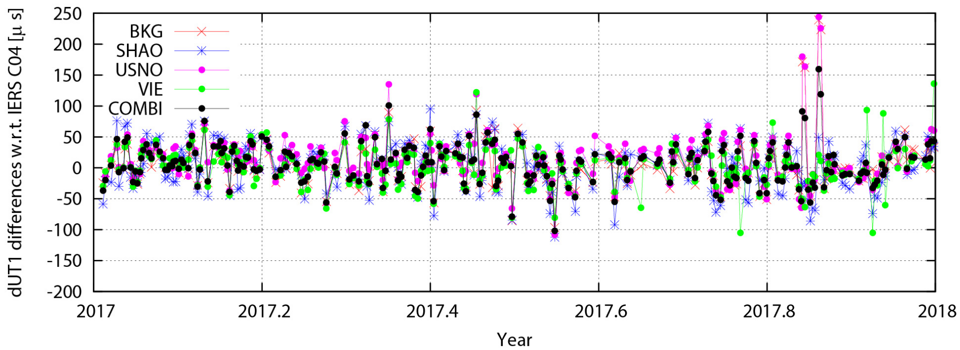

Fig. 3: dUT1 residuals w.r.t. IERS 14C04.

the separation of the test and the production system and security improvement. In the course of updating the server architecture, we revised the content of the Web site, added a new plotting tool allowing a more flexible interactive plot representation, and extended the product presentation by adding additional EOP comparisons and station coordinate representations.

At DGFI, the following relevant software developments were realized in 2017 and 2018:

- Application of non-tidal loading corrections at the normal equation level.
- Extension of similarity transformation program [8].

For more information on the DGFI-TUM VLBI activities please refer to the DGFI-TUM IVS AC report in this volume.

3 Staff

The list of the staff members of the BKG/DGFI-TUM Combination Center in 2017+2018 is given in Table 2.

4 Current Status

At the end of 2018, in total nine IVS ACs (ASI, BKG, DGFI-TUM, GFZ, GSFC, IAA, NMA, OPAR, and USNO) contributed regularly to the IVS combined rapid and quarterly products (see [7]). Several new potential ACs are currently under review: AUS (Geoscience Australia), VIE (Technical University Vienna / BEV Bundesamt für Eich- und Vermessungswesen, Austria), IGE (National Geographic Institute of Spain), and ESA (European Space Agency), which will probably become an IVS Operational AC in the near future. The rapid solutions only contain R1 and R4 sessions, and new data points are added twice a week as soon as the SINEX files of at least four IVS ACs are available. Long-term series are generated quarterly and include all 24-h sessions since 1984. The quarterly series include long-term EOP, station positions, and velocities. Furthermore, a VLBI TRF is generated and published. The software was extended to process source parameters for session-wise combination as well as for a consistent generation of TRF and CRF. For this reason, the current ICRS realization ICRF3 was implemented. The results of the combination process are archived by the BKG Data Center in Leipzig. The combined rapid EOP series, as well as the results of the quality control of the AC results, are also available directly at the BKG/DGFI-TUM Combination Center Web site [7] or via the IVS Analysis Coordinator Web site.

5 Future Plans

In 2019 and 2020, the work of the BKG/DGFI-TUM Combination Center will focus on the following aspects:

- Operationally providing consistently combined TRF, CRF, and EOP products.
- Extending the number of sources and the number of stations in the consistent TRF/CRF generation.

Table 2: Staff members of the BKG/DGFI-TUM Combination Center.

Name	Affiliation	Function	E-Mail
Sabine Bachmann	BKG	Combination procedure development and operational combination	ccivs@bkg.bund.de
Linda Janssen	BKG	Operational combination and Web site maintenance (until August 2018)	ccivs@bkg.bund.de
Sonja Geist	BKG	Web site maintenance (since August 2018)	ccivs@bkg.bund.de
Daniela Thaller	BKG	Combination strategies and strategical planning	ccivs@bkg.bund.de
Mathis Bloßfeld	DGFI-TUM	Software development and combination strategies	mathis.blossfeld@tum.de
Matthias Glomsda	DGFI-TUM	Software development and combination strategies	matthias.glomsda@tum.de

- Including new ACs into the routine rapid and quarterly combination.
- Improving the combination strategy for Intensive sessions and adding more ACs to the combined dUT1 product.
- Establishing a combined Intensive product.
- Generating the official IVS combined contribution to the upcoming ITRF2020.

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Matera CGS VLBI Analysis Center

Roberto Lanotte [1], Simona Di Tomaso [1], Giuseppe Bianco [2]

Abstract This paper reports the VLBI data analysis activities at the Space Geodesy Center (CGS) of the Italian Space Agency (ASI) in Matera, from January 2017 through December 2018, and the contributions that the CGS intends to provide in the future as an IVS Analysis Center.

1 General Information

The CGS VLBI Analysis Center is located at the Matera VLBI station close to the town of Matera in the middle south of Italy. The Matera VLBI station became operational at the ASI/CGS in May 1990. Since then, it has been active in the framework of the most important international programs. The CGS, operated by E-GEOS S.p.A. (an ASI/Telespazio company) under an ASI contract, provides full scientific and operational support using the main space geodetic techniques: VLBI, SLR, and GPS. The work presented in this report is carried out by the E-GEOS staff consisting of Roberto Lanotte and Simona Di Tomaso.

2 Activities during the Past Years

During 2017–2018, the following activities were performed at CGS:

- Global VLBI Solutions asi2017a and asi2018a.
  We continued the annual realization of global VLBI solutions. The solutions are named asi2017a and 2018a and were realized using the CALC/SOLVE software developed at NASA/GSFC. The main and final characteristics of them are:

  asi2017a:

  – Data span: 1984.01.04–2016.12.29 for a total of 4,979 sessions
  – Estimated Parameters:
    · Celestial Frame: Right ascension and declination as global parameters for 1,406 sources;
    · Terrestrial Frame: Coordinates and velocities for 106 stations as global parameters;
    · Earth Orientation: X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dX and dY.

  asi2018a:

  – Data span: 1984.01.04–2017.12.28 for a total of 4,638 sessions
  – Estimated Parameters:
    · Celestial Frame: Right ascension and declination as global parameters for 1,368 sources;
    · Terrestrial Frame: Coordinates and velocities for 106 stations as global parameters;
    · Earth Orientation: X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dX and dY.

- IVS Tropospheric Products.
  Regular submission of tropospheric parameters (wet and total zenith path delays, east and north horizontal gradients) for all VLBI stations observing in the IVS R1 and R4 sessions continued during 2017–2018. Currently, 1,642 sessions have

1. E-GEOS S.p.A., Centro di Geodesia Spaziale
2. Italian Space Agency, Centro di Geodesia Spaziale

CGS Analysis Center

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been analyzed and submitted, covering the period from 2002 to 2018. The results are available at the IVS data center.

- Daily Solution Files (DSNX).
  Regular submission of daily sinex files for the IVS project "Daily EOP & station-coordinates solutions" continued during 2017–2018. All sessions lasting at least 18 hours were analyzed and at the present about 5,200 sessions have been submitted to IVS.
- Software development.
  We continued the development of the software "*resolve*". The main goal of this software is the visual editing of a VLBI database. One of the reasons that led us to the development of this software was to have the capability of work on the output obtained from a run of SOLVE in BATCH mode. At the present we have used *resolve* to edit approximately all of the databases of the daily sinex production.

2.1 Staff at CGS Contributing to the IVS Analysis Center

- Dr. Giuseppe Bianco, responsible for CGS/ASI (primary scientific/technical contact).
- Dr. Rosa Pacione, responsible for scientific activities, E-GEOS.
- Dr. Roberto Lanotte, geodynamics data analyst, E-GEOS.
- Dr. Simona Di Tomaso, geodynamics data analyst, E-GEOS.

3 Future Plans

- Continue and improve the realization of our global VLBI solution, providing its regular update on time.
- Continue to participate in the IVS analysis projects.

DGFI-TUM Analysis Center Biennial Report 2017+2018

Younghee Kwak, Matthias Glomsda, Michael Gerstl, Detlef Angermann, Manuela Seitz

Abstract This report describes the activities of the DGFI-TUM Analysis Center (AC) in 2017 and 2018. Besides regular IVS submissions, DGFI-TUM continued to reprocess past 24-hour sessions including the estimation of source positions. Starting in 2017, we have adopted DOGS-RI as the VLBI analysis software after successful internal/external validation.

1 General Information and Component Description

DGFI-TUM has been acting as an IVS AC since the establishment of the IVS in 1999. Starting from November 2008, we are an operational AC regularly submitting datum-free normal equations for 24-hour sessions in the SINEX format. Since 2008, we have also been involved in the BKG/DGFI-TUM Combination Center by maintaining the combination software.

DGFI-TUM is an institute of the Technische Universität München (TUM) since January 2015 and is located in the city center of Munich, Germany. The research performed at DGFI-TUM covers many different fields of geodesy (reference systems, satellite altimetry, Earth system modelling, etc.) and includes contributions to national and international scientific services and research projects, as well as various functions in scientific organizations (see http://www.dgfi.tum.de).

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)

DGFI-TUM Analysis Center

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2 Staff

In March 2017, Younghee Kwak took over the operational IVS analysis from Ralf Schmid, who left DGFI-TUM at that time. Michael Gerstl and Matthias Glomsda (who joined the institute in April 2017) are in charge of the development of our proprietary VLBI analysis software DOGS-RI (DGFI Orbit and Geodetic parameter estimation Software - Radio Interferometry). Table 1 lists the staff members and their main areas of activity.

Table 1 Staff members and their main areas of activity.

Detlef Angermann	Group leader.
Michael Gerstl	Develoment of the analysis software DOGS-RI.
Matthias Glomsda	Develoment of the analysis software DOGS-RI; operational data analysis (starting 2019).
Younghee Kwak	Operational data analysis (2017-2018); CRF/TRF combination; combination of different space geodetic techniques.
Manuela Seitz (returned from maternity leave in December 2018)	CRF/TRF combination; combination of different space geodetic techniques.
Ralf Schmid (left in March 2017)	Operational data analysis.

3 Current Status and Activities

Analysis Activities

In 2017 and 2018, we had a lot of changes in our solutions. In March 2017, the submission of VLBI solutions processed with OCCAM@DGFI was suspended. After thorough internal/external validation [1], our new in-house VLBI software, DOGS-RI, was launched and started to contribute a new IVS solution (dgf2018a). The performance of DOGS-RI is equal to or even better than OCCAM@DGFI. A processing of old sessions backward until 1984 was conducted. Table 2 contains a summary of all sessions analyzed with DOGS-RI.

The implementation of reading vgosDB in DOGS-RI has also been a big evolvement. The IVS decided to provide correlated VLBI data only in vgosDB format starting from October 1, 2018. Therefore, every AC had to be ready to handle vgosDB within its analysis software. Since vgosDB is based on netCDF and the structure of the data has also been reconstructed entirely, the subroutines for input data reading had to be thoroughly revised.

Table 2 Sessions processed in 2017 and 2018.

Year	vgosDB	Total (NGS + vgosDB)
1984-1990	-	629
1991-2000	-	1328
2001-2010	-	1428
2011-2017	-	1052
2018	33	96

Software Development

The processing with DOGS-RI is on track, but there are always new developments that have to be implemented to keep the software up-to-date and meet the intended accuracy goals. Furthermore, a major enterprise is to fully consolidate DOGS-RI with the other components of DOGS, OC (Orbit Computation) and CS (Combination & Solution), to share common routines and upgrade to a more flexible data format. Another important innovation will be the integration of the recently established new International Celestial Reference Frame (ICRF3), which for the first time makes use of Galactic Aberration, i.e., the proper motions of radio sources. In anticipation of the next International Terrestrial Reference Frame (ITRF2020), it will also be necessary to account for the gravitational deformation of VLBI telescopes. Other projects are the inclusion of more non-tidal loading effects, the treatment of source structure, and the completion of a simulation mode.

Consistent Realization of CRF and TRF

The IUGG urged "that highest consistency between the ICRF, the ITRF, and the EOP as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS", according to Resolution No. 3 of the IUGG adopted by the General Assembly in 2011.

As a research of consistent realization of the CRF and the TRF in accordance with the IUGG Resolution, DGFI-TUM conducted a project "Consistent celestial and terrestrial reference frames by improved modelling and combination" as part of the DFG Research Unit FOR1503, "Space-time reference systems for monitoring global change and for precise navigation in space".

For the consistent realization, VLBI, GNSS, and SLR single-technique solutions of 11 years (2005.0–2016.0) were processed homogeneously and combined on the normal equation level. Several types of combined solutions were computed following the selections of different local ties (LTs), EOP combination setups, and different weights of the techniques. Finally, the impact of these combination setups on CRF, TRF, and EOP was investigated. The main conclusions are as follows (more details can be found in [2]):

- The combination of different space geodetic techniques improves the precision of the estimated parameters due to the larger number of observations.
- The selection of the LTs mostly affects the TRF.
- The CRF benefits from the precise terrestrial x/y-pole coordinates estimated by GNSS.
- The combination of ΔUT1 from VLBI and the satellite techniques impacts the right ascension and thus the CRF z-rotation (Figure 1).
- Emphasizing satellite techniques (down-weighting VLBI observations) significantly influences the

CRF and causes systematic rotations of the source positions.

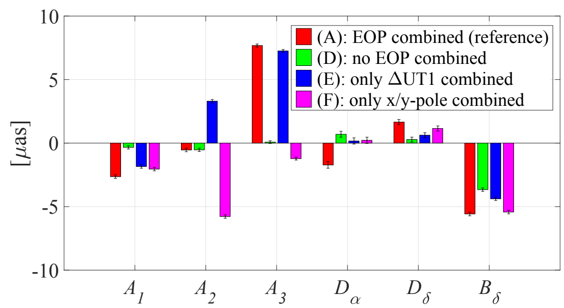

Fig. 1 CRF transformation parameters and their standard deviations (error bars) of different EOP combination setups w.r.t. the VLBI-only solution [2]. A1, A2, and A3 denote the rotations between two CRFs w.r.t. the three axes, D_α and D_δ represent the drifts of right ascension and declination, and B_δ means a bias in declination.

4 Future Plans

In 2019, we will continue to submit solutions to the IVS, but the persons in charge will change (see Table 1). There will be a new DGFI-TUM solution tag when the planned software enhancements have been implemented. The IVS Combination Center at BKG might introduce the combination of Intensive sessions, and consequently we might extend our IVS contribution to Intensives as well. Finally, of course, we want to take part in the data generation for ITRF2020.

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GFZ Analysis Center 2017/2018 Biennial Report

Robert Heinkelmann [1], James Anderson [1,2], Kyriakos Balidakis [1,2], Santiago Belda [3], Georg Beyerle [1], Susanne Glaser [1,2], Suxia Gong [1,2], Okky Syahputra Jenie [1,2], Maria Karbon [4], Chaiyaporn Kitpracha [1,2], Susanne Lunz [1,2], Nicat Mammadaliyev [2], Sadegh Modiri [1,2], Tobias Nilsson [5], Minghui Xu [1,2,6,7], Harald Schuh [1,2]

Abstract This report briefly provides general information and the component description of the IVS Analysis Center at GFZ. Recent results are mentioned, and the planned future activities are outlined.

1 General Information

Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences is the national research center for Earth sciences in Germany. At this research facility, within Department 1 "Geodesy" and Section 1.1 "Space Geodetic Techniques", a VLBI group that is an associate Analysis Center (AC) of the IVS has existed since the end of 2012.

2 Component Description

GFZ is an associate AC of the IVS. We have installed and partly automatized our VLBI analysis process in preparation for becoming an operational AC. We are also performing as an IVS Combination Center for tropospheric products.

3 Staff

Since the 2015/2016 Biennial Report [16], Santiago Belda, Maria Karbon, Li Liu, Julian Mora-Diaz, Tobias Nilsson, Chinh Nguyen Thai, and Termitope Seun Oluwadare have left the VLBI group, and we want to wish them the best of luck in their future careers. Li Liu has successfully defended her PhD thesis [20]. Additionally, we have had the pleasure of welcoming the following new colleagues to our group, all of which will be pursuing a PhD (in alphabetical order):

- Suxia Gong, MSc degree from TU Berlin, is investigating the comparison of dispersive delays and ionospheric parameters obtained from microwave space geodetic techniques.
- Okky Syahputra Jenie, MSc from TU Berlin, works on fringe fitting and ambiguity resolution for VLBI group delay observables.
- Chaiyaporn Kitpracha, M.Eng, from Thailand, works on tropospheric effects in VLBI/GNSS data and tropospheric ties.
- Susanne Lunz, MSc from TU Dresden, is working within the ECORAS-2 project with a focus on the comparison of VLBI and Gaia CRFs.
- Nicat Mammadaliyev, MSc from TU Berlin, is investigating co-location in space of all four space geodetic techniques within GGOS-SIM2.

1. Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany
2. Technische Universität Berlin, Institute of Geodesy and Geoinformation Science, Germany
3. Image Processing Laboratory, Laboratory of Earth Observation, University of Valencia, Spain
4. CNRS - Observatoire de Paris SYRTE, France
5. Lantmäteriet, Swedish Mapping, Cadastral and Land Registration Authority, Gaevle, Sweden
6. Huazhong University of Science and Technology, China
7. Shanghai Astronomical Observatory, China

GFZ Analysis Center

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Table 1 Current members of the VLBI group at GFZ without MSc students.

Name	Main activity
Harald Schuh	Director of Department 1 at GFZ
Robert Heinkelmann	Head of VLBI group
James Anderson	Source structure, D-VLBI
Kyriakos Balidakis	Atmospheric & geophysical effects
Georg Beyerle	Software development
Suxia Gong	Ionospheric effects
Susanne Glaser	Combination of space techniques
Okky Syahputra Jenie	Fringe fitting & ambiguity resolution
Chaiyaporn Kitpracha	Tropospheric effects
Susanne Lunz	Celestial reference frame
Nicat Mammadaliyev	Co-location in space
Sadegh Modiri	Copula-based analysis
Minghui Xu	Source structure

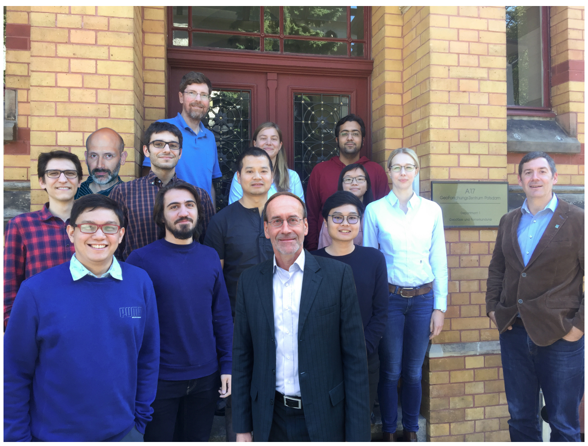

Fig. 1 A picture of the GFZ VLBI group.

The current members of the VLBI group and their main functions are listed in Table 1, and a picture of the group is displayed as Figure 1.

4 Current Status and Activities

- **VLBI Data Analysis Software Development**
  The VLBI group at GFZ Potsdam employs the "Potsdam Open Source Radio Interferometry Tool" (PORT) for data processing and analysis. The MATLAB source code of PORT was originally based on the "Vienna VLBI Software" (VieVS); since 2012, PORT development at GFZ has been directed towards operational data processing in support of GFZ's IVS activities, as well as implementation of alternative analysis algorithms, such as parameter estimation using Kalman filters. Within the last year, efforts were directed at refactoring tasks to improve code efficiency and modularity. The code is open source and will be available to the VLBI community via GFZ's source code repository.
- **ICRF3 Contribution**
  The GFZ VLBI group delivered input to the current International Celestial Reference Frame, ICRF3 [10], within the corresponding IAU Working Group. For this purpose, we created several realizations of ICRS by updating the input data, considering galactic aberration, and testing different approaches in this respect. We also worked on the improvement of the terrestrial reference frame and the analysis software to serve this purpose.
- **Reference Frame Simulations towards GGOS**
  Within project GGOS-SIM[1] "Simulation of the Global Geodetic Observing System" (DFG, project no. SCHU 1103/8-1), we simulated all four space geodetic techniques (GNSS, SLR, DORIS, VLBI) currently contributing to the ITRF [24]. This is a joint project of TU Berlin and GFZ Sec. 1.2 Oberpfaffenhofen. Starting with VLBI simulations of the current network [11], the VLBI station network was extended with single additional stations and combined with SLR using local ties and global ties [12]. The impact of different local tie scenarios on the combined frame of GPS, SLR, and VLBI was investigated in [14]. The future network developments of SLR within the combination of GPS, SLR, and VLBI can be found in [13]. In the second phase of GGOS-SIM starting on January 1, 2019, we focus on co-location–in–space simulations of all four space-geodetic techniques.
- **Space Applications**
  The GFZ VLBI group contributed to the Research Unit (FOR 1503) "Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space", funded by the German Research Foundation, with the project "Ties between kinematic and dynamic reference frames" (D-VLBI)[2]. The application of the D-VLBI tech-

[1] https://www.earth.tu-berlin.de/menue/research/running_projects/ggos_sim/parameter/en/
[2] http://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/d-vlbi/

nique (differential-VLBI, otherwise known as phase referencing) to geodetic observations of near-field spacecraft to demonstrate the potential of D-VLBI to directly tie spacecraft dynamic frames, including GNSS frames, to the celestial frame was studied. Automatic D-VLBI scheduling software was developed, and initial test observations of GPS satellites and the Gaia spacecraft were performed. Simulations of D-VLBI and standard VLBI observations of various Earth-orbiting spacecraft were also carried out in order to estimate the ability of the D-VLBI and VLBI techniques to determine spacecraft orbital parameters and perform frame ties [2, 20]. These simulations also contributed to the GRASP proposal to NASA and the E-GRASP & Eratosthenes proposals to ESA.

- **Source Structure and the Connection to the Gaia Frame**
  The last activity in the first installment of the research project "Extension of the coordinate parameterization of radio sources observed by VLBI" (ECORAS), funded by the German Research Foundation, was the modification of the source position parameterization to multivariate adaptive regression splines [18]. ECORAS has entered its second phase (ECORAS-2). The optical astrometric satellite mission Gaia (ESA) is providing positions and proper motions of hundreds of thousands of quasars at a level of precision comparable to or even better than the current ICRF3 position accuracies. In the second phase of project ECORAS, the comparison of the Gaia and VLBI celestial coordinates is being exploited to determine systematic, possibly technique-dependent, reference frame effects. As part of the efforts to improve the alignment of the radio and optical frames, and the agreement of the positions of individual sources, we have studied the detection, modeling, and correction of radio source structure effects on celestial coordinates and observables [see, for example, 25, 3]. In addition, we are investigating effects such as core shift, that potentially induce frequency-dependent position variations, and apparent proper motions induced by the evolution of intrinsic source structure.
- **Climatological Studies**
  Long-term variations in water vapor content are climate change indicators, since water vapor is the most efficient and abundant greenhouse gas. We have investigated integrated water vapor variations from the analysis of VLBI and GNSS data, as well as from state-of-the-art weather models, such as ERA Interim and ERA5. The results can be found in [6, 1].
- **Atmospheric Refraction Effects**
  In addition to an appropriate parameter set-up in the geodetic adjustment, improved atmospheric delay modeling is necessary to improve the accuracy of geodetic products. Employing the in-house ray-tracing software [26] and state-of-the-art NWMs such as ERA5 (31 km) and ECMWF's operational model (9 km), we have worked on the development of accurate ray-traced delays, mapping functions, and non-linear asymmetric delay models and assessment thereof in VLBI data analysis [6].
- **Geophysical Loading Effects**
  Developed at GFZ, geophysical loading models that simulate the displacements due to mass transport in the atmosphere, the oceans, and continental water storage were extensively tested in the analysis of VLBI and GNSS data [21].
- **IVS Tropospheric Combination**
  The algorithm for the IVS tropospheric combination was revised, making it more robust. Several changes are in progress regarding IVS Tropospheric Combination, including the epochs at which the tropospheric products are reported (from HH:00 to HH:30), and the combination of gradients. Following the expression of interest on behalf of IGS and EUREF, we look forward to more ACs contributing to the product, thus increasing its diversity and quality.
- **Atmospheric Ties**
  To explore the potential of atmospheric ties being used in addition to local/global/space ties in the multi-technique combination, an IAG working group (JWG 1.3[3]) has been established by R. Heinkelmann. At GFZ, we have studied the intra- and inter-technique differences mainly induced by varying frequency, position, and observing system [4]. Employing simulated observations we can perform the multi-technique combination utilizing NWM-derived atmospheric ties, to the advantage of the combined solution [5].
- **Machine Learning for Tropospheric Delay Prediction**

3 https://iag.geo.tuwien.ac.at/c1/jwg/jwg13/

To predict zenith wet delays, we have utilized machine learning techniques, in particular Long-short term memory and a combination of singular spectrum analysis (SSA) and Copula. We have obtained promising results for tropospheric delay prediction at Wettzell; however, this approach needs to be refined further to achieve geodetic accuracies [19].

- **Ionospheric Effects**
  We are working on the determination of ionospheric delays from microwave-based observations. We have obtained promising results by performing comparisons of slant total electron content (STEC) between VLBI and GNSS observations [15].
- **Earth Orientation Parameters**
  We have studied the Free Core Nutation (FCN), a main component of celestial pole offset variations, and derived a new empirical FCN model based on VLBI data [7]. We determined a new set of empirical corrections to the precession offsets and rates and to the amplitude of a wide set of terms included in the IAU 2006/2000A precession-nutation theory [9]. We are investigating the potential for applying the Copula method to model EOP, and we introduce the combination of SSA and Copula-based analysis in a novel hybrid method to predict EOP [22]. Also, we have tested a new method for CPO prediction based on the recent availability of sophisticated empirical FCN models [8]. We have investigated how to improve the estimation of UT1-UTC from the analysis of Intensive sessions, by means of improving the modeling of atmospheric refraction and geophysical loading [see, for example, 23]. We have also studied high-frequency ocean tidal variations in Earth rotation [17].

5 Future Plans

In addition to continuing to improve VLBI data analysis by better understanding systematic and random effects, the following activities are planned for 2019–2020: (i) Public release of PORT source code, (ii) VLBI data analysis starting from the correlator output, and (iii) IVS tropospheric combination reprocessing.

Acknowledgements

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BKG/IGGB VLBI Analysis Center

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Abstract In 2017 and 2018, the activities of the BKG/IGGB VLBI Analysis Center, as in previous years, consisted of routine computations of Earth orientation parameter (EOP) time series and of a number of research topics in geodetic VLBI. The VLBI group at BKG continued its regular submissions of time series of tropospheric parameters and the generation of daily SINEX (Solution INdependent EXchange format) files. In 2017, quarterly updated solutions were computed to produce terrestrial reference frame (TRF) and celestial reference frame (CRF) realizations. The analysis of *Intensive* sessions for UT1–UTC estimation was continued. All solutions are based on the Calc/Solve software, release 2014.02.21 [10], using the old Mark 3 database format. At the end of 2018, the geodetic VLBI software νSolve [12] was successfully installed and tested for the analysis of sessions in the new vgosDB data format.
At IGGB, the emphasis has been placed on individual research topics such as atmospheric turbulence investigations, celestial reference frame combinations, and VLBI near-field investigations. On September 30, 2019, the IGGB part of the Analysis Center will stop operations. After forty years of existence, there will be no formal successor of the Bonn geodetic VLBI activities due to reasons of restructuring of the institute.

1. Federal Agency for Cartography and Geodesy (BKG)
2. Institute of Geodesy and Geoinformation of the University of Bonn (IGGB)

BKG/IGGB Analysis Center

IVS 2017+2018 Biennial Report

1 General Information

The BKG/IGGB VLBI Analysis Center was established jointly by the analysis groups of the Federal Agency for Cartography and Geodesy (BKG), Leipzig, and the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB). Both institutions cooperate intensely in the field of geodetic VLBI. The responsibilities include both data analysis for generating IVS products and special investigations with the goal of increasing accuracy and reliability. BKG is responsible for the computation of time series of EOP and tropospheric parameters, for the generation of SINEX files for 24-hour VLBI sessions and one-hour *Intensive* sessions, and for the generation of quarterly updated global solutions for TRF and CRF realizations. Besides data analysis, the BKG group is also responsible for writing schedules for the *Int2* UT1-UTC observing sessions. Details of the research topics of IGGB are listed in Section 3.

2 Data Analysis at BKG

At BKG, the Mark 5 VLBI data analysis software system Calc/Solve, release 2014.02.21 [10], has been used for VLBI data processing. It is running on a Linux operating system. Simultaneously first successful tests with the newly developed geodetic VLBI software νSolve [12], a replacement of the interactive mode of Solve, could be realized for sessions in the new vgosDB data format. Calc/Solve allows the generation of so-called tropospheric path delay (TRP) files derived from the Vienna Mapping Function (VMF1) data. They contain external information about the troposphere on a scan-by-scan basis, specifically the a priori delay, dry and wet mapping functions, and gradient mapping functions. The BKG VLBI group uses TRP files to input data related to VMF1. The VMF1 data were downloaded daily from the server of the Vienna University of Technology.

Furthermore, from the middle of 2018, the construction of an additional processing chain of vgosDB databases for the generation of IVS products has been started. In addition to the use of the νSolve software, another necessary prerequisite is the successful installation of the new Calc/Solve software, release 2018.06.30 [11], which was not yet operational in the reporting period.

- **Processing of correlator output**
  The BKG group continued the generation of calibrated databases in the old MK3 format for the sessions correlated at the Max Planck Institute for Radio Astronomy (MPIfR)/BKG Astro/Geo Correlator at Bonn (e.g., EURO, OHIG, and T2) until mid-2018 and submitted them to the IVS Data Centers.
- **Scheduling**
  In cooperation with IGGB, BKG continued scheduling the Int2 *Intensive* sessions, which are mostly observed on the ISHIOKA-WETTZELL baseline. In 2017 and 2018, a total of 183 schedule files were created.
- **BKG EOP time series**
  The BKG EOP time series bkg00014 was continued. The main features of this solution were not changed. But the station coordinates of the VLBI sites KUNMING in China and SEJONG in Korea were estimated as global parameters because of an observation period of more than three years. Further, three new VLBI stations (AGGO in Argentina, DSS36 in Australia, and RAEGSMAR on the island of Santa Maria, Azores) could be included successfully in the data processing.
  Each time after the preprocessing of any new VLBI session (correlator output MK3 database version 1), a new global solution with 24-hour sessions since 1984 was computed, and the EOP time series bkg00014 was extracted. Altogether, 5,494 sessions were processed. The main parameter types in this solution are globally estimated station coordinates and velocities together with radio source positions. The datum definition was realized by applying no-net-rotation and no-net-translation conditions for 25 selected station positions and velocities with respect to VTRF2008a and a no-net-rotation condition for 295 defining sources with respect to ICRF2. The station coordinates of the telescopes AGGO (Argentina), AIRA (Japan), CHICHI10 (Japan), CTVASTJ (Canada), DSS13 (USA), DSS36 (Australia), ISHIOKA (Japan), KASHIM11 (Japan), KASHIM34 (Japan), KOGANEI (Japan), PT_REYES (USA), RAEGSMAR (Azores), RAEGYEB (Spain), SEST (Chile), SINTOTU3 (Japan), TIANMA65 (China), TIDBIN64 (Australia), TIGOCONC (Chile), TSUKUB32 (Japan), UCHINOUR (Japan), VERAISGK (Japan), VERAMZSW (Japan), WETTZ13N (Germany), WIDE85_3 (USA), and YEBES40M (Spain) were estimated as local parameters in each session.
- **BKG UT1 *Intensive* time series**
  Regular analysis of the UT1-UTC *Intensive* time series bkgint14 was continued. The series bkgint14 was generated with fixed TRF (VTRF2008a) and fixed ICRF2. The a priori EOP were taken from final USNO series [13]. The estimated parameter types were only UT1-TAI, station clock, and zenith troposphere.
  The algorithms related to the semi-automatic process for handling the *Intensive* sessions Int2/3 with station TSUKUBA after the Japan earthquake [2] were still used, but from 2017 for station ISHIOKA (Japan), because station TSUKUBA was shut down at the end of December 2016.
  A total of 6,418 UT1 *Intensive* sessions were analyzed for the period from 1999.01.01 to 2018.12.31.
- **Quarterly updated solutions for submission to IVS**
  In 2017, quarterly updated solutions were computed for the IVS products TRF and CRF. There are no differences in the solution strategy compared to the continuously computed EOP time series bkg00014. The results of the radio source positions were submitted to IVS in IERS format. The TRF solution is available in SINEX format, version 2.1, and includes station coordinates, station velocities, and radio source coordinates together with the covariance matrix, information about constraints, and the decomposed normal matrix and vector.
- **Tropospheric parameters**
  The VLBI group of BKG continued regular submissions of long time series of tropospheric param-

eters to the IVS (wet and total zenith delays and horizontal gradients) for all VLBI sessions since 1984, which were still available in the old MK3 data format. The tropospheric parameters were extracted from the standard global solution bkg00014 and transformed into SINEX format.

- **Daily SINEX files**
  The VLBI group of BKG also continued regular submissions of daily SINEX files for all available 24-hour sessions in the old MK3 data format for the IVS combined products and for the IVS time series of baseline lengths. In addition to the global solutions, independent session solutions (bkg2014a) were computed for the station coordinates, radio source coordinates except for 295 defining sources of ICRF2, and EOP parameters including the X,Y-nutation parameters. The a priori datum for TRF is defined by the VTRF2008a, and ICRF2 is used for the a priori CRF information. A second series of daily SINEX files was generated with estimated source positions for all sources in each session.
- **SINEX files for *Intensive* sessions**
  The generation of SINEX files for all *Intensive* sessions (bkg2014a) in the old MK3 data format continued in 2017 and 2018. The parameter types are station coordinates, pole coordinates and their rates, and UT1-TAI and its rate. But only the normal equations stored in the SINEX files are important for further intra-technique combination or combination with other space geodetic techniques.

3 Research Topics at IGGB

- **ivg::ASCOT: Continued development of VLBI software package**
  The VLBI group of IGGB continued extending the IGG VLBI Group – Analysis, Scheduling and Combination Toolbox (ivg::ASCOT, [1]). The software is written in C++ and has particpated in the last VLBI Software Comparison Campaign with great success.
  The last improvements were related to alternative estimation procedures for atmospheric parameters including turbulence theory. This leads to a fully populated variance covariance matrix [4] which also eliminates the need for a reweighting of the observations.
  The software is freely available to any group interested in taking over its further developments. Please contact Axel Nothnagel for details.

Fig. 1 Logo of the VLBI analysis software package ivg::ASCOT (IGG VLBI Group – Analysis, Scheduling and Combination Toolbox).

- **Observing the Chang'E-3 Lander with VLBI**
  Analysis of the VLBI observations of the Chang'E-3 Lander in project OCEL (Observing the Chang'E-3 Lander with VLBI) were continued [3]. For producing group delay observables from DOR tone observations (DOR = Differential One-way Ranging), a specialized version of the *fourfit* was developed [5]. The first results stemming from two of the 12 sessions were published [9].
- **Studies on VLBI observations of Earth satellites**
  In the context of the OCEL project, it became clear that the theoretical model for near-field VLBI observations needed to be optimized. For this reason, an analytical model for Earth satellites was developed [6].
- **Combination of radio source catalogs on the level of normal equation systems**
  In conjunction with the generation of ICRF3, the group was involved in the combination of catalogs of radio source positions on the level of normal equation systems. Different avenues can be followed for this. When a combination is done on a session-by-session basis for inputs of several Analysis Centers, the final catalog can be composed by stacking all sessions to a full global matrix and its inversion. For catalogs combining input derived from observations at different observing frequencies, the path of choice is to stack the full normal equation systems of the individual catalogs after the session-wise stacking had been done for each frequency band individually. This path has been followed for the generation of a multi-frequency celestial reference frame with full variance-covariance information [7].

- **Gravitational deformation of radio telescopes**
  In November 2015, the main reflector of the 20-m telescope of the Onsala Space Observatory in Sweden was scanned with a terrestrial laser scanner (TLS). In 2018, a model was developed for computing corrections for the group delay observables due to gravitational deformation of this telescope [8]. The revised manuscript is under review at the moment.

4 Personnel

Table 1 Personnel at the BKG/IGGB Analysis Center. All phone numbers begin with +49.

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GSFC VLBI Analysis Center Report

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Abstract This report presents a description of the GSFC VLBI Analysis Center and its activities during 2017 and 2018. The GSFC VLBI Analysis Center analyzes all IVS sessions, makes regular IVS submissions of data and analysis products, and performs research and software development aimed at improving the VLBI technique.

1 Introduction

The GSFC VLBI Analysis Center is located at NASA's Goddard Space Flight Center in Greenbelt, Maryland. It is part of a larger VLBI group which also includes the IVS Coordinating Center, the CORE Operation Center, a Technology Development Center, and a VGOS station. The Analysis Center participates in all phases of geodetic and astrometric VLBI analysis, software development, and research. We provide several services and maintain several important data and information files for IVS and the larger geodetic community. These services include an atmospheric pressure loading service, a hydrology loading service, a nontidal ocean loading service, a ray tracing service, and an ECMWF meteorological data service. Data and information files include VMF1/VMF3 TRP files for every IVS session, the IVS Source Name Translation Table, various station information files, a file of source and station apriori's, a mean gradients file, a JPL planetary ephemeris file for *Calc/Solve/νSolve*, and several other files.

1. NVI, Inc./NASA Goddard Space Flight Center
2. NASA Goddard Space Flight Center

GSFC Analysis Center

IVS 2017+2018 Biennial Report

2 Staff

The Analysis Center staff consists of one GSFC civil servant and six NVI Inc. employees who work under contract to GSFC. Dr. Chopo Ma, a civil servant since the late 1970s, retired in September 2017. Dr. Leonid Petrov joined the group in September 2018 as a civil servant and the VLBI Lead Scientist. Dr. John Gipson is the GSFC VLBI Project Manager for NVI as well as the IVS Analysis Coordinator and an IVS Directing Board member. Other NVI analysis personnel include Dr. Daniel MacMillan, Dr. David Gordon, Dr. Karine Le Bail, Dr. Sergei Bolotin, and Ms. Karen Baver.

3 Analysis Activities

The GSFC VLBI Analysis Center analyzes all IVS sessions using the *Calc/Solve/νSolve* system, and performs the *fourfit* fringing and *Calc/Solve/νSolve* analysis of the VLBA-correlated RDV and other VLBA sessions. The group submitted analyzed databases to IVS for all R1, RV, R&D, AUST, AUG, AOV, AUA, APSG, CRF, CRDS, C17, V17, INT01, and INT03 sessions. During 2017/2018, GSFC analyzed approximately 375 24-hour IVS sessions and approximately 745 one-hour UT1 sessions (INT01, INT02, and INT03). Updated EOP and daily Sinex files were submitted to IVS immediately following analysis.

During 2018, the GSFC group led the transition from the old Mark3 database file system to the new vgosDB format within IVS. Currently all IVS correlators use the new format for database submission, and most other IVS Analysis Centers have now also switched to the vgosDB format.

4 Research Activities

- Third Realization of the International Celestial Reference Frame (ICRF3): Two NVI personnel (D. Gordon and S. Bolotin) actively participated in the generation of ICRF3 as members of the IAU ICRF3 Working Group. D. Gordon managed the data set used by the working group and generated two of the three ICRF3 catalogs. These included the X/S band catalog with 4,536 sources and the K-band catalog with 824 sources. This work included scheduling and processing of 22 VLBA astrometry sessions which were used to significantly improve ICRF3.
- Galactic Aberration: D. MacMillan, as chair of the IVS Galactic Aberration Working Group, investigated the estimation of the solar acceleration vector by many global solutions. He wrote a final report of the Working Group for IVS and made a presentation summarizing this report at the 2018 IVS General Meeting. He and the Working Group also wrote a paper on their results and will submit it to Astronomy and Astrophysics in early 2019. Using the ICRF3 data set, a galactocentric acceleration constant of 5.8 μas/yr in the direction of the galactic center was estimated and this value was adopted by the ICRF3 Working Group. This acceleration vector was within 8° (less than a 2-sigma deviation) of the direction of the galactic center.
- Gravitational Deformation: J. Gipson studied the effect of gravitationally induced deformation of VLBI antennas. Searching the literature he found models for Effelsberg, Gilcreek, Noto, Medicina, Onsala60, and Yebes40m, with the change in path lengths ranging from 2.5 mm (Gilcreek) to 100 mm (Effelsberg). He modified *Solve* to include the effects of these gravitational deformation models. *Solve* uses a table of the change in delays as a function of elevation angle, and uses spline-fitting to calculate delays at intermediate values. The dominant effect is a change in the estimate of the local Up component.
- High Frequency EOP: J. Gipson is chairing an IERS Working Group on HF-EOP. The goals of this Working Group are to recommend a replacement for the current IERS model, which is $\sim$20 years old. The new model will be used for ITRF2020. He gathered ten different HF-EOP models and put them in a common format. He also wrote software to calculate the predicted HF-EOP. As of the end of 2018, tests done using VLBI and GPS data indicate that the two best models are one based on TPX 8 altimetry data by Desai & Sibois, and an empirical model based on VLBI data by Gipson. The Working Group expects to make a final recommendation by June 30, 2019.
- EOP and TRF Scale from CONT Campaigns: D. MacMillan investigated the precision of EOP and scale from the CONT campaigns and found that these precisions have improved by more than a factor of two since 2002. CONT precision is significantly better than the R1 and R4 sessions, most likely because the same network is used continuously for all 15 days of each CONT campaign. Simulations showed that the expected precision with future VGOS networks should improve by a factor of 2–3 relative to current CONT precision. A paper discussing this investigation was published in the Journal of Geodesy in 2017.
- Source Declination Bias: D. MacMillan worked with L. McCallum (Univ. Tasmania) to develop an approximate model to correct for possible azimuthal errors at the KATH12M and HOBART12 antennas, based on the azimuthal dependence of phasecal group delays. The model removed about 75% of the declination bias observed between source positions estimated with data through 2017 versus ICRF2 source positions. The bias reached a maximum of about 90 μas at a declination of about -20° to -30° However, this correction was not used for ICRF3, because it increased the difference between the VLBI and Gaia positions, and it was believed that ICRF2 actually had a bias produced by galactic aberration.
- Geodyn VLBI Solution: D. MacMillan worked with F. Lemoine (GSFC) and D. Pavlis (U. Maryland) to validate VLBI processing with the new version of *Geodyn* by analyzing the 15-day CONT14 campaign. They found reasonably close agreement between EOP, wet zenith delays, and station position estimates from *Calc/Solve* versus *Geodyn* solutions. But there were some biases between some of the station position time series, which will require some further investigation.
- VGOS CONT17 Campaign: The GSFC group analyzed the VGOS CONT17 broadband sessions. Their analysis revealed the effects of source structure in the group delay residuals. To take this ef-

fect into account, S. Bolotin developed a multi-point source structure model and implemented it in *νSolve*.

- Source Work: We continued to monitor the proposed 195 Gaia transfer sources and observed the 30 weakest in R&D sessions. K. Le Bail selected sources for the CONT17 Legacy-1 network based on minimum fluxes, success rates, and structure indices. Lastly, the IVS Source Name Translation Table was maintained and updated numerous times, with a flag being added to indicate the source of the J2000 names.
- Source Noise Study: K. Le Bail collaborated with the Bordeaux Observatory and the Paris Observatory on using the Allan variance to study source time series. She also used the Allan variance to determine if different observation networks impacted the determination of source stability. And she developed a tool to compute the noise floor of source position time series using the Allan variance.
- INT01 Scheduling Improvement: K. Baver, with others, investigated INT01 scheduling improvement. She finished testing of the "BA 50" strategy of using 50 sources chosen to balance source strength and sky coverage (with J. Gipson), used new *Sked* algorithms to re-distribute the sources chosen for observing (with Gipson), evaluated the effect of source flux catalog latency (with Gipson and D. MacMillan), investigated improving the scheduling of Svetloe Intensives (with D. Behrend), and investigated mitigation of observing with a warm receiver (with E. Himwich). Baver also supported the start of the NEOS Operation Center's use of the BA 50 strategy.
- NVI, Inc. hosted four summer interns from Chalmers University during 2017 and 2018. In 2017, Johanna Renman and Sara Hällgren took different approaches to modeling the residual nutation estimates using techniques such as sliding least-squares, Kalman filtering, and ARIMA. Their goal was to see if we could come up with an a priori model of nutation for use in Intensive sessions. In 2018, Martin Henoch worked on Python codes to calculate atmospheric pressure loading using data from a coupled ocean-atmosphere model developed at GFZ to account for ocean bottom pressure changes due to the atmosphere. Also in 2018, Tilda Sikström worked on gathering gravitational deformation models from the literature. She found that these models could be well approximated by cubic splines and this has since been incorporated into the latest version of *Solve*.

5 Software Development

The GSFC VLBI Analysis Center develops and maintains the *Calc/Solve* analysis system, a package of ∼120 programs and 1.2 million lines of code. Several new versions were released in 2017 and 2018. An important new feature of *Solve* is the ability to estimate a galactic aberration constant.

S. Bolotin continued development of *νSolve* and the *vgosDB* software and utilities. *νSolve* is now fully operational and replaces the legacy interactive *Solve* program. These utilities as well as *νSolve* are distributed in one package, called "nusolve" and are available at https://sourceforge.net/projects/nusolve.

6 Publications

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D. Gordon, 'Impact of the VLBA on reference frames and earth orientation studies', J. Geodesy, 91:735-742, 2017. doi 10.1007/s00190-016-0955-0.

K. Le Bail, D. Gordon, J. M. Gipson, D. S. Macmillan, 'Investigating the noise floor of VLBI source positions', in Proceedings of the 23rd European VLBI Group for Geodesy and Astrometry, 2017, p. 186-189.

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L. McCallum, D. Mayer, K. Le Bail, M. Schartner, J. McCallum, J. Lovell, O. Titov, F. Shu, S. Gulyaev, 'Star Scheduling Mode—A New Observing Strategy for Monitoring Weak Southern Radio Sources with the AuScope VLBI Array', in Publications of the Astronomical Society of Australia, 34, 2017. doi:10.1017/pasa.2017.58.

IAA VLBI Analysis Center 2017–2018 Biennial Report

Elena Skurikhina, Sergei Kurdubov, Vadim Gubanov, Svetlana Mironova, Alexey Kudelkin

Abstract This report presents an overview of the IAA VLBI Analysis Center activities during 2017 and 2018, its current status, and its future plans.

1 General Information

The IAA IVS Analysis Center (IAA AC) operates at the Institute of Applied Astronomy of the Russian Academy of Sciences in St. Petersburg, Russia. The IAA AC contributes to IVS products, such as daily SINEX files, TRF- and CRF-solutions, rapid and long-term series of EOP and tropospheric parameters, which are obtained from the IVS observational sessions. The IAA AC also converts NGS files from Mark III DBH (beginning from version 3). We stopped submitting NGS files to IVS because IVS started using the VGOS format since the middle of 2018. The IAA AC has started to convert NGS files from the VGOS format since the end of year 2018 for QUASAR and OCCAM/GROSS software usage. Besides IVS VLBI data, IAA AC processes domestic observations produced by both the RT-32 radio telescopes (SVETLOE, ZELENCHK, and BADARY) and the RT-13 VGOS radio telescopes (ZELRT13V, BADRT13V, and SVERT13V).

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2 Activities during the Past Years

During 2017 and 2018, the IAA AC analyzed the data of IVS and domestic observations and made some investigations.

2.1 Rapid Analysis

In 2017 and 2018, the IAA AC continued to generate daily SINEX (DSNX) files from the analysis of IVS-R1 and IVS-R4 sessions using QUASAR software. Some delay in operational data analysis was due to the IVS transition to the new VGOS data format. DSNX files were submitted to the IVS for combination with the results of other Analysis Centers. The IAA AC processed the 24-hour and Intensive VLBI sessions using OCCAM/GROSS software and submitted the results to IERS and IVS on a regular basis.

2.2 Global Solution

Several celestial reference frame (CRF) solutions have been calculated with the QUASAR software. The latest CRF catalog, submitted for the ICRF3 prototype research, contains 4,466 radio sources with three or more observations. It was calculated from analysis of 6,202 daily VLBI sessions (13,093,744 observational delays) observed from 1980 through March 2018.

A new global solution was calculated using 5,713 sessions from April 1979 through December 2018. A total of 11,107,906 delays were processed. The stochastic parts of the signals (for WZD and clock offsets) were estimated using the least-squares collocation technique (LSC). The radio source coordinates, station coordinates, and velocities were estimated as global parameters. EOP, troposphere gradients, and polynomial coefficients for WZD and station clocks were considered as arc parameters for each session. We prepared a new source position catalog iaa2019a.crf for 4,214 sources and a station position and velocity catalog iaa2019a.trf for 214 stations.

2.3 Data Analysis from Domestic VLBI Observations

The IAA Analysis Center processes all the observational data of domestic VLBI programs RuE, RI, R, and test sessions. Table 1 presents the main types of Russian domestic sessions at X/S range. The standard IVS designation of the stations is used in the table: Sv – Svetloe, Zc – Zelenchukskaya, and Bd – Badary for RT-32 and Bv – Badary, Zv – Zelenchukskaya, and Sw – Svetloe for RT-13. Test 0.5-hour sessions named RX over the S/X/Ka range were performed once a day as a rule, on the baseline BvZv.

Observational data from all these sessions are transmitted to the correlators using e-VLBI data transfer. The processing of RI sessions is fully automated. The calculated UT1-UTC time series is available at [1]. The EOP time series calculated from RuE data is available at [2].

In 2017 and 2018, 78 RuE and 735 RI sessions were observed. During 2017–2018 the new Badary-Zelenchukskaya VGOS radio interferometer observed 2,687 R domestic program one-hour sessions. For the R sessions, the dUT1 RMS with respect to IERS series finals.dat is about 35 μs.

Coordinates for the new radio telescopes (ZELRT13V and BADRT13V) were improved from the set of 22 series of 24-hour sessions on the five station network SVETLOE, ZELENCHK, BADARY, ZELRT13V, and BADRT13V. The SVERT13V positions were improved from one six-station session on November 22, 2018. The results are given in Table 2. RT-13 station velocities were fixed for the solution by the values from ITRF2014 for corresponding RT-32 antennas.

Table 2 RT-13 station positions at 2010.0 epoch.

Station	ZELRT13V	BADRT13V	SVERT13V
X, m	3451257.389	-838326.608	2730074.965
	± 0.001	± 0.002	± 0.001
Y, m	3060268.147	3865797.208	1562230.721
	± 0.003	± 0.003	± 0.010
Z, m	4391933.204	4987598.308	5530072.747
	± 0.004	± 0.004	± 0.010

2.4 UT1 Series Combination from Set of IVS Intensive Sessions

Our first attempt to combine IVS Intensive SINEX files using SINCOM software [3] has been made. A series of UT1 was built for 385 IVS Intensive 2017–2018 sessions. BKG, GSF, IAA, and USNO SINEX files were used. The RMS, after removal of the bias of the difference between the computed UT1 series and IERS C04, is 32 μs, with finals.dat - 20 μs. The difference between the combined UT1 series with C04 and finals is shown in Figure 1.

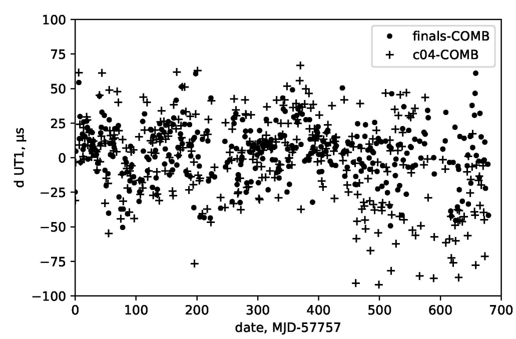

Fig. 1 The difference between the combined UT1 and IERS series (C04 and finals).

2.5 Covariance Functions for Stochastic Signals for LSC on Hourly Intervals

Covariance functions are used in the processing of VLBI measurements to determine the stochastic sig-

Table 1 Domestic X/S range session description.

Program	RI	RuE	R	RI(RT13)
Network	BdZc(Sv)	SvZcBd	ZvBv(Sw)	ZvBv
Duration, hours	1	24	1	1
Aim	dUT1	EOP	dUT1	dUT1
Turn-around time, hours	2	120	2–6	2–6
Schedule	daily	weekly	3–7 times a day	daily
Start time, UT	20:00	Fri, 20:00		20:00
Scan duration, s	22-127	60	10	22-127
Sources set	150 (>0.25 Jy)	60 (>0.5 Jy)	156	150 (>0.25 Jy)
Sour.number per session	20	50	60	20
Sampling, bit	1	1	2	1
Bandwidth, MHz	8	8	512	512
Data rate, Mbit/s	256	256	2048	2048
Scan number	25	350	120	25
Number of observations	25	1000	45–120	25
Correlator	IAA ARC	IAA ARC	RASFX, DiFX	RASFX, DiFX

nals of clock offset and troposphere delay (WZD) with the QUASAR software. Average covariance functions for WZD were constructed from the data of the Badary station Water Vapor Radiometer. The clock covariance function was constructed from the data analysis of the clock offsets. The parameters of the function used by the QUASAR software were refined according to the results of VLBI session processing from 1980–2018. In the left part of Figure 2, the covariance functions of the troposphere are presented over the daily and hourly intervals (the bottom and the upper part of the figure, respectively). The covariance functions of the clock (the right-hand picture) at the daily and hourly intervals (the bottom and the upper part of the figure, respectively) are shown below.

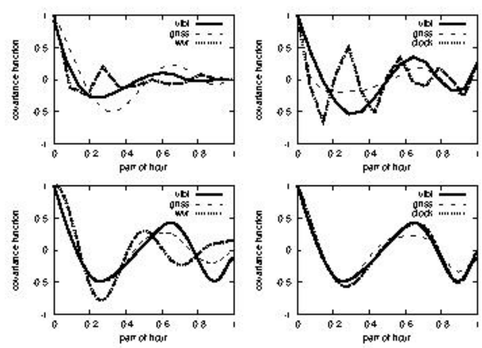

Fig. 2 Covariance functions for WZD (left column plots) and clocks (right column) over hourly (upper row) and daily (bottom row) intervals.

2.6 Intensive Session Scheduling Study

Studies aimed at improving the scheduling for the Intensive sessions were made. A new improved algorithm for the covariance matrix optimization strategy was proposed. The numerical simulations were performed in order to compare the algorithm proposed with the algorithms implemented in the Sked software [5] and VieVS (The Vienna VLBI and Satellite) software [6]. It was shown that, using the improved algorithm, one can obtain better variance of the ΔUT1 parameter.

3 Current Status

The IAA AC processes the data of all kinds of VLBI geodetic observation sessions. We use the QUASAR and the OCCAM/GROSS types of software for VLBI data analysis. All the observation models in these packages conform to the IERS Conventions (2010). Both packages use NGS files as input data. The QUASAR and the OCCAM/GROSS software packages are supported and are being developed. Some modifications were made to QUASAR and OCCAM/GROSS.

The IAA AC staff are:

- Sergey Kurdubov: the development of the QUASAR and the analysis software.
- Prof. Vadim Gubanov: the development of the QUASAR software and the methods of stochastic parameter estimation.
- Elena Skurikhina: the team coordination; VLBI data processing, and OCCAM/GROSS software development.
- Svetlana Mironova, PhD Student: the development of the QUASAR software, VLBI data processing, global solution and DSNX file calculation, data combination with SINCOM software.
- Alexey Kudelkin, PhD Student: the development of the new technique of scheduling VLBI observations.

4 Future Plans

- To continue submitting all types of IVS product contributions.
- To continue investigations of EOP, station coordinates, and tropospheric parameter time series.
- To improve algorithms and software for processing VLBI observations.
- To continue studying in the field of improving the scheduling technique.

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Italy INAF Analysis Center

Monia Negusini, Roberto Ricci, Matteo Stagni

Abstract This report summarizes the activity of the Italian INAF VLBI Analysis Center. Our Analysis Center is located in Bologna, Italy and belongs to the Institute of Radio Astronomy (IRA), which is part of the National Institute of Astrophysics (INAF). IRA runs the observatories of Medicina and Noto, where two 32-m twin VLBI AZ-EL telescopes are located. This report contains the AC's VLBI data analysis activities and illustrates the latest experiments, involving the Italian antennas and correlator, carried out in the last two years.

1 Current Status and Activity

Following the installation of the software correlator DiFX in 2012 in Bologna, there were a number of experiments to test the correlation pipeline for geodesy. These VLBI experiments were performed mainly on the single baseline Medicina–Noto and subsequently extended to Matera after seeking a collaboration with ASI, who manages the antenna facility. The VITA (ITAlian Vlbi network) project was launched as a national pilot project, obtaining observing time at the stations. We obtained first successful fringes on the three baselines in April 2015, and carried out five 24-hour experiments until the end of 2018.

In these last years the group was involved in the LIFT (Italian Link for Frequency and Time) project in collaboration with INRIM (National Institute of Metrology), which set up a distributed time and frequency optical link in Medicina. VLBI tests in a geodetic setup were performed, to verify the accuracy and reliability of their solution compared to standard maser clock timing in use at the antenna. After the first VLBI experiment, during EUR137 in 2015, VITA experiments were set up to try to solve the issues raised after the first tests. There were updates to the INRIM system in Medicina, so the infrastructure has become much more reliable. A detailed description of the optical fiber link is provided in [1] and [2]. Results of this test are published in [3].

In November 2018, the Matera antenna was connected to the distributed time and frequency link, thanks to the new founded MeTGeSp (Metrology for Geodesy and Space) project. The link serves the Milan Financial District, the Medicina observatory, the Italian Laboratory for Non-linear Spectroscopy (LENS) in Florence, and the Telespazio Facility in the Fucino Plain, where one of the main stations of the European Galileo satellite network for global navigation is located to reach finally the Matera fundamental geodetic station.

Moreover, a new type of experiment (Timing VLBI) was carried out with the aim of comparing the synchronicity of atomic clocks located at a few European stations (Medicina, Noto, Yebes, Torun, and Matera) by means of the interferometric phase RMS noise statistics. VLBI clock timing should be a valid alternative to satellite-based techniques such as the Global Navigation Satellite System or the Two-Way Satellite Time and Frequency Transfer. First results were presented at the IVS 2018 General Meeting.

The presence of the LIFT infrastructure linking Medicina to Turin, where an optical clock was developed, allowed the installation of a Japanese small an-

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tenna (NICT's Marble 2.4-m antenna) with the aim of comparing optical clocks at intercontinental scale via VLBI.

2 Data Analysis and Results

The IRA started to analyze VLBI geodetic databases in 1989, using the CALC/SOLVE package on an HP workstation, first located at the Medicina observatory and later at the Bologna headquarters. Since 2007, Linux workstations have been set up for the migration of all the VLBI data analysis, and the CALC/SOLVE software was installed. During the last years, our Analysis Center had some internal problems and we did not participate regularly in IVS activities. However, we continued to update the catalog and we installed and tested the latest releases of CALC/SOLVE and νSolve.

3 Outlook

We hope that in the next few months, we will start contributing again to IVS activities, submitting INAF tropospheric parameters to the IVS Data Center, regularly. We will also produce an updated long-term geodetic solution.

In 2019, a VITA experiment with a remote common clock, delivered by INRIM at both Medicina and Matera stations, will be performed, involving other European VLBI antennas.

Further VLBI timing experiments will be performed, with local or remote clocks, to exploit this promising technique.

In the framework of the collaboration between NICT - INRIM - INAF, observations collected with the small Japanese antennas will be analyzed as feedback analysis for the clock comparison project.

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KTU-GEOD IVS Analysis Center Biennial Report (2017-2018)

Emine Tanır Kayıkçı [1], Kamil Teke [2], Mehmet Fikret Öcal [2], Özge Karaaslan [1]

Abstract This report summarizes the activities of the KTU-GEOD IVS Analysis Center (AC) in 2017 and 2018 and outlines the planned activities for the years 2019 and 2020. Accuracy improvement of UT1-UTC through using a priori GNSS troposphere gradients when analyzing VLBI observations of Intensives was our specific interest in this period.

1 General Information

In 2018, a research project related to accuracy improvement of UT1-UTC determination from IVS [1] Intensive sessions was successfully finalized. This project also constitutes one of the main parts of the MSc thesis of Mr. Mehmet Fikret Öcal [2]. He successfully defended his MSc thesis under the supervision of Dr. Kamil Teke on 31 May 2019 (see Figure 1).

The Geodesy Lab at Hacettepe University was equipped with two high-performance workstations running on Linux (Ubuntu 16.04, LTS: Long Term Support) that are dedicated to VLBI and GNSS automatic analysis. The analyses on these workstations are performed automatically using VieVS (Vienna VLBI and Satellite Software, [3]) and Bernese Software [4]. Automatic analyses are carried out on a daily basis, and corresponding products are published on the Hacettepe University Web servers [5].

1. Karadeniz Technical University, Department of Geomatics Engineering
2. Hacettepe University, Department of Geomatics Engineering

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Fig. 1 A photo after the successful defense of Mehmet Fikret Öcal's MSc thesis with the examiners.

2 Staff at KTU-GEOD Contributing to the IVS Analysis Center

Members of KTU-GEOD IVS Analysis Center (AC) are listed in Table 1 (in alphabetical order) with their main focus of research and work location [6, 7]:

3 Current Status and Activities

During the report period, we focused on accuracy improvement of UT1-UTC determination from the analysis of IVS Intensive sessions using a priori GNSS troposphere gradients. IVS suggested an analysis procedure that covers the estimation of the azimuthally symmetric part of the troposphere delays (i.e., zenith wet delay [ZWD] and zenith hydrostatic

Table 1 Staff of the KTU-GEOD Analysis Center.

Name	Work Location	Main Focus of Research
Emine Tanır Kayıkçı	Karadeniz Technical Univ., Dept. of Geomatics Eng., Trabzon, Turkey.	responsible person for AC, parameter combination
Kamil Teke	Hacettepe Univ., Dept. of Geomatics Eng., Ankara, Turkey.	troposphere
Mehmet Fikret Öcal	Hacettepe Univ., Dept. of Geomatics Eng., Ankara, Turkey.	data analysis, signal processing
Özge Karaaslan	Karadeniz Technical Univ., Dept. of Geomatics Eng., Trabzon, Turkey.	data analysis, parameter estimation

delay [ZHD]). However, according to IVS standard analysis procedure, troposphere gradients, which have significant effect on UT1 determination, are not estimated [8]. The International GNSS Service (IGS) [9] is providing troposphere gradients from the analysis of GNSS observations for five minute intervals from 01.01.2008 onward with three weeks latency through FTP archives. We reduce troposphere gradients derived from the observations of GNSS sites co-located with VLBI stations from the observations of Intensives a priori to the parameter estimation. We have tested two different analysis strategies in addition to IVS standard analysis (A1): analysis-2 (A2) reduces troposphere east and north gradients from the observations, and analysis-3 (A3) estimates troposphere gradients additionally to A2. Thus, we analyzed all IVS Intensive sessions (INT1, INT2, and INT3) with three different analysis strategies as well as IVS-R1 and IVS-R4 sessions as a reference UT1-UTC series (see Figure 2) from the beginning of 2008 to the end of 2018. Statistical comparisons between the estimates of the Intensives (A1, A2, and A3) and standard sessions (IVS-R1 and IVS-R4) over weighted-root-mean-square (WRMS) of differences (see Table 2) showing slight differences led us to evaluate our new analysis methods over length-of-day (LOD) variations instead of UT1.

The IGS analysis centers, such as ESA/ESOC, NASA/JPL, and NOAA/NGS, are publishing Length-of-day (LOD) estimates online. LOD observations of GNSS are assumed to be more accurate than those of VLBI [9]. Thus, our LOD values calculated from

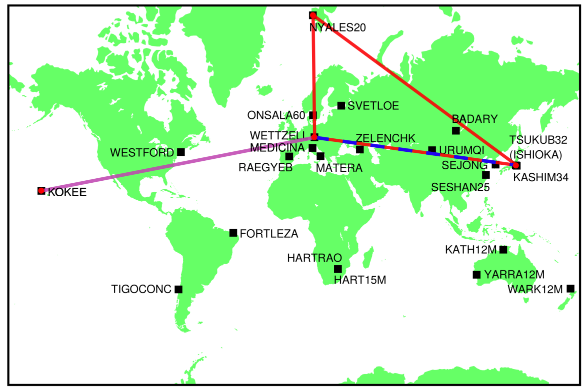

Fig. 2 VLBI stations mostly participating in IVS-R1 and -R4 sessions (black squares) as well as Intensives (red dots). INT1, INT2, and INT3 baseline vectors are plotted as purple, blue (dashed) and red lines, respectively.

Table 2 WRMS of differences of UT1 estimates from INT1 sessions and from R1 and R4 sessions.

Analysis	WRMS of UT1 differences in µs INT1 Sessions (548 UT1 pairs)
StandardUT1(A1)-R1R4	±38.0
NewUT1(A2)-R1R4	±37.7
NewUT1(A3)-R1R4	±38.8

UT1 estimates of IVS Intensives are compared with the LOD provided by the IGS analysis centers. These comparisons, as seen in Table 3, show that our analysis strategies, especially A2, improve the UT1-UTC estimation accuracy from IVS Intensive sessions by about 2–3 µs/day.

Table 3 WRMS differences of the LOD estimates of the analysis centers ESA(ESOC), NASA(JPL), and NOAA(NGS) with INT1 sessions in µs/day. Analysis-1, Analysis-2, and Analysis-3 series have the same epochs (1,610 values considered).

	StandardUT1(A1)	NewUT1(A2)	NewUT1(A3)
ESA/ESOC	± 34.2	± 31.6	± 33.7
NASA/JPL	± 36.9	± 34.1	± 36.2
NOAA/NGS	± 37.6	± 35.6	± 36.6

IGS troposphere zenith signal delays and gradients have been determined at five minute intervals from the analysis of the observations of hundreds of GNSS stations around the world with the PPP technique [10] using modified Bernese software [4] by the GNSS analysis center at the United States Naval Observatory (USNO) every day from July of 2011. Besides, we started to produce GNSS troposphere delays and gradients using the Bernese software with similar analysis parametrization in the scope of our research project.

4 Future Plans

In 2019 and 2020, we will be working on testing the accuracy of UT1-UTC that is observed by IVS Intensives. We will use our own GNSS troposphere delay estimates for incorporation into the analysis of Intensive sessions in addition to those of IGS. This will give us the ability to compare our troposphere gradients with those derived from IGS. A new subroutine for producing troposphere delays from PPP observation model as an alternative to Bernese software is planned to be built.

Acknowledgements

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NICT VLBI Analysis Center Report for 2017–2018

Mamoru Sekido

Abstract The VLBI analysis activities at NICT focus on the development and application of broadband VLBI for precise frequency comparisons. A pair of small diameter broadband VLBI stations and a high sensitivity antenna have been jointly used to derive broadband group delays between the small antenna pair by using the closure delay relation ('Node-Hub'–style VLBI). This Node-Hub–style VLBI was verified in domestic experiments for frequency comparisons between NMIJ and NICT. Then one of the small antennas was transported to Medicina station in Italy in 2018, and VLBI experiments for optical clock comparisons have started.

1 General Information

The Space-Time Standards Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT) has been conducting broadband VLBI system development for application to intercontinental precise frequency comparisons. The VLBI group of NICT is working at the Kashima Space Technology Center, where two radio telescopes, Kashima 34-m and Kashima 11-m, are located. We developed a broadband VLBI system named GALA-V [1], which has a similarly broad observation frequency range (3.2–14 GHz) as VGOS [2]. Unique features of our data acquisition system utilize the originally developed broadband 'NINJA' feeds and the RF-Direct sampling with a 16-GHz sampling rate and following digital filtering. Additionally, Node-Hub–style VLBI [4], which utilizes group delay observables between a small antenna pair using the closure delay relation, is a challenging approach for geodetic VLBI and frequency transfer.

This report describes the activities of the VLBI analysis in NICT's VLBI group, focusing on the analysis for geodesy and frequency transfer with the broadband VLBI system.

2 Component Description

NICT is in charge of keeping and supplying national Japanese Standard Time (JST) and standard frequency traceable to the 'second' of the International System of Units (SI). The current definition of the 'second' of time is made by using the microwave emission of the Cs atom. This is expected to be replaced by a new definition using a more accurate optical frequency emission of a certain kind of atom in the near future [5]. Several kinds of atoms are investigated as candidates for the new definition. Then, an accurate frequency comparison technique between different optical frequency standards is required, especially one that can be used over intercontinental distances. Based on this background, the VLBI application for frequency transfer is the mission of the VLBI group at NICT. The observation scheme of a VLBI session for clock comparison is basically identical to a standard VLBI session for geodesy. We have decided to use transportable, small-diameter telescopes as nodes for the frequency comparison; they need to be installed at a metrological institute

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where an optical frequency standard is operated as the subject of comparison.

Here, a VGOS-like broadband VLBI system brings two benefits: 1) enhancement of the signal-to-noise ratio (SNR) by an increased number of samples, and 2) improvement in precision of group delay measurement via one order wider observation frequency range with respect to conventional VLBI system using S/X band receivers. The correlation amplitude of VLBI is proportional to the geometrical mean of the aperture area of two antennas. Thus, the combined use of a small antenna with a high sensitivity antenna enables the small antenna to function as a node of an interferometer. Due to the increased SNR and delay precision, a transportable small VLBI station can be used as the node for frequency comparisons on intercontinental baselines.

The GALA-V [1] system acquires four channels at 1-GHz bandwidth. Cross-correlation processing and post-processing (fringe-fitting) of the broadband VLBI data is made by the GICO3 [6] software correlator and the wideband bandwidth synthesis software 'komb' [7], respectively. The derived delay observable and auxiliary data are stored in a Mk3 database using MK3TOOLS [8]. VLBI data analysis has been made with CALC Ver. 11.01 and SOLVE Ver. 2014.02.21 developed at NASA/GSFC.

3 Staff

Members who are contributing to the Analysis Center at NICT are (in alphabetical order):

- KONDO Tetsuro: Development of broadband bandwidth synthesis software 'komb'.
- SEKIDO Mamoru: Coordination of broadband VLBI observations and in charge of data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Maintaining and operating the correlation software 'GICO3' for broadband data processing.

4 Activities during 2017–2018

4.1 Testing GALA-V System in Domestic Network

The concept of the GALA-V project based on 'Node-Hub'–style VLBI is displayed in Figure 1. When the observed radio source is a point source, the circular sum of the time delay, which is the arrival time difference of an identical wavefront at each station, of a closed triangle becomes zero. By using this closure delay relation, the delay observable (τ_{AB}) between the small diameter antenna pair (AB) is computed by the linear combination of the delays (τ_{RA}, τ_{RB}) of the small and the large diameter baselines (RA, RB). Because the time tag of the delay is defined as the signal arrival epoch at station **X** of baseline **XY**, the closure delay is given by the following formula with better than one picosecond accuracy on any baseline on the earth:

$$\begin{aligned}
&\tau_{AB}(t_{prt}) \\
&= \tau_{RB}(t_{prt} - \tau_{RA}(t_{prt})) - \tau_{RA}(t_{prt} - \tau_{RA}(t_{prt})) \\
&\cong \tau_{RB}(t_{prt}) - \tau_{RA}(t_{prt}) - \frac{d}{dt}\tau_{AB}(t_{prt}) \times \tau_{RA}(t_{prt}),
\end{aligned} \tag{1}$$

where t_{prt} is the reference epoch of the delay data.

A transportable broadband VLBI station with a 1.6-m diameter antenna and equipped with a high speed data acquisition system was installed at the

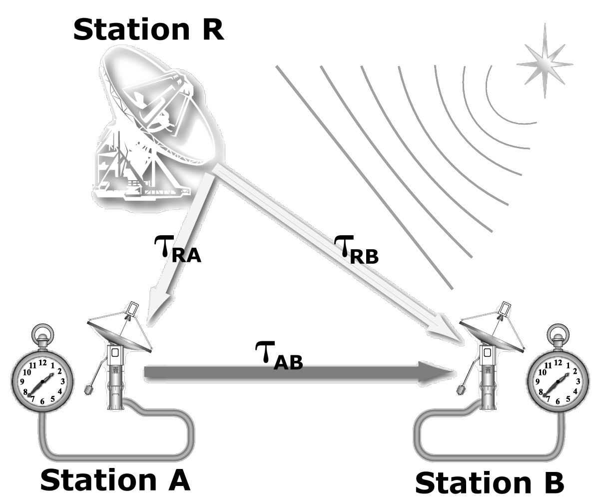

Fig. 1 The concept of the 'Node-Hub'–style VLBI by combination use of transportable, small-diameter VLBI stations and a high sensitivity antenna.

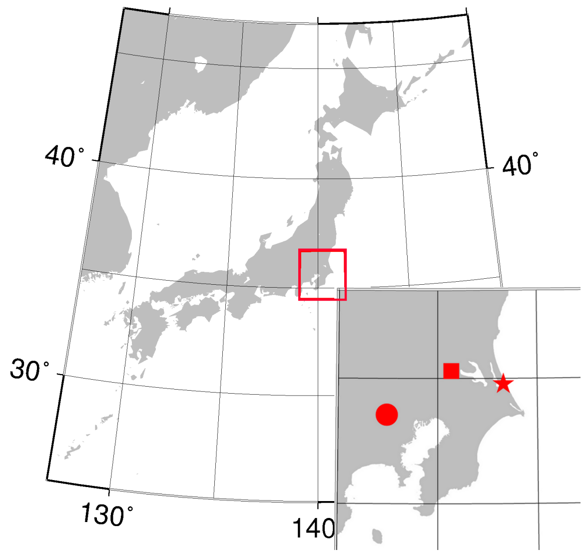

Fig. 2 Location of the small broadband VLBI stations MARBLE1 (■) at NMIJ and MARBLE2 (●) at NICT Headquarters as well as the Kashima 34-m antenna (★).

Table 1 Broadband VLBI experiments conducted in 2017–2018. Abbreviation of station names are as follows: Kas34: Kashima 34-m antenna, MBL1: MARBLE1 2.4-m diameter antenna at NMIJ, MBL2: MARBLE2 2.4-m diameter station at NICT Koganei, OTNE: Onsala Twin Telescope North East.

Session Date	Stations	No. Scans (Used/Total)	Session Length
13-14 Jan. 2017	Kas34-MBL2	110/110	21 hours
21-23 Apr. 2017	Kas34-MBL1-MBL2	1707/1722	49.5 hours
12-13 May 2017	Kas34-MBL1-MBL2	948/1210	28 hours
09-12 Jun. 2017	Kas34-MBL1-MBL2	2237/2284	64.7 hours
03-06 Jul. 2017	Kas34-MBL1-MBL2	2120/2182	70 hours
10-14 Aug. 2017	kas34-MBL1-MBL2	Failed	77.5 hours
25-28 Aug. 2017	Kas34-MBL1-MBL2	Failed	66 hours
11-13 Nov. 2017	Kas34-MBL1-MBL2	Failed	60 hours
18-20 Dec. 2017	Kas34-MBL1-MBL2	1222/1231	40 hours
22-23 Dec. 2017	Kas34-MBL1-MBL2	998/1011	30 hours
26-27 Dec. 2017	Kas34-MBL1-MBL2	1087/1175	33 hours
03-05 Jan. 2018	Kas34-MBL1-MBL2	Failed	42 hours
12-13 Jan. 2018	Kas34-MBL1-MBL2	826/864	50 hours
18-21 Jan. 2018	Kas34-MBL1-MBL2	1431/2444	69.5 hours
31-28 Jan. 2018	Kas34-OTNE	1431/2444	17 hours
27-28 Mar. 2018	Kas34-OTNE	158/199	17 hours

National Meteorology Institute of Japan (NMIJ) in Tsukuba in 2014. Another 1.5-m diameter antenna is located at NICT Headquarters in Koganei, Tokyo. These small antennas were originally designed with prime focus optics. In 2016 and 2017, these antenna systems at NICT and NMIJ were replaced by 2.4-m diameter Cassegrain focus optics.

NMIJ and NICT are the national institutes that keep the time series UTC (NMIJ) and UTC (NICT), respectively. And their time data is routinely reported to BIPM (Bureau International des Poids et Mesures). Thus, frequency comparisons between UTC (NMIJ) and UTC (NICT) are possible in multiple ways other than VLBI. For this it is a good testbed to examine the performance of our VLBI frequency link.

In March 2017, the antenna system of MARBLE1 was replaced with a 2.4-m diameter Cassegrain focus optics. A series of test VLBI sessions were conducted in 2017 as shown in Table 1. The longer the session, the better the frequency comparison. This is the reason for session lengths longer than 24 hours, which is the standard geodetic VLBI session length. In August 2017, the optical fiber cable at MARBLE2 broke. It was subsequently repaired by using a spare fiber cable. Another issue with the stability of the wideband optical RF signal transmission system occurred at MABLE1. It was mended by replacing the optical signal transmission system from a Sumitomo E18000 to a FiberOptic TX:10341C/Rx:10458E.

As described above, we are testing Node-Hub–style VLBI, which uses a delay observable derived from the linear combination based on closure delay relation. The closure delay relation is affected if the radio source has structure [9]. Since its influence becomes larger as the baseline becomes longer, it does not have a significant effect in VLBI experiments using domestic short baselines ($\leq$ 100 km). One of the benefits of the Node-Hub–style VLBI is the cancellation of the delay variation introduced by large diameter antenna. We have confirmed the benefit of the new VLBI observable approach on this baseline. The improvement of the delay residual by using this technique is described in the NICT Analysis Center report for 2015–2016 [10].

4.2 Clock Comparison between UTC (NMIJ) and UTC (NICT)

We conducted a series of experiments from 18 December 2017 to 3 January 2018 with about four days interval. A comparative evaluation of the frequency transfer performance was made between different techniques.

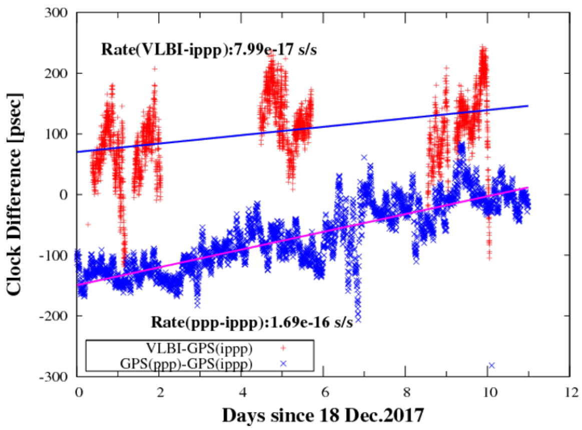

Fig. 3 Comparison of frequency techniques by double difference between VLBI–IPPP and PPP–IPPP.

Data for UTC (NMIJ)–UTC (NICT) from Precise Point Positioning (PPP) processing of GPS data is available from the FTP site of BIPM. In addition, courtesy of G. Petit and J. Leute of BIPM, frequency comparison by integer PPP (IPPP) processing of GPS data, which has a 1^{-16} precision for frequency transfer [11], was provided for the evaluation of the VLBI frequency link. Double difference data of UTC (NMIJ)–UTC (NICT) for the pairs of VLBI–IPPP and PPP–IPPP are plotted in Figure 3. This data shows that the VLBI frequency link has the potential to give a more accurate frequency transfer than PPP processing of GPS data. Phase ambiguity is a potential cause of wrong delay derivation in the case of GPS using carrier phase. Long-term stability of VLBI data in terms of clock comparison is thought to be based on the fact that VLBI uses the group delay observable instead of phase. Especially in the case of broadband VLBI, the absolute delay is obtained without ambiguity.

4.3 Other Activities

Space Geodesy Software C5++ : Space geodesy analysis software package “C5++” [12][1], was developed under multi-organization collaborations. M. Sekido is taking part in the development and keeping maintenance of the software.

MK3TOOLS : Software package MK3TOOLS is a package of platform independent VLBI database read and write software originally developed by T. Hobiger. Currently T. Hobiger at the University of Stuttgart in Germany and M. Sekido of NICT are jointly maintaining the package. MK3TOOLS is freely available from the Web at http://hg.hobiger.org/MK3TOOLS/.

5 Future Plans

We have started broadband VLBI experiments for optical clock comparisons in collaboration with the Istituto Nazionale di Ricerca Metrologica (INRiM), National Institute for Astrophysics (INAF), and NICT. Node-Hub–style VLBI using closure delay relation is tested on this over 8000-km baseline.

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Norwegian Mapping Authority Analysis Center 2017–2018 Report

Ann-Silje Kirkvik

Abstract During 2017 and 2018, the Norwegian Mapping Authority has continued the development of the analysis software **Where** that was started in 2015. The goal is to be able to use this software to analyze VLBI data and contribute to operational IVS products. Extensive testing of the software has been performed by analyzing over 20 years of 24-hour sessions and submitting the solution to the IVS Combination Center for comparison with other analysis centers. After seven submissions with intermediate corrections of detected problems, **Where** finally produced results that were comparable to other analysis centers and were ready to be included in the IVS combination. Once the quality of the results were verified, the next step was to start regular operational submissions to test timeliness and operational robustness. This activity is anticipated to continue throughout 2019.

1 General Information

The Norwegian Mapping Authority (NMA) has been an Associate Analysis Center within the IVS since 2010. The analysis center is operated by the Geodetic Institute at NMA with main offices in Hønefoss, Norway. NMA is a governmental agency with approximately 800 employees, and the IVS activities at NMA are completely funded by the Norwegian government.

NMA is using the analysis software **Where**, which is developed at NMA. The goal is to be able to use this software to analyze VLBI data and contribute to operational IVS products. **Where** is freely available as open source at GitHub[1]. Currently, the released version of **Where** can process individual VLBI sessions. **Where** relies on vgosDB version 4 as input, and, for the moment, it only supports the legacy S/X observations.

Development is underway to support SLR and various applications of GNSS data. In addition, a lot of the functionality in **Where** has been separated into a library called **Midgard**, which is also available on GitHub under the same license[2].

2 Staff

The Geodetic Institute at NMA has approximately 50 employees. Some of the responsibilities include maintaining the national reference frame, geoid, and height system. The Geodetic Institute also provides a network-RTK positioning service and operates the VLBI station in Ny-Ålesund.

The **Where** development team has lost a few members due to changes in priorities and resignations, but it has also gained some resources. The current staff is summarized in Table 1.

3 Current Status and Activities

NMA has been working on the development of **Where** since August 2015. In spring 2017, the software demonstrated the ability to calculate theoretical delays

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[1] https://kartverket.github.io/where

[2] https://kartverket.github.io/midgard

Table 1 **Where** developers and users at NMA.

Name	Tasks
Laila Løvhøiden	System owner
Michael Dähnn	GNSS developer
Mohammed Ouassou	GNSS developer
Ingrid Fausk	SLR developer
Ann-Silje Kirkvik	VLBI developer
Åsmund Skjæveland	VLBI analyst

comparable to other software packages [2]. This was done by comparing results from **Where** with results obtained in the VLBI Analysis Software Comparison Campaign 2015 [4].

By the beginning of 2018, all the building blocks needed to do a complete analysis of a VLBI session were completed, but a lot of testing and validation remained [3].

At the 10th IVS General Meeting in Longyearbyen **Where** was released as an open source software [1]. At the time there were still some problems to solve before the results obtained with **Where** were reliable, but the General Meeting seemed like a suitable arena for making the announcement. The choice of releasing **Where** as open source was twofold. For one, it would enable greater transparency about how results obtained with **Where** actually are produced. Additionally, it opens up the possibility for others outside NMA to contribute to the software.

After the General Meeting, the testing and improvement of **Where** continued. After submitting a total of six solutions to the IVS Combination Center (CCIVS), **Where** finally produced results that were ready to be included in the combination. The sixth solution contained all 24-hour sessions from the beginning of 2002 to the end of 2017.

However, the abrupt hardware failure of some critical components in the IVS production chain forced the transition from NGS file format to the vgosDB format for the VLBI observables. All submitted solutions up to this point were based on the NGS file format. Therefore, to test the vgosDB format a seventh solution was analyzed and submitted to the CCIVS. The seventh solution contained all 24-hour sessions from the beginning of 1994 to the end of 2018.

With the exception of some differences in the quality code flag for some observations for some older sessions, the vgosDB data seemed to produce the same results as the NGS files. There were also some larger differences compared to the combined solution in the parameter estimates for the older data (1994–2002) that was only included in the latest solution (Figure 1). This should be investigated further. One possibility is that the same parameterization was used for the whole dataset regardless of session geometry and might have an effect on the results before and after R1s and R4s were introduced in 2002.

However, for newer sessions **Where** v0.16.2 and higher seems to produce results that can be included in the IVS combination. The statistics of the Earth Orientation Parameters (EOP) for the seventh solution are summarized in Table 2, and Figure 1 shows the value of UT1–UTC compared to the combination for the same solution.

In relation to the new antennas being built in Ny-Ålesund [5], NMA and IGN (Spain) have a “Memorandum of Understanding” where IGN develops the broadband receivers for the new antennas and NMA provides the analysis software **Where** and some training to IGN. In November 2018, four people from IGN visited NMA in Oslo, and a VLBI analysis workshop with **Where** was held for five days (Figure 2). IGN also plans to use **Where** to become an analysis center.

4 Future Plans

With the promising results from the testing period, NMA is now ready to try to contribute to the operational analyses. The submission of regular timely analyses of R1 and R4 sessions will start at the beginning of 2019. NMA also plans to contribute to the next realization of the international terrestrial reference frame (ITRF2020).

The development of **Where** will also continue. Some possible extensions are to support analysis of VGOS data, support vgosDB version 1, provide better support for analysis of Intensive sessions, support estimation of global solutions across multiple sessions, support different estimators, or to look into further automation of the analysis. It is still not decided which of these tasks should be prioritized.

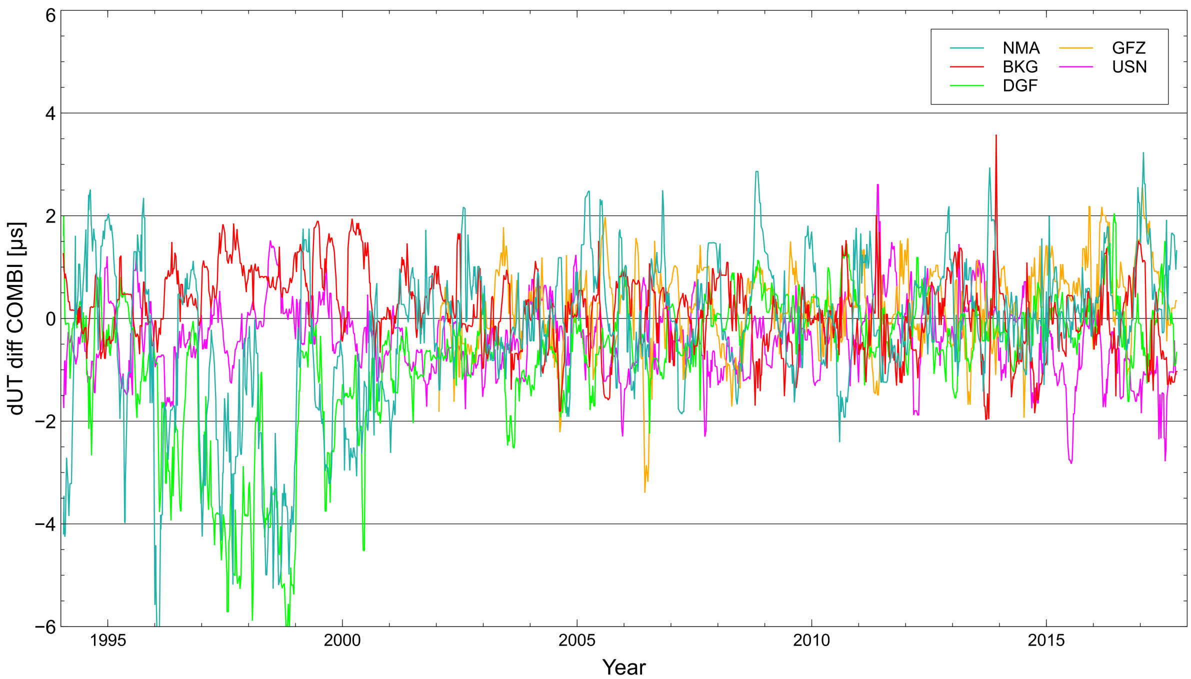

Fig. 1 Difference between UT1–UTC and the combined solution for different analysis centers from the seventh solution. Provided by Sabine Bachmann, BKG.

Fig. 2 Workshop with IGN (Spain) at NMA offices in Oslo in November 2018. From the left: Ann-Silje Kirkvik, Susana Garcia Espada, Yaiza Gómez Espada, Victor Puente, and Esther Azcue. Photo: Geir Arne Hjelle.

Table 2 Statistics for a combined solution of the EOP parameters: Polar motion (x_p, y_p), Polar motion rate $(\dot{x}_p, \dot{y}_p)$, UT1–UTC, Length of Day (LOD), and Celestial Pole Offset (dX, dY). Provided by Sabine Bachmann, BKG.

AC	WRMS	RMS	Offset	Offset σ	Rate	Rate σ	WRMS	RMS	Offset	Offset σ	Rate	Rate σ
	x_p [μas]						y_p [μas]					
COMBI	85.482	147.797	4.996	2.005	-3.899	0.257	84.872	137.949	17.215	1.904	0.624	0.253
BKG	104.468	167.126	12.367	2.247	-4.980	0.301	102.267	159.001	19.341	2.140	0.880	0.293
ASI	93.082	154.545	10.131	2.057	-4.881	0.270	90.687	141.814	23.470	1.888	1.091	0.256
DGFI	64.588	178.511	36.369	2.256	-5.143	0.305	57.148	141.185	0.466	1.977	-0.715	0.270
GFZ	100.864	171.606	8.712	2.367	-7.669	0.454	99.952	173.951	13.286	2.283	0.075	0.454
GSFC	89.657	144.076	14.993	2.029	-5.319	0.267	89.160	138.541	21.088	1.885	0.737	0.257
IAA	105.975	162.680	24.609	3.179	-4.749	0.403	105.060	150.436	21.690	2.772	3.429	0.358
NMA	112.984	234.652	21.267	2.385	-6.474	0.336	113.388	414.675	15.222	2.295	-0.391	0.337
OPA	90.188	150.517	11.564	1.997	-4.737	0.266	89.323	149.928	23.111	1.854	0.966	0.257
USNO	90.251	143.294	20.773	2.179	-4.920	0.286	91.614	140.434	27.073	2.076	0.995	0.280
VIE	213.394	247.003	25.398	6.620	-4.159	1.303	178.649	213.642	21.028	5.347	3.994	1.089
	$\dot{x}_p$ [$\mu as/d$]						$\dot{y}_p$ [$\mu as/d$]					
COMBI	264.471	469.659	-24.695	6.050	-0.919	0.788	247.053	450.571	-8.792	5.451	1.947	0.734
BKG	325.188	566.456	-39.181	7.290	1.910	0.961	310.450	537.123	-30.838	6.647	1.613	0.911
ASI	308.093	499.264	-32.979	6.590	1.587	0.877	288.749	460.081	-14.195	5.948	1.098	0.817
DGFI	183.665	533.381	-98.879	7.057	-4.252	0.951	194.537	542.673	-154.085	7.713	-16.915	1.045
GFZ	319.974	501.040	-20.847	7.511	2.294	1.465	316.942	647.830	-26.661	7.258	-1.871	1.461
GSFC	283.276	459.236	-48.099	6.182	2.489	0.828	274.679	425.088	-22.325	5.753	1.654	0.795
IAA	308.771	465.454	-73.600	8.691	3.182	1.095	315.316	435.988	-30.030	8.094	3.668	1.049
NMA	413.736	1688.182	-14.232	8.724	-1.461	1.219	389.543	1603.694	-52.370	7.899	5.033	1.147
OPA	303.316	549.385	-43.161	6.477	2.196	0.878	286.488	554.111	-20.991	5.887	0.762	0.827
USNO	283.643	458.030	-45.041	6.664	2.638	0.876	273.728	431.237	-20.899	6.169	1.777	0.835
VIE	522.554	764.064	18.635	15.751	-4.356	3.230	524.599	820.935	31.969	16.131	8.995	3.219
	UT1–UTC [μs]						LOD [$\mu s/d$]					
COMBI	9.159	11.505	-2.073	0.170	0.435	0.030	17.719	27.904	-2.200	0.370	0.410	0.055
BKG	9.455	11.856	-2.482	0.175	0.428	0.031	19.590	29.297	-0.925	0.393	0.139	0.059
ASI	9.301	11.513	-2.000	0.172	0.389	0.030	19.432	26.668	-0.322	0.375	0.159	0.058
DGFI	9.987	12.430	-2.980	0.186	0.545	0.034	8.860	30.054	0.016	0.426	1.534	0.058
GFZ	6.981	11.189	-0.691	0.185	0.155	0.039	19.103	36.399	-2.388	0.429	0.086	0.088
GSFC	9.118	11.127	-2.333	0.169	0.416	0.030	19.083	27.683	-0.686	0.373	0.204	0.059
IAA	10.231	10.965	-4.327	0.223	0.501	0.036	21.588	25.348	-1.667	0.512	0.082	0.072
NMA	10.367	14.944	-2.194	0.203	0.511	0.037	22.785	70.958	-4.430	0.450	0.379	0.072
OPA	9.199	12.245	-2.385	0.171	0.416	0.030	19.479	31.390	-0.518	0.378	0.210	0.059
USNO	8.937	10.735	-3.124	0.178	0.434	0.032	19.342	27.826	-0.244	0.410	0.164	0.063
VIE	15.821	16.683	-0.944	0.515	-0.003	0.101	56.137	63.877	-1.526	1.609	0.228	0.344
	dX [μas]						dY [μas]					
COMBI	45.741	70.212	-5.969	0.963	-2.202	0.128	40.390	80.073	1.771	0.862	1.777	0.114
BKG	67.782	94.817	-6.517	1.413	-2.870	0.191	61.826	100.966	0.188	1.308	2.666	0.175
ASI	53.265	75.964	-8.905	1.075	-1.367	0.145	49.918	88.444	2.044	1.017	1.650	0.137
DGFI	40.674	105.057	-19.264	1.418	-5.223	0.192	34.031	106.957	0.566	1.223	1.328	0.165
GFZ	78.905	110.921	-13.869	1.808	-4.343	0.360	73.225	122.437	10.874	1.686	4.505	0.335
GSFC	47.793	70.765	-16.549	0.981	-1.332	0.133	44.033	77.582	0.194	0.915	1.705	0.124
IAA	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMA	94.091	221.678	-17.820	1.863	-3.208	0.264	91.552	214.698	7.402	1.837	3.001	0.260
OPA	48.586	86.868	-8.856	0.979	-1.306	0.135	48.760	91.834	-0.009	0.994	1.539	0.136
USNO	52.302	68.892	18.141	1.157	-2.195	0.154	46.457	65.989	9.763	1.042	0.639	0.139
VIE	92.079	142.458	-13.915	2.796	-1.193	0.564	94.641	139.353	-3.818	2.890	2.115	0.582

Acknowledgements

Thanks to Sabine Bachmann (BKG) at the IVS Combination Center for analyzing our solutions and providing great feedback and insights.

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Paris Observatory (OPAR) Analysis Center

Sébastien Lambert, Christophe Barache, Teddy Carlucci, Niu Liu, Jean Souchay, Elisa Felicitas Arias

Abstract We report on operational and research activities directly related to VLBI at the Paris Observatory VLBI Analysis Center (OPAR) for calendar years 2017 and 2018. In addition to the operational activity, our main achievements are the contribution to the ICRF3 and to the validation process of the Gaia Data Release 2 catalog that took benefit from the skills of our personnel in terms of assessments of reference frames.

1 Analysis Service

Paris Observatory Analysis Center OPAR continued operational analyses of VLBI diurnal and Intensive sessions. All of the products, except SINEX files, were published on the OPAR Web site at

`http://ivsopar.obspm.fr`

together with exhaustive technical explanations and plots. SINEX files were only sent to the Data Centers. The Analysis Center is using the latest version of Calc/Solve and, since fall 2018, it has processed the databases in vgosDB format. The current global solution (opa2019a) is now using the ICRF3 as an a priori radio source catalog and includes a model for the Galactic aberration, i.e., a dipolar displacement field of the quasars toward the Galactic center of amplitude 5.8 μas per year, as recommended by the IVS Working Group 8 (MacMillan et al., 2019) and as used for the production of the ICRF3 catalog (Charlot et al., 2019). The reference epoch of the Galactic aberration modeling is 2015.0, consistent with the ICRF3. As a consequence, the opa2019a celestial reference frame (quasar coordinate catalog) should be read as follows: coordinates listed in the catalog correspond to the apparent position of the sources at 2015.0; at another epoch, the position of the sources should be corrected by the Galactic aberration effect using the above amplitude. As for the previous solutions, the free core nutation is constantly monitored at OPAR (Figure 1).

A web page is dedicated to the radio source coordinate time series that allows one to follow the evolution of the radio center along time at

`http://ivsopar.obspm.fr/radiosources`

This page is especially useful for monitoring the defining sources and determining whether some of them should be excluded from the constraint because of unstable behavior (Figure 2).

2 Contribution to Celestial Reference Frames

Personnel of OPAR were involved in the generation of the ICRF3 (Charlot et al. 2019, in preparation) that was adopted as the fundamental reference frame by the International Astronomical Union (IAU) in August 2018. In more detail, people from OPAR, namely E. F. Arias, J. Souchay, and S. Lambert, were members of the dedicated IAU Working Group and contributed at two levels: (i) providing prototype solutions together with other Analysis Centers and, more importantly, (ii) setting up the validation chain that allowed the group to

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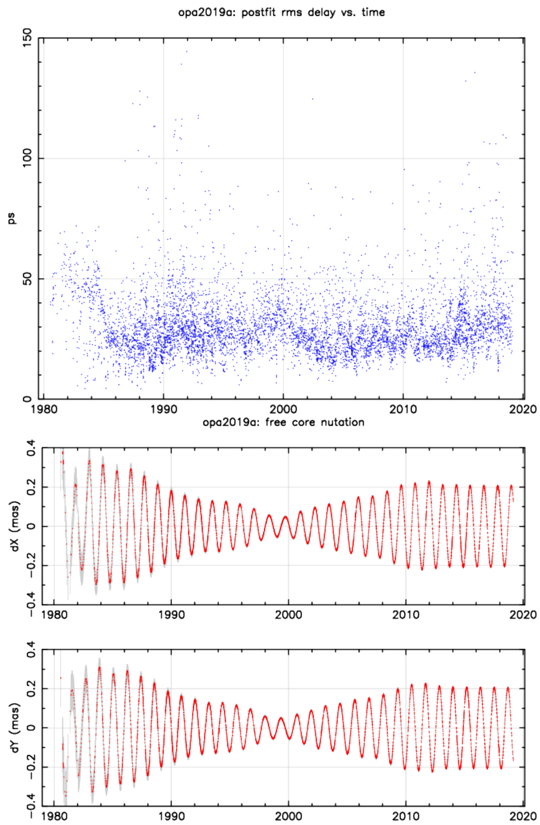

Fig. 1 Top panel: the postfit rms delays of the opa2019a global solution. Bottom panel: the free core nutation as adjusted to the nutation time series obtained in the opa2019a global solution. Plots are shown as they appear on the OPAR web site. These series are updated as new sessions are analyzed at OPAR.

make extensive comparisons between the prototype solutions and the existing reference frames (e.g., ICRF2 and Gaia). Comparisons were realized in terms of individual positions of the radio sources and in terms of large-scale systematics (rotations and higher-order deformations). The validation chain permitted clarification of the causes and the amplitude of the declination-dependent errors, especially thanks to the comparison with the Gaia DR2 counterpart.

Though the accuracy of the ICRF3 was determined internally to the Working Group by a method similar to Charlot et al. (2019), N. Liu and S. Lambert undertook similar investigations on independent solutions and with two complementary methods based on comparisons between standard errors, scatter, and differences between subset solutions. Our conclusion is that the current optimal accuracy of VLBI catalogs is close to 10 μas for sources having the longest observational history (Liu et al., 2018).

S. Lambert investigated the variability of the radio source coordinates using the Allan variance, which is a tool designed for separating the noise types at various time scales. The study revealed that one can grossly consider that none of the sources really behave as Gaussian noise. Rather, all sources are subject to either flicker noise or random walk episodes that constitute serious issues in terms of increasing their positional accuracy by adding new observations (Gattano et al., 2018).

Finally, S. Lambert, T. Carlucci, and C. Barache were involved in the validation phase of the first Gaia Data Release (Gaia DR2) in the framework of the Gaia Data Processing and Analysis Consortium (DPAC) coordination unit 9 (CU9) (Arenou et al., 2018). Our segment of the full validation process consisted essentially of characterizing the deformation between the Gaia DR2 catalog and the ICRF3 for which we provided and tested a six-parameter transformation consisting of three rotations and a glide. The same authors contributed also to the establishment of the first Gaia celestial reference frame aligned onto the ICRF3, so-called Gaia-CRF2 (Mignard et al., 2018).

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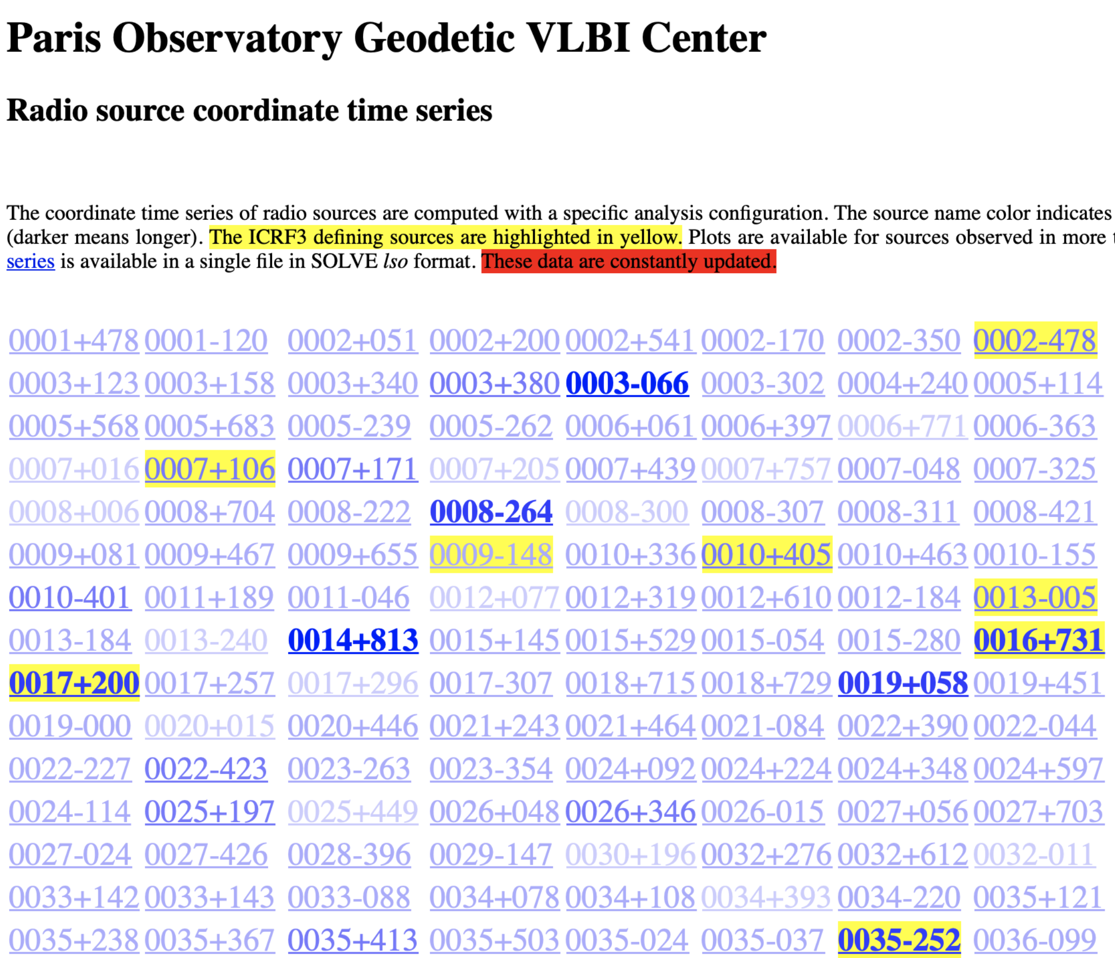

Paris Observatory Geodetic VLBI Center

Radio source coordinate time series

The coordinate time series of radio sources are computed with a specific analysis configuration. The source name color indicates th (darker means longer). The ICRF3 defining sources are highlighted in yellow. Plots are available for sources observed in more tha series is available in a single file in SOLVE *lso* format. These data are constantly updated.

0001+478	0001-120	0002+051	0002+200	0002+541	0002-170	0002-350	0002-478
0003+123	0003+158	0003+340	0003+380	**0003-066**	0003-302	0004+240	0005+114
0005+568	0005+683	0005-239	0005-262	0006+061	0006+397	0006+771	0006-363
0007+016	0007+106	0007+171	0007+205	0007+439	0007+757	0007-048	0007-325
0008+006	0008+704	0008-222	**0008-264**	0008-300	0008-307	0008-311	0008-421
0009+081	0009+467	0009+655	0009-148	0010+336	0010+405	0010+463	0010-155
0010-401	0011+189	0011-046	0012+077	0012+319	0012+610	0012-184	0013-005
0013-184	0013-240	**0014+813**	0015+145	0015+529	0015-054	0015-280	**0016+731**
0017+200	0017+257	0017+296	0017-307	0018+715	0018+729	**0019+058**	0019+451
0019-000	0020+015	0020+446	0021+243	0021+464	0021-084	0022+390	0022-044
0022-227	0022-423	0023-263	0023-354	0024+092	0024+224	0024+348	0024+597
0024-114	0025+197	0025+449	0026+048	0026+346	0026-015	0027+056	0027+703
0027-024	0027-426	0028-396	0029-147	0030+196	0032+276	0032+612	0032-011
0033+142	0033+143	0033-088	0034+078	0034+108	0034+393	0034-220	0035+121
0035+238	0035+367	0035+413	0035+503	0035-024	0035-037	**0035-252**	0036-099

Fig. 2 Main page to access the radio source time series on the OPAR web site. Series are updated as new sessions are analyzed at OPAR. ICRF3 defining sources are displayed against a highlighted yellow background (e.g., 0007+106).

Onsala Space Observatory – IVS Analysis Center Activities During 2017–2018

Rüdiger Haas, Thomas Hobiger, Hans-Georg Scherneck, Niko Kareinen, Grzegorz Klopotek, Periklis-Konstantinos Diamantidis, Joakim Strandberg

Abstract This report briefly summarizes the activities of the IVS Analysis Center at the Onsala Space Observatory during 2017–2018 and gives examples of results of ongoing work.

1 General information

We concentrate on research topics that are relevant for space geodesy and geosciences. These research topics are related to data observed with geodetic VLBI and complementary techniques.

2 Activities during the Past Two Years

We worked primarily on the following topics:

- Optimizing VLBI Intensive schedules
- Extension of the c5++ analysis software
- VLBI observing GNSS signals
- Analysis of VLBI observations of an artificial radio source on the Moon
- Distributed VLBI correlation
- Deformation of radio telescopes
- Coastal sea level observations with GNSS
- Ocean tide loading

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3 Optimizing VLBI Intensive Schedules

In recent years a number of new VLBI stations for VGOS (VLBI Global Observing System) have been installed. This opens up possibilities to add new stations to the so-called IVS Intensive (INT) sessions. The currently observed INT sessions include primarily long east-west oriented baselines so that UT1-UTC can be derived from short observation sessions (one to two hours) on a daily basis. Using simulations for a complete year of INT observations, we studied the impact of adding a third station in tag-along mode to the INT

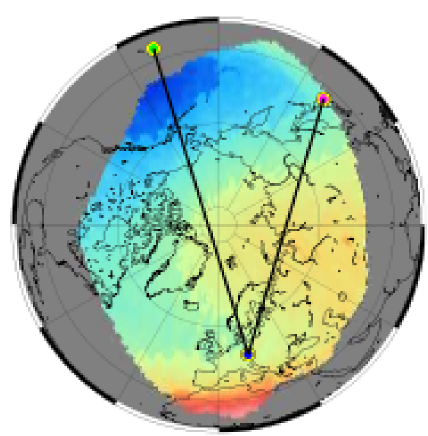

Fig. 1 Ratio of UT1–UTC weighted root-mean-square values obtained with adding a third tag-along station compared to the corresponding single-baseline session. The map is a combination referring to both IVS INT series, INT1 and INT2, with the corresponding baselines indicated. The color scale covers 0.6 (dark blue) to 0.9 (red), i.e., adding a tag-along station always gives an improvement. The largest improvement is found for stations at the Pacific coast of North America. The figure is taken from [1].

sessions [1]. The impact on the accuracy of the derived UT1–UTC is primarily controlled by a) geometry and b) atmospheric turbulence. We found that we can identify areas where the addition of a third station in tag-along mode improves the UT1–UTC estimates by up to 60%, compared to the results from the original single-baseline observations, see Figure 1. In these areas there are several upcoming VGOS sites as well as currently operational legacy S/X VLBI stations. Thus, it is easily possible to improve the performance of the IVS products for UT1–UTC.

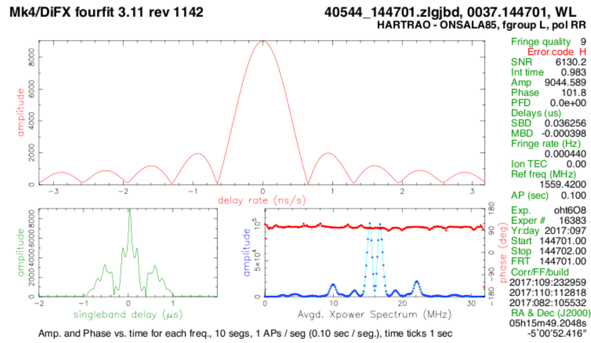

Fig. 2 Upper half of a fringe plot for a 1 s long observation of Galileo satellite PE26 on the baseline Onsala–Hartebeesthoek. Clearly, the BOC signal of Galileo is visible in the cross-power spectrum. Even with just 1 s of data, SNR $>$ 6000 is achieved.

4 Extension of the c5++ Analysis Software

The c5++ analysis software package [2] is able to perform combined data analysis of VLBI, GNSS, and SLR on the observation level. During the last two years we have been working on extending the software.

One addition is that support for the analysis of VLBI observations to near-field radio sources was included [3]. Now it is possible to a) create so-called ".im-files" for the correlation of near-field targets with DiFX, as well as b) analyzing VLBI observations of near-field targets such as, e.g., GNSS satellites (see Section 5) or the Chinese lunar lander (see Section 6), including the estimation of corresponding parameters.

Another extension concerns the analysis strategy in c5++, which so far has been based on the least-squares approach. To improve the possibilities of handling stochastic processes and to improve the combination of large data sets, an analysis strategy based on a Kalman Filter has been implemented. This allows, e.g., analysis of a complete 15 day long CONT campaign in one step while combining VLBI and GNSS on the observation level and avoiding discontinuities at day boundaries.

5 VLBI Observing GNSS Signals

We continued our efforts concerning VLBI observations of GNSS signals [4]. Several new observing sessions were performed, involving intercontinental baselines and observations of signals of GPS and GLONASS as well as Galileo. We streamlined our data processing and analysis, which is now done with DiFX, Fourfit, and c5++. As an example of the post-correlation analysis, a fringe plot using 1 s of data observed on the baseline Onsala–Hartebeesthoek for Galileo satellite PE26 is presented in Figure 2. This shows that scan lengths as short as 1 s are sufficient to reach more than sufficient an SNR.

Data analysis was done with c5++, which had been extended for analysis of observations of near-field targets (see Section 4). Because the observations were performed at one L-band frequency only, ionospheric corrections were applied based on global TEC maps provided by the IGS. However, these are neither accurate nor detailed enough; thus, additional station-dependent ionospheric biases were estimated. A priori

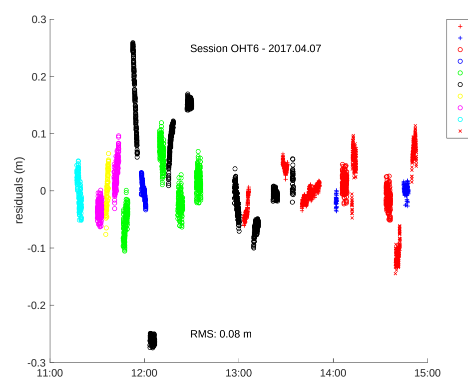

Fig. 3 Post-fit residuals of the analysis of session OHT6 (Hartebeesthoek–Onsala) on 7 April 2017. Several GPS (PGxx) and Galileo satellites (PExx) were observed, see legend. The RMS of the residuals is 8 cm.

tropospheric information was used based on the GPT2 model, and corrections in the form of zenith wet delays (ZWD) were estimated. To account for further instrumental effects, also satellite-specific time biases were estimated. Using this approach, post-fit residuals on the order of less than 10 cm can be achieved. As an example, the post-fit residuals for the observing session OHT6 are presented in Figure 3.

6 Analysis of VLBI Observations of an Artificial Radio Source on the Moon

A lot of work has been spent on the so-called OCEL (Observations of the Chang'E Lander) sessions. There are twelve OCEL sessions that were observed from 2014 to 2016 with global networks of VLBI stations, see [5]. A Monte Carlo simulation study [6] based on the actual OCEL schedules showed that under perfect conditions it should be possible to achieve a 2D position precision of about 10 cm on the Moon's surface, see Figure 4.

In a follow-up simulation study [7] we investigated whether observations of the lunar lander could be included in regular IVS R1-sessions using a scan-replacement strategy. Again, extensive Monte Carlo simulations were performed which led to the result that such a strategy appears feasible and could result in a 2D position accuracy on the order of better than 0.5 m, assuming the same lunar observation precision as before. Performing a corresponding simulation study and including lunar lander observations in VGOS schedules, the expected 2D accuracy could even be as good as 5 cm.

The analysis of real data of two of the OCEL sessions resulted in horizontal position uncertainties on the lunar surface of 8.9 m and 4.5 m in latitude and longitude [8].

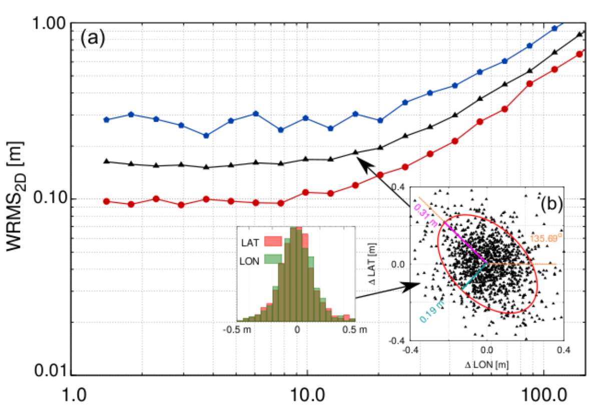

Fig. 4 (a) Performance of OCEL sessions for the 2D position accuracy of the lunar lander, as a function of assumed measurement precision of lunar observations. The mean performance based on all twelve OCEL sessions is depicted in black, while the results of the best and the worst performing sessions are depicted in red and blue, respectively. (b) Scatter plot and histograms of the lander's 2D position solutions from Monte Carlo simulations based on all OCEL sessions and assuming a lunar observation precision of 15.97 mm. The error ellipse represents the 1-σ confidence level. The figure is taken from [6].

7 Distributed Correlation

We participated in an IVS Pilot Project on distributed correlation [9]. Several hours of data of two R1 sessions were distributed to a number of "branch correlators", among them Onsala. Each branch correlator received one (individual) hour of data from all stations involved in the R1 sessions. These data were correlated at the branch-correlators with DiFX and the corresponding output files were sent to the central correlator at MPIfR in Bonn. The Bonn correlator followed two approaches: a) correlating all data, including post-correlation analysis and creation of databases, and b) using the data correlated at the branch correlators for the post-correlation analysis and creation of another set of databases. The comparison between these two approaches showed that there are no significant differences detectable. The pilot project should be continued with further sessions, also including VGOS observations. However, these first results show that distributed correlation can become an interesting approach for the upcoming VGOS era where huge amounts of data will be collected and need to be correlated. Distributed correlation could reduce the load of individual correlation centers.

8 Geometry of Radio Telescopes

During the last two years, the geometry of the radio telescopes at Onsala was studied. This includes both the gravitational deformation of the 20-m radio telescope [10], as well as the investigation of the surface accuracy of the new Onsala twin telescopes [11].

9 Scheduling of Twin Telescopes

With three VGOS twin telescopes becoming operational, an important question is how to use them in an optimal way. The VLBI scheduling software packages need to be extended accordingly by implementing corresponding scheduling rules. Using the example of the Onsala twin telescopes, different scheduling approaches were tested. Schedules were prepared with four different approaches, forcing the telescopes to either 1) observe the same source, 2) observe in orthogonal directions, 3) observe in opposite azimuth but identical elevation directions, or 4) observe in random directions. Additionally, different radio source distributions were tested: square-root or uniformly distributed. Using Monte Carlo simulations, observations were generated based on these schedules. The simulated data were analyzed in a simplified point-positioning strategy, and station positions and tropospheric parameters were estimated and compared to the a priori used (true) simulation parameters. Preliminary results are presented in Figure 5 and show that, compared to the same source approach, all alternative scheduling approaches give improved results for station positions and zenith wet delays. While the performance is rather identical for station positions, there appears to be an advantage concerning ZWD when forcing the telescopes to observe in opposite directions.

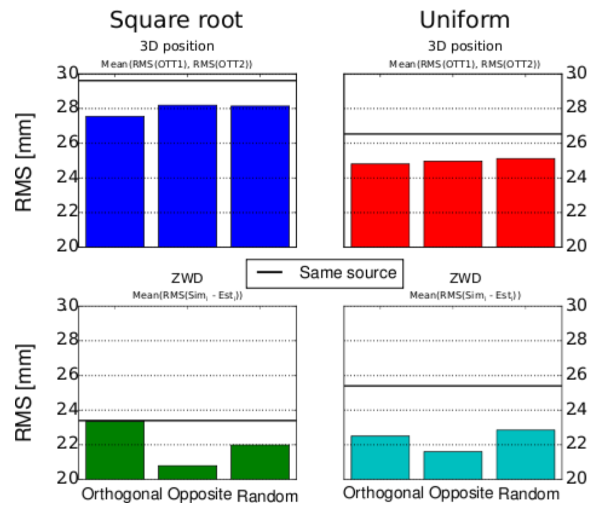

Fig. 5 Root mean square (RMS) comparisons of results for station position and zenith wet delay (ZWD) for different scheduling approaches for twin telescopes. The figure is taken from [12].

10 Coastal GNSS Reflectometry

We continued our research in the field of GNSS reflectometry. The analysis strategy was extended to successfully allow the detection of sea ice [13]. Furthermore, the analysis software was developed to enable real-time GNSS-R results based on Kalman filter analysis [14]. We showed that it is advantageous to use multi-GNSS signals to derive sea level with GNSS-R [15]. The standard deviation of the multi-GNSS solution (GPS+GLONASS+Galileo) for sea level, compared to a co-located traditional tide gauge, is lower than each of the individual solutions, or combinations of just two GNSS (see Figure 6).

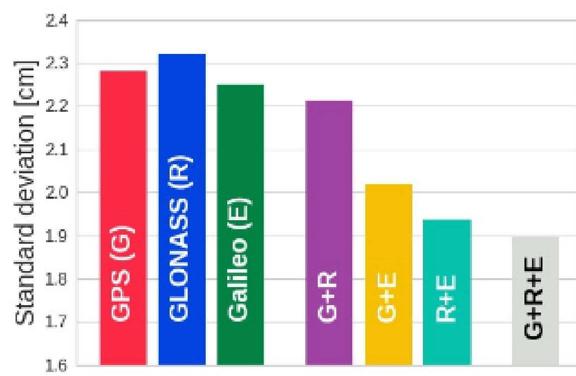

Fig. 6 Standard deviation between a traditional tide gauge and GNSS-R results for sea level. The figure is taken from [15].

11 Ocean Tide Loading

The Automatic Ocean Tide Loading service was operated throughout the year. It is heavily used by the international scientific community. Both new ocean models and new Green's functions were included during the last two years, see `http://holt.oso.chalmers.se/loading/`.

12 Future Plans

The IVS Analysis Center at the Onsala Space Observatory will continue its efforts to work on specific topics relevant to space geodesy and geosciences. We plan to intensify our work in particular concerning tropospheric parameters sensed by space geodetic techniques. The motivations are that the Onsala twin telescopes will become operational and are expected to contribute with a very interesting data set and also that a third microwave radiometer has been installed at Onsala. Thus, a special focus for the next two years is on the Onsala twin telescopes, to connect them to the legacy S/X VLBI network, and to analyze tropospheric parameters and their spatial and temporal variation. We will also continue our efforts concerning VLBI observations of GNSS signals.

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2017–2018 Report of the IVS Associate Analysis Center PMD

Vincenza Tornatore

Abstract The activities related to geodetic VLBI performed at the IVS AC PMD during 2017 and 2018 were focused on different topics that are detailed below. As in previous years, routine computations of European baselines were carried out.
For the Ny-Ålesund VLBI station detailed studies have been executed on velocity estimations and comparisons with results from geodetic satellite techniques. In parallel, investigations on running or preparing VGOS stations were developed. In particular, the RFI threat to the new broadband system, due to several new commercial services that operate in VGOS bands, wasinvestigated. This work was developed also under the framework of the Committee on Radio Astronomy Frequencies (CRAF).
From the observation point-of-view, AC PMD has coordinated the three Italian VLBI stations (Matera, Medicina, and Noto) for the realization of the experiment *s7615b* on phase referencing VLBI observations of the Chang'E-3 lander.
Another topic investigated at PMD was under the COST project Action ES1206. In particular, several simulations and comparisons of different algorithms developed to detect inhomogeneity in the GPS Integrated Water Vapor (IWV) time series were tested. These studies can be applied in the future also to the VLBI IWV time series.

Politecnico di Milano, Department of Civil and Environmental Engineering (DICA), Geodesy and Geomatic Area

PMD Analysis Center

IVS 2017+2018 Biennial Report

1 General Information

No relevant changes with respect to the previous biennium (2015–2016) have occurred at the Politecnico di Milano DICA (PMD) IVS Analysis Center (AC) concerning its location, funding agency, and staff members.

2 Current Status and Activities

2.1 European VLBI Experiments and Investigations on Ny-Ålesund Observatory

European sessions carried out since 1990 through the end of 2018 have been processed. Most recent modeling conditions and different values for parameterizations have been tested. Solutions have been calculated with the VieVS (Vienna VLBI Software) software versions 2.3 and 3.0 [1], developed by the members of the VLBI group of the Institute of Geodesy and Geophysics (IGG), Vienna University of Technology (TU Wien). European site coordinates and baseline lengths (with respective variance-covariance matrices) have been estimated to study their temporal evolution. The adjustments were performed using single session approach.

Detailed studies were dedicated to the Arctic station of Ny-Ålesund. In particular, we have derived velocities from the VLBI coordinate time series (N, E, Up) and compared them to those derived from the International Terrestrial Reference Frame (ITRF2014) [2]. Furthermore, motions derived for Ny-Ålesund

(ITRF2014) were compared with the three space geodetic techniques VLBI, GNSS, and DORIS. Earlier studies have revealed inconsistent results among different observing techniques. Discontinuity or jump detections and estimations are recognized as a critical issue for offset-related velocity biases. In order to further reduce effects due to non-coherent processing strategies, we have used the same methods for all techniques to handle and estimate discontinuities. The harmonic analysis shows also some differences in the detected periodic signals frequency, phase, and amplitude, which are clearly of non-geophysical origin. These studies are near to be submitted for publication.

2.2 VGOS Stations

Threats to the frequency spectrum observed by VGOS stations have been increasing very fast during the last years. Currently the most remarkable risks are represented by the upcoming 5G infrastructure for cell phone & Internet and upcoming satellite-based Internet infrastructure like SpaceX/Starlink or OneWeb, which will occupy massively frequency bands in the range of 2–14 GHz [3]. This will limit the possibility to observe undisturbed up to 1-GHz-wide spectral bands in the VGOS mode. Tools to carry out compatibility studies have been developed [4], and simulations have demonstrated that separation zones for 5G base stations from radio telescope sites in Europe are reaching 200 km.

VGOS came up too late to claim the entire 2–14 GHz range for the exclusive use of VLBI; however, since the VGOS range covers many Radio Astronomy Service (RAS) bands, VGOS radio telescopes may be registered as RAS sites. A site registered as an RAS one should then be protected from strong signals according to RAS bands and other bands where footnotes in the regulations apply in favor of RAS.

5G, for example, will make use of up to 2.69 GHz and RAS is primary user of 2.69–2.70 GHz. As the VGOS range covers many RAS bands, it is higly recommended that VGOS radio telescopes register as RAS sites [5].

At PMD AC a list of approximate coordinates for VGOS sites was compiled, distinguishing radio telescopes already observing from those still under tests, or in contruction, or with plan approved. The list has been updated various times thanks to the collaboration with several IVS Members and in particular with the VGOS Technical Committee (VTC). The list of VGOS sites as of May 2019 is reported in Table 1, where approximate geografic coordinate values and antenna dish sizes can also be found.

The stations are also shown in Figure 1, where the three International Telecommunication Union (ITU) region borders [6] are also indicated. The ITU is the authority responsible to regulate globally the spectrum management. The treaty organization that deals with radio waves is the Radiocommunication Sector of the ITU (ITU-R). It divides the world into three administrative regions R1, R2, and R3.

The interests of the European radio astronomers in ITU-R1 are represented by the Committee on Radio Astronomy Frequencies (CRAF) [7], an Expert Committee of the European Science Foundation (ESF) [8]. Similar organizations to protect radio astronomy interests also exist for the Americas (Committee on Radio-Frequency, CORF) [9] in ITU-R2 and for the Asia-Pacific region (Radio Astronomy Frequency Committee, RAFCAP) [10] in ITU-R3.

2.3 Inhomogeneity Estimations in IWV Time Series

Under COST Action ES1206 Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC), the sub-WG *Data Homogenization* was set to tackle first on the IGS repro 1 tropospheric dataset as a case study. Among its activities, the Working Group carried out the following:

- inventory of the existing homogenization software to study GNSS tropospheric delay and water vapor time series;
- production of synthetic datasets (based on characteristics of the IGS repro 1 dataset, and with known offsets included);
- benchmark (blindly) the performance, weakness and advantages of each method using statistical scores, CRMEs, and trend differences;
- assessment of different methods for computing trends and their uncertainties in the time series.

Table 1 Approximate coordinates of the VGOS sites currently running, under tests, in construction, or planned, together with their respective ITU Region and dish size.

ITU Region	Country	Common name	North Latitude [°]	[′]	[″]	East Longitude [°]	[′]	[″]	Dish size [m]
R1	Finland	Metsähovi	60	13	4.8	24	23	38.4	13.2
R1	Germany	Wettzell N	49	8	38.4	12	52	40.8	13.2
R1	Germany	Wettzell S	49	8	34.8	12	52	40.8	13.2
R1	Italy	Matera	40	38	56.4	16	42	18.0	(13.0)
R1	Italy/Jp	MBL1 Medicina	44	31	29.95	11	38	43.28	2.4
R1	Norway	Ny-Ålesund N	78	56	34.8	11	51	18.0	13.2
R1	Norway	Ny-Ålesund S	78	56	34.8	11	51	18.0	13.2
R1	Portugal	Flores	39	28	1.2	−31	−13	−37.2	13.2
R1	Portugal	Santa Maria	36	59	6.0	−25	−7	−33.6	13.2
R1	Russia	Badary	51	46	12.0	102	14	2.4	13.2
R1	Russia	Svetloe	60	31	48.0	29	46	48.0	13.2
R1	Russia	Zelenchukskaya	43	47	16.8	41	33	54.0	13.2
R1	South Africa	Hartebeesthoek	−25	−53	−16.8	27	41	9.6	13.2
R1	Spain	Gran Canaria	28	1	33.6	−15	−40	−15.6	13.2
R1	Spain	Yebes	40	31	22.8	−3	−5	−16.8	13.2
R1	Sweden	Onsala NE	57	23	38.4	11	55	12.0	13.2
R1	Sweden	Onsala SW	57	23	34.8	11	55	8.4	13.2
R2	Brazil	Fortaleza	–	–	–	–	–	–	(12.0)
R2	USA	GGAO	39	1	19.2	−76	−49	−37.2	12.0
R2	USA	Kokee	22	7	33.6	−159	−39	−54.0	12.0
R2	USA	McDonald	30	40	48.0	−104	−1	−26.4	12.0
R2	USA	Westford	42	36	46.8	−71	−29	−38.4	18.3
R3	Australia	Hobart	−42	−48	−21.6	147	26	16.8	12.0
R3	Australia	Katherine	−14	−22	−30.0	132	9	7.2	12.0
R3	Australia	Yarragadee	−29	−2	−49.2	115	20	45.6	12.0
R3	China	Seshan13	31	5	56.4	121	11	56.4	13.0
R3	China	Tianma13	31	5	27.6	121	8	13.2	13.0
R3	China	Urumqi13	43	28	16.0	87	10	40.0	13.2
R3	Tahiti (FR)	Tahiti	−17	−31	−4.8	−149	−26	−13.2	12.0
R3	Japan	Kashima34	35	57	21.26	140	39	36.37	34.0
R3	Japan	MBL2 Koganei	35	42	28.55	139	29	16.55	2.4
R3	Japan	Ishioka	36	6	10.8	140	5	20.4	13.2
R3	Thailand	Chiang Mai	18	51	56.0	99	13	3.4	(13.0)

The work is nearly finished and a corresponding manuscript is going to be submitted. The COST Action being ended, this work is now continued in the framework of the IAG WG 4.3.8 "GNSS Tropospheric Products for Climate."

2.4 Chang'E-3 Observations

Chang'E-3 is an unmanned lunar exploration mission operated by the China National Space Administration (CNSA), incorporating a robotic lander (see Figure 2 [11]), and China's first lunar rover. It was launched in December 2013 as part of the second phase of the Chinese Lunar Exploration Program. The planned landing site was Sinus Iridum, but the lander actually descended on Mare Imbrium (see Figure 3 [12]).

An experiment of Chang'E-3 lander observations at X-band in phase referencing VLBI mode was planned and carried out at the following interval: UTC 2017-06-15 21:30 – 2017-06-16 03:10. The experiment on Chang'E-3 lander has been called *s7615b*.

The three Italian VLBI stations Medicina (32 m), Noto (32 m), and Matera (20 m) joined the experiment. The AC PMD supported and coordinated the three stations during the preparation and running of the experiment. A preliminary ad-hoc test at the three stations was also planned and realized on 13 and 14 of June

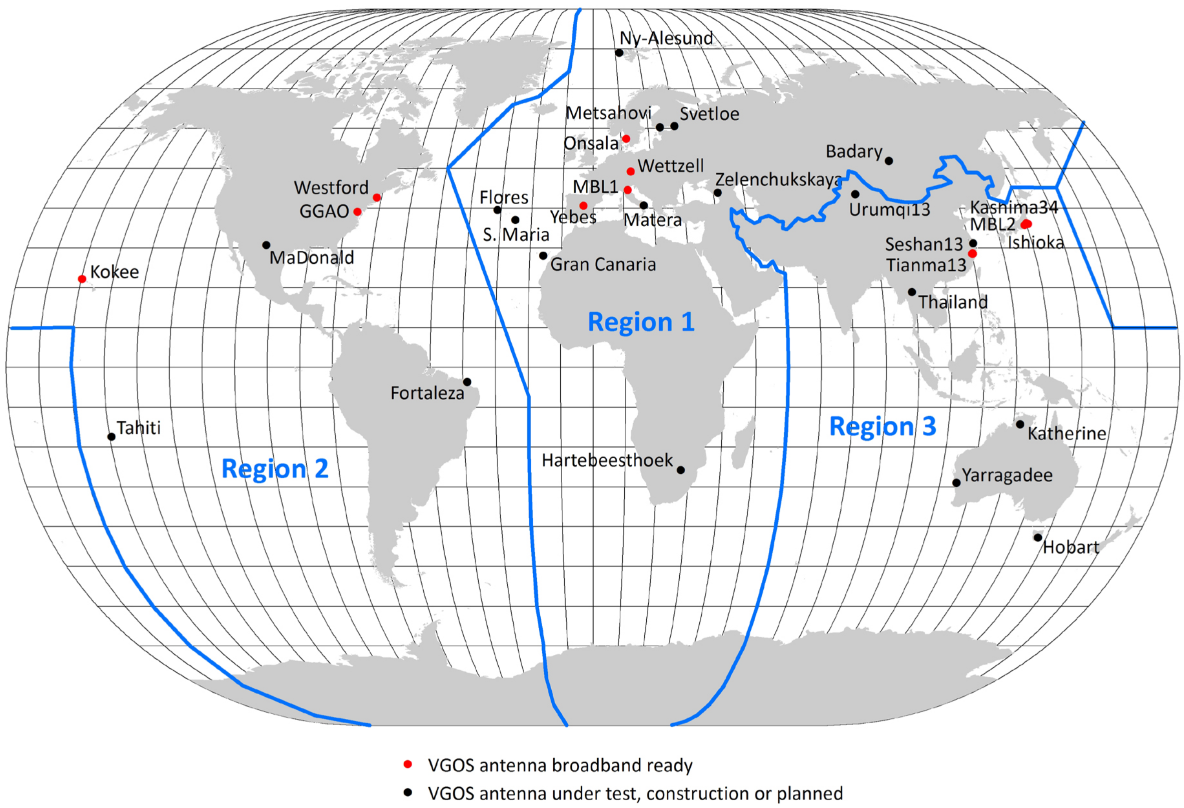

Fig. 1 Distribution of the current and future VGOS sites in the three ITU Regions.

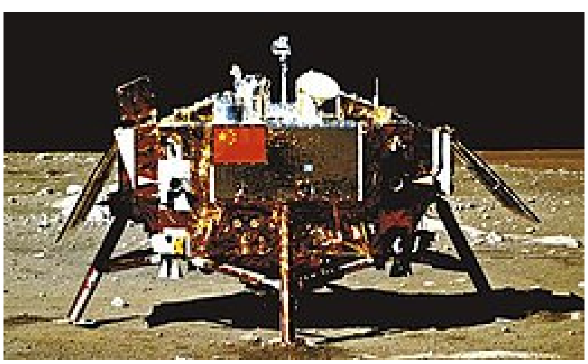

Fig. 2 Chang’E-3 lander on the lunar surface.

Fig. 3 Mare Imbrium where the Chang’E-3 lander descended.

2017. The three Italian antennas tracked the lander using a step-wise tracking mode.

The tones transmitted by the lander are:

8450.75 MHz
8466.15 MHz
8470.00 MHz (carrier)
8673.85 MHz
8489.25 MHz
8496.00 MHz (downlink signal)

Four DOR at 8450.75 MHz, 8466.15 MHz, 8673 MHz, and 8489.25 MHz

Data recorded at each station were transferred and correlated at SHAO. Good fringes to the lander were obtained between Chinese and Italian stations.

3 Future Plans

About data processing, it is foreseen to continue at PMD the data processing of European legacy VLBI stations, and to start analysis of experiments where VGOS stations are involved. Analysis of time series of baselines and site coordinates will be continued and it is planned to broaden the study to time series of tropospheric and ionospheric parameters both for VLBI and GNSS techniques. The work to find out the best algorithms to be applied to detect inhomegeneity will be deepened. As concerns the observations of space probes and GNSS satellites through VLBI technique, it is planned to carry out activities in collaboration with national and international observatories and research centers.

Acknowledgements

We thank the Department of Civil and Environmental Engineering (DICA) of Politecnico di Milano University, in particular the Geodesy and Geomatics Area, for hosting and supporting the IVS PMD AC activities.

We thank the technical staff at Medicina, Noto, and Matera for fruitful collaboration to realize the Chang'E-3 observations. We are grateful to SHAO staff for their collaboration in the realization of the experiment and data correlation and processing. We also thank the COST project Action ES1206.

We acknowledge CRAF and IVS people for their activities to defend VGOS frequencies and for collaboration to fill in the list of VGOS sites already carrying out the observations and projects planned or in preparation.

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Pulkovo Observatory IVS Analysis Center (PUL) Report 2017–2018

Zinovy Malkin, Yulia Lopez

Abstract This report briefly presents the PUL IVS Analysis Center activities during 2017–2018 and plans for the coming year. The main topics of the scientific investigations of the PUL staff in that period were ICRF related studies, EOP series analysis, celestial pole offset (CPO), and free core nutation (FCN) modeling. Regular activities include UT1 Intensive data processing, OCARS catalog support, and support of the PUL archives of data and products.

1 General Information

The PUL IVS Analysis Center was organized in September 2006. It is located at and sponsored by the Pulkovo Observatory of the Russian Academy of Sciences. It is a part of the Pulkovo EOP and Reference Systems Analysis Center (PERSAC) [1]. The main topics of our IVS related activity are:

- Regular computation of UT1 from Intensive IVS sessions.
- Improvement of the International Celestial Reference Frame (ICRF).
- Modeling of the celestial pole offset (CPO) and free core nutation (FCN).
- Analysis of Earth rotation parameters (EOP) and source position time series.
- Computation and analysis of observation statistics.

The PUL Analysis Center Web page [2] is supported. Its contents were described in previous reports.

Pulkovo Observatory

Pulkovo Analysis Center (PUL)

IVS 2017+2018 Biennial Report

PUL staff members participated in activities of several IAU, IAG, IERS, and IVS committees, commissions, and Working Groups.

2 Staff

The following persons contributed to the PUL activity in 2017–2018:

1. Zinovy Malkin (70%) — team coordinator, EOP and CRF analyst;
2. Yulia Lopez (née Sokolova) (50%) — CRF analyst.

3 Activities and Results

The main activities and results of the PUL IVS Analysis Center during 2017–2018 included the following topics.

3.1 ICRF related research.

- Team members participated in the preparation of the third ICRF release, ICRF3, which was finalized and approved by the IAU General Assembly in 2018 (Charlot et al., in preparation).
- The link problem between radio (ICRF) and optical (*Gaia*-CRF) celestial reference frames was analyzed [7]. Both systems should be a realization of the ICRS (International Celestial Reference System) at the microarcsecond level of accuracy. Therefore, the link between the ICRF and *Gaia*-

CRF should be obtained with similar accuracy, which is not a trivial task due to relatively large systematic and random errors in source positions at different frequency bands. In this work, additional possibilities of improving the *Gaia*-CRF–ICRF link's accuracy are discussed. In particular, a possibility of increasing the number of ICRF and *Gaia*-CRF common objects is considered using advanced scheduling of the regular IVS sessions such as R1 and R4. It is shown that inclusion of supplemental prospective southern sources in these sessions allows enrichment of the southern ICRF zone without noticeable loss of accuracy of geodetic results. Another topic discussed in this presentation is using the correlations between radio source coordinates, which can impact the orientation angles between two frames at a level of a few tens of μas.
- A new combined catalog of the radio source positions was constructed and compared with ICRF2. An overview of the works of the Pulkovo Observatory in the field of comparison and combination of radio source position catalogs in 2006–2017 was published [4]. The adopted procedure of the construction of the combined catalog consists of two stages. First, the difference between input catalogs and the celestial reference system ICRF (ICRF2) is presented in a series of spherical functions using the Brosche method. Each catalog is then corrected for the found differences (catalog system), and the corrected catalogs are averaged. Then the input catalog systems obtained at the first stage are averaged, and the resulting average system is considered to be a systematic correction to the ICRF catalog. The addition of the average system to the catalog that was obtained at the first stage results in a final combined catalog. The first Pulkovo combined catalog was computed in 2006, and it allowed us to substantially improve the accuracy of the computation of Universal Time and celestial pole coordinates. The second catalog was computed in 2013, and it allowed us to get preliminary estimates of the systematic errors of the ICRF2 catalog. The third catalog of 2016 described in this paper made it possible to get more reliable estimates of these errors.
- A method was developed to compute the structure delay of extended radio sources without constructing their radio images [9]. The residuals derived after the adjustment of geodetic VLBI observations are used for this purpose. We show that the simplest model of a radio source consisting of two point components can be represented by four parameters (the angular separation of the components, the mutual orientation relative to the poleward direction, the flux-density ratio, and the spectral index difference) that are determined for each baseline of a multi-baseline VLBI network. The efficiency of this approach is demonstrated by estimating the coordinates of the radio source 0014+813 observed during the two-week CONT14 program organized by the International VLBI Service (IVS) in May 2014. Large systematic deviations were detected in the residuals of the observations for the radio source 0014+813. The averaged characteristics of the radio structure of 0014+813 at a frequency of 8.4 GHz can be calculated from these deviations. Our modeling using four parameters has confirmed that the source consists of two components at an angular separation of 0.5 mas in the north-south direction. Using the structure delay when adjusting the CONT14 observations leads to a correction of the average declination estimate for the radio source 0014+813 by 0.070 mas.
- The OCARS catalog (Optical Characteristics of Astrometric Radio Sources) is being supported [3]. The catalog provides source type, redshift information, photometric data in 11 visual and three NIR bands, and cross-identification with several catalogs at different bands [8].

3.2 CPO and FCN related research

- Two CPO and two FCN series are being updated daily and are available at the PERSAC Web page [1].
- Three combined celestial pole offset (CPO) series computed at the Paris Observatory (C04), the United States Naval Observatory (USNO), and the International VLBI Service for Geodesy and Astrometry (IVS), as well as six free core nutation (FCN) models, were compared from different perspectives, such as stochastic and systematic differences and FCN amplitude and phase variations [5]. The differences between the C04 and IVS CPO series were mostly stochastic, whereas a low-frequency bias at the level of several tens of

μas was found between the C04 and USNO CPO series. The stochastic differences between the C04 and USNO series became considerably smaller when computed at the IVS epochs, which can indicae possible problems with the interpolation of the IVS data at the midnight epochs during the computation of the C04 and USNO series. The comparison of the FCN series showed that the series computed with similar window widths of 1.1 years to 1.2 years were close to one another at a level of 10 μas to 20 μas, whereas the differences between these series and the series computed with a larger window width of four years, and seven years reached 100 μas. The dependence of the FCN model on the underlying CPO series was investigated. The RMS differences between the FCN models derived from the C04, USNO, and IVS CPO series were at a level of approximately 15 μas, which was considerably smaller than the differences among the CPO series. The analysis of the differences between the IVS, C04, and USNO CPO series suggested that the IVS series would be preferable for both precession-nutation and FCN-related studies.
- The accuracy of prediction of the celestial pole coordinates (precession-nutation angles) was investigated using the actual predictions obtained in 2007–2017 at the Pulkovo Observatory and at the United States Naval Observatory (USNO) [6]. To get a reliable and comprehensive comparison, three estimators of the prediction errors were computed: root-mean-square error, mean absolute error, and maximum error. It was found that the accuracy of the predictions computed at the Pulkovo Observatory is substantially better than that for the predictions provided by the USNO.

3.3 Regular Activities

- Operational data processing of IVS Intensive sessions in operational automated mode and submission of results to IVS was continued. The latest UT1 time series includes ∼5,700 UT1 estimates for 1999–2018 and is available at the IVS Data Centers and at the PERSAC Web page [1].
- The PUL archive of VLBI data and products obtained in the framework of IVS activity is supported. At present, all available X-band NGS cards for ∼16.5 thousand sessions observed in 1979–2018 are stored. The PUL NGS archive contains ∼17 million (∼14 million good) observations and looks to be the most complete among other IVS NGS card archives.
- Development of algorithms and software for data processing and analysis continued.

4 Future Plans

Plans for the coming years include:

- Continuing ICRF related studies.
- Continuing CPO/FCN related studies.
- Continuing OCARS catalog support.
- Continuing development of algorithms and software for data processing.
- Continuing support of the PUL archives of data and products.

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SAI-VNIIFTRI VLBI Analysis Center in 2017–2018

Vladimir Zharov [1], Sergey Pasynok [2]

Abstract This report presents an overview of the SAI-VNIIFTRI VLBI Analysis Center activities. The AC analyzes all IVS sessions for computations of the Earth orientation parameters (EOP) and time series of ICRF source positions and performs research and software development aimed at improving the VLBI technique.

1 General Information

The SAI-VNIIFTRI VLBI Analysis Center is located at Sternberg State Astronomical Institute (SAI) of Lomonosov Moscow State University in Moscow and at the National research institute of physicotechnical and radio engineering measurements (VNIIFTRI), Mendeleevo, Russia. The Analysis Center participates in geodetic and astrometric VLBI analysis, software development, and research aimed at improving the VLBI technique, especially for support of the ASC correlator during the Radioastron mission [1].

2 Activities during the Past Two Years

The AC SAI-VNIIFTRI performs data processing of all kinds of VLBI observing sessions. For VLBI data analysis we use the ARIADNA software package developed by V. Zharov [4]. Version 4.11 of this software was finished and tested at the end of 2018. All reductions are performed in agreement with the IERS Conventions (2010). Now the package uses files in VGOS(NetCDF) [2] and NGS format as input data and creates SINEX output files for every IVS session. The package was automated for the purposes of the Russian EOP operative service, and now it is used at VNIIFTRI for operational VLBI session processing [3].

The staff of the joint AC is

- Vladimir Zharov, Prof.: development of the ARIADNA software, development of the methods of parameter estimation (SAI);
- Sergey Pasynok, scientific researcher: development of control scripts, global solution (VNIIFTRI);
- Natalya Shmeleva, engineer: VLBI data processing (SAI).

3 Current Status

- **Software Development for VLBI Processing**
  The ARIADNA software is being developed to provide contributions to IVS products. The software is used for calculating all types of IVS products. The main features of version 4.11 are: input data in vgosDB and NGS formats, performing all reductions in agreement with the IERS Conventions (2010), automatic generation of SINEX files, combination of some of the SINEX files to stabilize solutions, and non-interactive mode. Starting from version 4, the software has allowed the use of the CIO-based transformation matrix. The method that uses calculation of the equinox-based transformation matrix for precession-nutation was

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kept to compare new series with old ones. The equinox-based matrix $Q(t)$ that transforms from the true equinox and equator of date system to the GCRS is composed of the classical nutation matrix, the precession matrix including four rotations, and a separate rotation matrix for the frame biases.
The EOP series was obtained from observations that were made in 2017–2018.

- **Routine Analysis**
During 2017–2018 the routine data processing was performed with the ARIADNA software using the least-squares method with rigid constraints.
The AC SAI-VNIIFTRI operationally processed the 24-hour and Intensive VLBI sessions. Forming the data bases of the VLBI sessions and processing of all sessions is fully automated. The EOP series vnf_2017.eoxy, vnf_2018.eoxy, vnf_2017.eopi, and vnf_2018.eopi were calculated. These series were computed with the VTRF2015 catalog of station positions and velocities.
SINEX files were generated for all sessions.
Weighted mean (WM) and weighted root mean square (WRMS) UT1 differences between AC SAI-VNIIFTRI and AC BKG, IAA, and USNO estimates from all Intensive sessions are shown in Figure 1, and those from 24-hour solutions are shown in Figure 2.

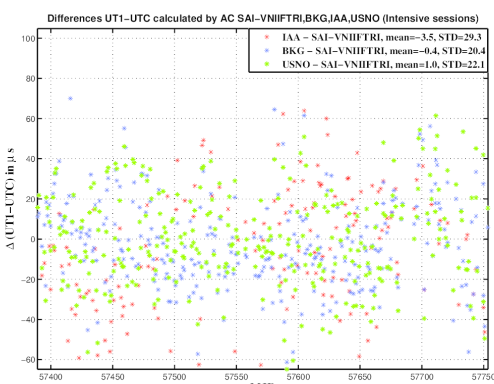

Fig. 1 AC BKG, IAA, and USNO to AC SAI-VNIIFTRI UT1 differences from the solutions of Intensive sessions.

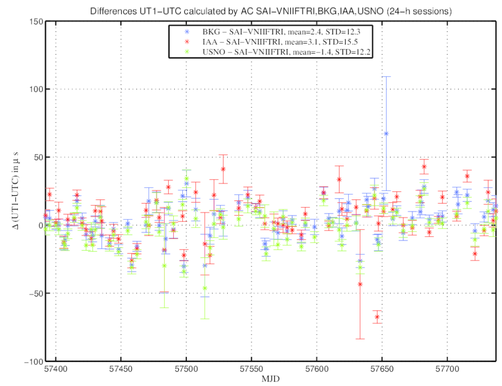

Fig. 2 AC BKG, IAA, and USNO to AC SAI-VNIIFTRI UT1 differences from the solutions of 24-hour sessions.

4 Future Plans

- Continuing investigations of VLBI estimation of EOP, station coordinates, source coordinates and their variability.
- Improvement of the ARIADNA software for processing of the GNSS troposphere zenith delays.

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IVS SHAO Analysis Center 2017–2018 Biennial Report

Guangli Wang, Minghui Xu, Zhibin Zhang, Shuangjing Xu, Li Guo, Bo Zhang, Fengchun Shu, Jinling Li, Liang Li, Zhihan Qian

Abstract This report presents the routine work and the research work carried out at the SHAO VLBI Analysis Center (AC) during 2017 and 2018. The SHAO AC continues the routine VLBI data analysis of IVS 24-hour geodetic/astrometric sessions and takes the responsibility of analyzing the CVN data. Research works related to VLBI astrometry and geodesy during these two years are reported.

1 General Information

The SHAO VLBI Analysis Center is located at Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences, China. It is a part of the Astrometry research group in the Center for Astro-geodynamics at SHAO. Some members are from the VLBI application in the Chinese deep space mission. We are processing the Chinese VLBI Network (CVN) data and IVS 24-hour routine sessions and one-hour Intensive UT1 sessions to provide our results and investigate some interesting topics in VLBI.

2 Component Description

The SHAO Analysis Center analyzed all the IVS sessions by using the Calc/Solve and nuSolve software package, and 16 CVN sessions (including solving ambiguities and determining the ionospheric effect from dual band data). We provided VLBI products, i.e., EOP, CRF, and TRF, for the Chinese EOP Services. We analyzed 347 Intensive sessions and submitted to the IVS in 2017. We continued to investigate the source structure effect in geodetic VLBI and attempted to correct the source structure effect in data analysis.

SHAO, Chinese Academy of Sciences

SHAO Analysis Center

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3 Staff

During 2017 and 2018, the staff of the SHAO AC consisted of one consultant, Professor Zhihan Qian, group leader Dr. Guangli Wang, and eight employees. Table 1 lists the staff members and their main areas of activity.

4 Current Status and Activities

- We submitted sinex file products from 347 Intensive sessions in 2017 to the IVS Combination Center for the test run of combination analysis of UT1 sessions and regular IVS 24-hour sessions.
- To study source structure effects in geodetic VLBI, we processed the VLBI data of the CONT17 continuous observing campaign, adopting standard geodetic and imaging techniques. From the results, we analyzed the influence of the station dependent errors, such as tropospheric and ionospheric errors, clock and cable length errors, and station position errors, on the combinations of interferometric measurements such as delay closures. Our study shows that source structure is a major contributor to errors in geodetic VLBI, and source structure must be taken into account in the entire VLBI operational

chain. The overall structure-effect magnitudes for 3,417 ICRF radio sources are quantified by closure analyzing of 40 years of VLBI historical data. The evolution of source structure for those sources has also been shown.

- As a subgroup of the IVS, the Asia-Oceania VLBI group for Geodesy and Astrometry (AOV) was founded in 2014. Thirty AOV observing sessions were conducted by the end of 2018. The scheduling of these sessions is shared between three institutes (GSI, SHAO, and UTAS) and the correlation amongst two (GSI and SHAO). From 2015 onwards the APSG sessions' scheduling and correlation is now handled by SHAO, under their commitment to the AOV region.
- The AOV and APSG networks are unique to the astrometry of weak sources in the middle southern hemisphere and the ecliptic plane. We have observed 357 weak sources in 17 AOV/APSG sessions. The observations of 194 target sources from 2015 to 2017 were included in the ICRF3 catalog released in August 2018. It is worth noting that there are 132 new sources firstly observed by the AOV. As shown in Figure 1, with additional data acquired in 2018, we have detected 326 target sources successfully. Among them, 109 sources are old ICRF2 sources with improved positions, 167 sources are newly included in the ICRF3, and 50 sources are newly introduced to the IVS data but not included in the ICRF yet.

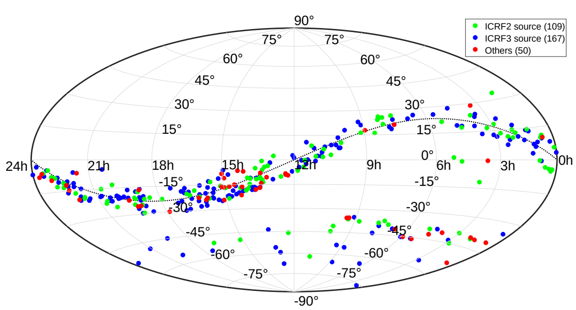

Fig. 1 We have detected 326 target sources successfully.

- For VLBI astrometry, we have measured a trigonometric parallax of the semi-regular variable RT Vir from multi-epoch Very Long Baseline Array observations of its circumstellar H2O masers at 22 GHz. The parallax of 4.417 ± 0.134 mas, corresponding to a distance of 226 ± 7 pc, is significantly different from the Hipparcos parallax of 7.38 ± 0.84 and the Gaia DR2 parallax of 2.050 ± 0.291 mas but is consistent with a distance derived from the period luminosity relation (PLR). This suggests that the optical parallax suffers from systematic bias, possibly owing to a variable photo-center for this giant star. As such, VLBI parallax measurements will serve as an important cross-check for Gaia (Zhang et al., 2017).
- We reported astrometric results of VLBI phase-referencing observations of 22 GHz H2O maser emission toward the red hypergiant VX Sgr (Figure 2), one of the most massive and luminous red hypergiant stars in our Galaxy, using the Very Long Baseline Array. A background source, J1820-2528, projected 4.4 degrees from the target VX Sgr, was used as the phase reference. Due to the low declination of these sources, such a large separation normally would seriously degrade the relative astrometry. We use a two-step method of tropospheric delay calibration, which combines the VLBI geodetic-block (or GPS) calibration with an image-optimization calibration, to obtain a trigonometric parallax of 0.64 ± 0.04 mas. The measured proper motion of VX Sgr is 0.36 ± 0.76 and -2.92 ± 0.78 mas/yr in the eastward and northward directions. The parallax and proper motion confirm that VX Sgr belongs to the Sgr OB1 association (Xu et al., 2018).
- We compared the parallaxes of stars from VLBI astrometry in the literature to those in the Gaia DR2 catalog (Figure 3). Our full sample contains young stellar objects, evolved AGB stars, pulsars, and other radio stars. Excluding AGB stars, which show significant discrepancies between Gaia and VLBI parallaxes, and stars in binary systems, we obtain an average, systematic, parallax offset of -75 ± 129 uas zero-point between -100 and 0 uas (Xu et al., 2019).
- We have evaluated the relative astrometric accuracy of the KVN and VERA Array (KaVA) with quasar-quasar observations. We confirmed that KaVA can potentially achieve positional accuracies of 20 uas in right ascension and 40 uas at K-band. With our result, KaVA opened the phase referencing mode for the first time in 2019 (KaVA Status Report for 2019A).

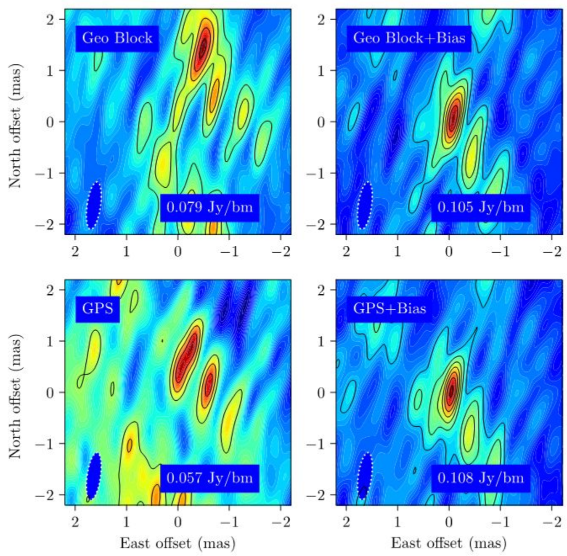

Fig. 2 Phase-referenced images with geodetic-like observations (upper left panel), with geodetic-like observations plus bias correction (upper right panel), with GPS data (bottom left panel), and with GPS data plus bias correction (bottom right panel) (Xu et al., 2018).

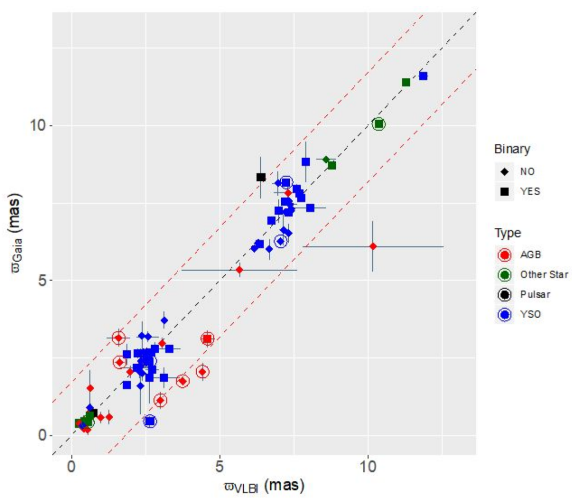

Fig. 3 Gaia DR2 vs. VLBI parallaxes. Colors denote different stellar types, and known binaries are shown in different shapes (Xu et al. 2019).

- We have been working on building a VGOS-type antenna in the yard of the new Tianma 65-meter antenna. The station is ready for testing.
- Most of our group is deeply involved in the Chang'E-4 mission, on s/c (spacecraft) post-correlation and positioning in real time.

5 Future Plans

We will mainly focus on data analysis of observations made by VGOS-type antennas in China and continue to participate in IVS routine analysis work.

Table 1 Staff members and their main tasks.

Dr. Guangli Wang	VLBI2010, data analysis, and leader
Dr. Jinling Li	Positioning, VLBI2010, and data analysis
Dr. Minghui Xu	Data analysis and imaging
Dr. Zhibin Zhang	Data analysis
Dr. Li Guo	Positioning and data analysis
Dr. Bo Zhang	Phase referencing and imaging
Dr. Shuangjing Xu	Imaging and data analysis
Dr. Fengchun Shu	Schedules, correlation, and data analysis
Prof. Zhihan Qian	Consulting
Dr. Liang Li	Data analysis and CRF

Tsukuba VLBI Analysis Center

Takahiro Wakasugi [1], Michiko Umei [1], Tetsuya Hara [1,2]

Abstract This report summarizes the activities of the Tsukuba VLBI Analysis Center during 2017 and 2018. The weekend IVS Intensive (INT-2) sessions were regularly analyzed in near real time using *c5++* analysis software.

1 Introduction

The Tsukuba VLBI Analysis Center, located in Tsukuba, Japan, is operated by the Geospatial Information Authority of Japan (GSI). A major role of the Analysis Center is to regularly analyze the weekend IVS Intensive (INT-2) sessions and deliver the results to the community. It should be noted that a UT1–UTC (=dUT1) solution becomes available rapidly after the end of each observing session. A dedicated link to the *SINET5* operated by the National Institute of Informatics (NII) and several process management programs make it possible to derive the solutions rapidly. Our products are utilized for more accurate dUT1 prediction by the U.S. Naval Observatory (USNO) as the IERS Rapid Service/Prediction Centre, which is responsible for providing earth orientation parameters on a rapid turnaround basis, primarily for real-time users and others needing the highest quality EOP information sooner than that available in the final EOP series [1].

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co.,Ltd.

Tsukuba VLBI Analysis Center

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2 Component Description

2.1 Analysis Software

An analysis software named *c5++*, which was jointly developed by Hitotsubashi University, National Institute of Information and Communications Technology (NICT), and Japan Aerospace Exploration Agency (JAXA) for various space geodetic techniques including SLR, GNSS, and VLBI, is officially used to provide dUT1 estimates in regular INT-2 sessions at the Analysis Center [2]. The current version of *c5++* is version 0.0.1 (rev. 907) as of December 2018.

The correlation and analysis management programs, so-called *rapid_*programs, developed by GSI can execute all processes from data transfer through analysis consecutively and automatically. *Rapid_c5pp* runs *c5++* on outputs of the bandwidth synthesis process and estimates dUT1 to be delivered to the community quickly. Please refer to the report "Tsukuba VLBI Correlator" in this volume for further details about the *rapid_*programs.

The version 4 databases are created by using *νSolve* at the Analysis Center. In response to the transition of the database format from Mark III to vgosDb at the instruction of the IVS, vgosDb-compatible utilities developed by NASA GSFC (*vgosDbMake*, *vgosDbProcLogs*, and *vgosDbCalc*) were installed and incorporated into the ordinary procedure [3]. The current version of *νSolve* is version 0.6.3 as of December 2018. The Mark III format databases are also created by using *MK3TOOLS* instead of *vgosDbMake* and *vgosDbProcLogs* based on requests from a few Analysis Centers [4].

Table 1 Analysis Center hardware capabilities.

Number of servers	four for VLBI analysis (*c5++*, *νSolve* and *MK3TOOLS*)
Operating System	CentOS version 6.9, 7.5, and Red Hat Enterprise Linux 6.3
CPU	Intel Xeon X3360 @2.83GHz 4 cores 2 × Intel Xeon X5687 @3.60GHz 4 cores Intel Xeon E3-1270V2 @3.50GHz 4 cores 2 × Intel Xeon X5680 @3.33GHz 4 cores
Storage capacity	2 × 3 Tbytes

2.2 Analysis Center Hardware Capabilities

C5++, *νSolve* and *MK3TOOLS* are installed on several general-purpose and commercially-produced Linux computers (Table 1). Two 3-TB HDDs are used for storing VLBI databases and necessary a priori files. One is used as main storage and mirrored by the other regularly.

3 Staff

The technical staff of the Tsukuba VLBI Analysis Center are:

- **Takahiro Wakasugi**: correlator/analysis chief, management.
- **Michiko Umei**: correlator/analysis operator, coordination.
- **Tetsuya Hara** (AES): correlator/analysis operator, software development.

4 Analysis Operations

4.1 New Intensive Solution gsiint2c

IVS has started the INT-2 series on the Ishioka–Wettzell baseline in January 2017 in response to the retirement of the Tsukuba 32-m telescope at the end of 2016 after parallel operations for three months to secure the consistency of products. Taking this opportunity, the analysis center renewed some things in the procedure. The a priori station position and velocity were updated to ITRF2014 instead of VTRF2008. The position and velocity of Ishioka were estimated by a global solution calculated by GSI aligned with ITRF2014. The analysis software *c5++* was shifted from the beta version to the release version. This software update included the full compliance of geophysical models with the IERS Conventions 2010 and a new automatic ambiguity estimation strategy [5]. In addition, our correlation and analysis management programs were slightly modified for fully automated processing. The new dUT1 estimation results, called *gsiint2c*, has been released since 2017 to IVS Data Centers. The new solution is also available on our FTP site:

```
ftp://ftp.spacegeodesy.go.jp/vlbi/
products/eopi/gsiint2c.eopi
```

As described in Section 2.1, the *gsiint2c* solution has been delivered in near real time by fully automated processes from data transfer to analysis in the same way as the previous solution.

Table 2 Intensive sessions processed at the Tsukuba Analysis Center.

2017	Baseline	# of sessions	Ave. of dUT1 formal uncertainties
Intensive 2	IsWz	79	11.44 μsec
	IsWn	2	13.15 μsec
	KkWz	8	16.26 μsec
	ShWz	4	5.80 μsec
	KbWz	1	4.20 μsec
Intensive 3	IsNyWnWz	1	5.30 μsec
Total		95	11.51 μsec

2018	Baseline	# of sessions	Ave. of dUT1 formal uncertainties
Intensive 2	IsWz	59	11.69 μsec
	IsWn	2	15.15 μsec
	KkWz	18	19.08 μsec
	KkWn	1	13.30 μsec
	ShWz	4	27.85 μsec
	ShWn	1	26.30 μsec
	KbWz	2	10.25 μsec
Intensive 3	IsWnWz	1	7.70 μsec
Total		88	14.12 μsec

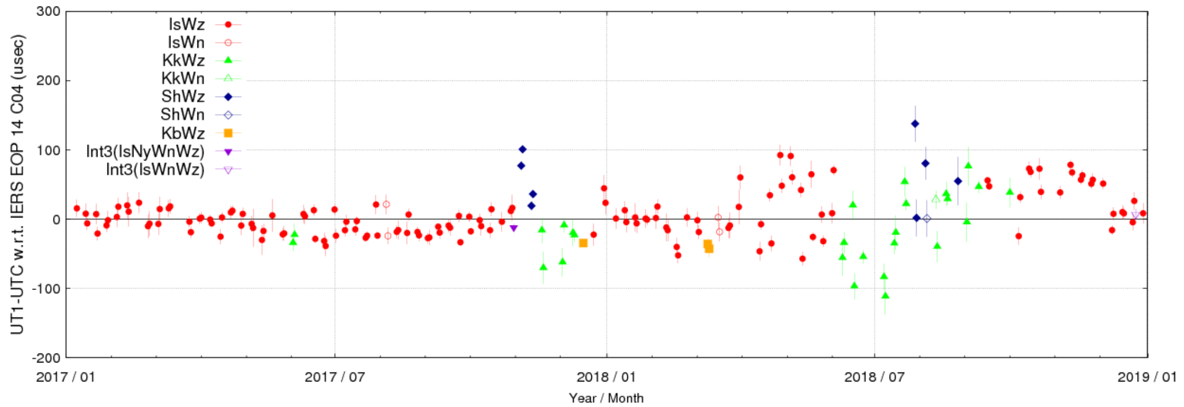

Fig. 1 Time series of UT1–UTC derived from IVS Intensive sessions with respect to IERS EOP 14 C04. Error bars are 1-σ formal uncertainties.

Table 3 Summary of automated processing results.

	2017	2018
# of sessions	95	88
Success in real time processing	49	61
– Average Latency	1 hour 15 min	1 hour 43 min
Failed in real time processing	46	27
– Data quality (outlier)	9	9
– *rapid*_programs failure	13	7
– Station or data transfer failure	24	11

4.2 Summary of UT1-UTC Results

All of the weekend Intensive series (INT-2) were analyzed at the analysis center automatically in near real time using the *rapid*_programs. The number of sessions processed in 2017 and 2018 are listed in Table 2. Ishioka in Japan and Wettzell 20-m in Germany have participated in INT-2 sessions usually. On the other hand, some telescopes such as Kokee Park in Hawaii, U.S., Sheshan in China, or Kashima 34-m in Japan were involved when Ishioka was not available during the VGOS test period for a few months a year. The 13.2-m Wettzell North Telescope also filled in occasionally during the absence of Wettzell 20 m. In addition, a few INT-3 sessions on Monday correlated at the Tsukuba VLBI Correlator were analyzed too.

The automated programs succeeded in near real time processing in 49 out of 95 sessions and 61 out of 88 sessions in 2017 and 2018, respectively (Table 3). Notably, a new automatic ambiguity estimation strategy implemented with the update of *c5++* worked well, resulting in near real time processing in eight and seven sessions in 2017 and 2018, respectively. The formal errors for the estimated dUT1 were also described in Table 2. The average formal error for the Ishioka–Wettzell baseline, which is the typical baseline of INT-2, was about 11 microseconds, and the average formal error for most baselines fell within the range of 20 microseconds. Figure 1 shows the differences between dUT1 solutions with each baseline and IERS EOP 14 C04 from January 2017 through December 2018. Estimated dUT1 became available within two hours after the end of the observation typically.

On the other hand, the automated analysis processing failed at times due to some sort of problem in the observation especially in 2017. The main reason for this is considered to be the initial failure. As described in Section 4.1, the Ishioka station became a regular participating station in 2017. Moreover, some stations such as Kokee Park or Sheshan have begun to be involved in INT-2 too. The imperfection in *rapid*_programs as well as procedures at station ends caused most of the failures. These errors considerably decreased in 2018. Unsuccessful runs of the automated processing using the *rapid*_programs in 2018 were mainly due to the data format conversion before correlation. To deal with this problem, the *rapid*_programs were modified so as to handle various data formats such as VDIF and Mark 5B without format conversion, and incorporated in automated procedure since December 2018 (please refer to the report "Tsukuba VLBI Correlator" in this volume).

5 Outlook

We will continue to analyze the data of the IVS Intensive sessions and deliver dUT1 products in near real time. In addition, we will keep updating our automated programs to secure more stable operation on various combinations of baseline or multiple baseline sessions.

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U.S. Naval Observatory VLBI Analysis Center

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Abstract This report summarizes the activities of the VLBI Analysis Center at the United States Naval Observatory for calendar years 2017–2018. Over the course of the two years, Analysis Center personnel continued analysis and timely submission of IVS-R4 databases for distribution to the IVS. During the calendar years 2017–2018, the USNO VLBI Analysis Center used the VLBI global solutions designated usn2016a, usn2017a, usn2017b, usn2018a, and usn2018b. Earth orientation parameters (EOP) based on the solutions and updated by the latest diurnal (IVS-R1 and IVS-R4) sessions, were routinely submitted to the IVS. Sinex format files based upon the bi-weekly 24-hour sessions were also submitted to the IVS. During the 2017–2018 calendar years, Analysis Center personnel continued a program to use the Very Long Baseline Array (VLBA) operated by the NRAO for the purpose of measuring UT1–UTC. Routine daily 1.5-hour duration Intensive observations continued using the VLBA antennas at Pie Town, NM and Mauna Kea, HI.

1 Introduction

The USNO VLBI Analysis Center is supported and operated by the United States Naval Observatory (USNO) in Washington, DC. The primary services provided by the Analysis Center are the analysis of diurnal sessions, the production of periodic VLBI global solutions for estimation of the Terrestrial Reference Frame (TRF), the Celestial Reference Frame (CRF), and Earth Orientation Parameters (EOP). The Analysis Center continued the submission to the IVS of Intensive (EOP-I) and session-based (EOP-S) Earth orientation parameters based on USNO VLBI global solutions. Analysis Center personnel maintain the necessary software required to continue these services to the IVS including periodic updates of the GSFC CALC/SOLVE software package. In addition to operational VLBI analysis, Analysis Center personnel are actively engaged in research related to future reference frames.

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2 Current Analysis Center Activities

2.1 IVS Experiment Analysis and Database Submission

During the 2017–2018 calendar years, personnel at the USNO VLBI Analysis Center continued to be responsible for the timely analysis of the IVS-R4 sessions, with the resulting databases submitted within 24 hours of correlation for dissemination by the IVS. Analysis Center personnel also continued analyzing IVS Intensive sessions for use in the USN-EOPI time series and continued a series of Intensive sessions using the VLBA antennas at Pie Town, NM and Mauna Kea, HI. The USNO Analysis Center continued the contributed analysis of the IVS-R1 sessions. Additionally, the Analysis Center transitioned to processing all IVS and VLBA sessions in the vgosDB format.

2.2 Global VLBI Solutions, EOP and Sinex Submission

USNO VLBI Analysis Center personnel used the periodic global TRF/CRF/EOP solutions usn2016a, usn2017a, usn2017b, usn2018a, and usn2018b over the course of the 2017–2018 calendar years. Analysis Center personnel continued to submit the USN-EOPS series, which is based upon the current global solution, and updated with new IVS-R1 and IVS-R4 sessions. The updated EOPS series is submitted to the IVS twice weekly within 24 hours of experiment correlation and is included in the IERS Bulletin A. Analysis Center personnel also continued routine submission of Sinex format files based upon the 24-hour VLBI sessions. In addition to EOPS and Sinex series, USNO VLBI Analysis Center personnel continued to produce and submit an EOPI series based upon the IVS Intensive sessions.

2.3 ICRF-3 Submission

The USNO VLBI Analysis Center generated and submitted numerous source position files from global VLBI solutions for use by the IAU ICRF-3 Working Group for comparison with those of other analysis centers.

2.4 VLBA Intensive Sessions

During the 2017–2018 calendar year, Analysis Center personnel continued a program to use the Very Long Baseline Array (VLBA) operated by the NRAO for the purpose of measuring UT1–UTC. Routine daily 1.5-hour duration Intensive observations continued using the VLBA antennas at Pie Town, NM and Mauna Kea, HI. High-speed network connections to these two antennas are now routinely used for electronic transfer of VLBI data over the Internet to a USNO point of presence. Once fully operational, it is anticipated that these VLBA Intensive sessions will be scheduled as IVS-INT4 and the data will be released to the IVS for community-wide distribution.

3 Staff

The staff of the VLBI Analysis Center is drawn from individuals in the Astrometry Department at the U.S. Naval Observatory. The staff and their responsibilities are as follows:

Name	**Responsibilities**
Alan Fey	Periodic global CRF/TRF/EOP solutions and comparisons; CRF densification research; VLBI data analysis.
Nicole Geiger	VLBI data analysis; EOP, database and Sinex submission.
Christopher Dieck	VLBI data analysis; EOP, database and Sinex submission.
Megan Johnson	VLBI data analysis; EOP, database and Sinex submission.
Lucas Hunt	VLBI calibration and image analysis; CRF source structure research
John Spitzak	USNO VLBA observing time manager; Image data archive developer

4 Future Activities

The following activities for 2019 are planned:

- Continue analysis and submission of IVS-R4 sessions for dissemination by the IVS.
- Continue the production of periodic global TRF/CRF/EOP solutions and the submission of EOP-S estimates to the IVS updated by the IVS-R1 and IVS-R4 sessions.
- Continue submission of Sinex format files based on the 24-hour sessions.
- Continue the analysis of IVS Intensive sessions and submission of EOP-I estimates to the IVS.
- Continue post-processing and analysis of VLBI Intensive data from the Mk and Pt VLBA stations.

USNO Analysis Center for Source Structure Report

Megan Johnson, Alan Fey, Lucas Hunt, John Spitzak, Christopher Dieck, Nicole Geiger

Abstract This report summarizes the activities of the United States Naval Observatory Analysis Center for Source Structure for calendar years 2017 and 2018.

1 Analysis Center Operation

The Analysis Center for Source Structure is supported and operated by the United States Naval Observatory (USNO). The charter of the Analysis Center is to provide products directly related to the IVS determination of the "definition and maintenance of the celestial reference frame." These include, primarily, radio frequency images of International Celestial Reference Frame (ICRF) sources, intrinsic structure models derived from the radio images, and an assessment of the astrometric quality of the ICRF sources based on their intrinsic structure.

The Web server for the Analysis Center is hosted by the USNO and can be accessed by pointing your browser to

`https://rorf.usno.navy.mil/ivs_saac/`.

The primary service of the Analysis Center is maintaining a Web-accessible data archive of radio frequency images of ICRF sources. We are currently in the midst of updating, improving, and expanding our archive. Historically, this Web-accessible data archive was called the Radio Reference Frame Image Database (RRFID). We are changing the name of the archive to the Fundamental Reference Image Data Archive (FRIDA) and debuting an improved, more functional interface.

FRIDA is currently in development and will contain tens of thousands of images from the Very Long Baseline Array (VLBA) as well as other radio VLBI networks at frequencies of 2.3, 8.4, 24, and 43 GHz. FRIDA will be accessible at

`https://rorf...mil/rrfid.shtml`.

FRIDA will also contain 74 images of 69 Southern Hemisphere ICRF sources using the Australian Long Baseline Array (LBA) at a radio frequency of 8.4 GHz.

Images of ICRF sources can also be obtained from the Bordeaux VLBI Image Database (BVID), which is also undergoing an update, at

`http://bvid.astrophy.u-bordeaux.fr`.

2 Current Activities

2.1 VLBA Imaging

Very Long Baseline Array (VLBA) observations for maintenance of the celestial and terrestrial reference frames have been carried out since about 1994. Since 1997, these VLBA RDV (Research and Development VLBI) observations have been part of a joint program between the USNO, Goddard Space Flight Center (GSFC), and the National Radio Astronomy Observatory (NRAO). During each 24-hour VLBA RDV session, about 100 ICRF sources are observed at S/X-band (2.3/8.4 GHz) using the VLBA together with up to ten additional geodetic antennas. Images are produced from these observations and made available through the FRIDA.

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Beginning in January 2017, USNO entered into a 50% timeshare agreement with the temporary VLBA management entity called the Long Baseline Observatory (LBO). The LBO has since been dissolved and the VLBA is once again part of the NRAO as of October 2018. Under the USNO–VLBA 50% timeshare agreement, we began observing ICRF sources for the purposes of geodesy and imaging.

In January 2017, in collaboration with Goddard Space Flight Center (GSFC), we began a new series of observations called the UF/UG-series. This series is observed at S/X-band (2.3/8.4 GHz) and is dual purposed in that the 24-hour experiments are designed for geodesy but scheduled to optimize the *uv*-coverage of each source for imaging. The UF/UG-series contain roughly 300 sources per session, most of which are primarily from the VLBA Calibrator Survey (VCS) catalog. Understanding the source structure characteristics of the objects in the VCS catalog is paramount to improving and maintaining the ICRF because of the high number density of VCS sources in the current ICRF-3 iteration.

In addition to the UF/UG-series, USNO has also been supporting a VLBA project at K-band under our timeshare agreement. The principal investigator of this project is Aletha de Witt from Hartebeesthoek Radio Astronomy Observatory (HartRAO). Nearly all of the K-band data that is included in the newly adopted ICRF-3 has come from this project. These observations are also maximized for imaging and we plan to include these K-band images in our FRIDA Web-accessible data archive once they become available.

3 Staff

The staff of the Analysis Center during 2017 and 2018 consisted of Megan C. Johnson, Alan L. Fey, Lucas R. Hunt, John Spitzak, Christopher A. Dieck, and Nicole P. Geiger.

4 Future Activities

The Analysis Center currently has a program of active research investigating the effects of intrinsic source structure on astrometric position determination. Results of this program are published in the scientific literature.

The following activities for 2019 are planned:

- Continue with the imaging and analysis of VLBA 2.3/8.4 GHz experiments.
- Continue the development of the Fundamental Reference Image Data Archive (FRIDA) as a Web-accessible database of radio frequency images of ICRF sources.
- Continue maintenance work of source structure for ICRF-3.

5 Relevant Publications

Publications of relevance to Analysis Center activities:

- "The Precious Set of Radio-optical Reference Frame Objects in the Light of *Gaia* DR2 Data," Makarov, V. V., Berghea, C. T., Frouard, J., Fey, A., & Schmitt, H. R., 2019, ApJ, 873, 132
- "Toward the ICRF3: Astrometric Comparison of the USNO 2016A VLBI Solution with ICRF2 and *Gaia* DR1," Frouard, J., Johnson, M. C., Fey, A., Makarov, V. V., & Dorland, B., 2018, AJ, 155, 229
- "Astrometric Evidence for a Population of Dislodged AGNs," Makarov, V. V., Frouard, J., Berghea, C. T., Rest, A., Chambers, K. C., Kaiser, N., Kudritzki, R.-P., & Magnier, E. A., 2017, ApJ, 835, 30
- "Second Epoch VLBA Calibrator Survey Observations: VCS-II," by Gordon, D., Jacobs, C., Beasley, A., Peck, A., Gaume, R., Charlot, P., Fey, A., Ma, C., Titov, O., & Boboltz, D., 2016, AJ, 151, 154
- "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry," by Fey, A., et. al., 2015, AJ, 150, 58
- "Relativistic Jets in the Radio Reference Frame Image Database. II. Blazar Jet Accelerations from the First 10 Years of Data (1994-2003)," Piner, B. G., Pushkarev, A. B., Kovalev, Y. Y., Marvin, C. J., Arenson, J. G., Charlot, P., Fey, A. L., Collioud, A., & Voitsik, P. A. 2012, ApJ, 758, 84
- "Characterization of long baseline calibrators at 2.3 GHz," Hungwe, F., Ojha, R., Booth, R. S., Bietenholz, M. F., Collioud, A., Charlot, P., Boboltz, D., & Fey, A. L. 2011, MNRAS, 418, 2113.
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Vienna Special Analysis Center Annual Report 2017/2018

Johannes Böhm [1], Sigrid Böhm [1], Jakob Gruber [1], Andreas Hellerschmied [2], Hana Krásná [1], Daniel Landskron [1], David Mayer [2], Markus Mikschi [1], Matthias Schartner [1], Helene Wolf [1]

Abstract Since July 2018, following the signing of a Memorandum of Understanding with the President of BEV, the Federal Agency of Metrology and Surveying in Austria, VIE is run as a joint Analysis Center by Technische Universität Wien (TU Wien) and BEV aiming at increased participation in the operational generation of geodetic products, such as the routine determination of Earth orientation parameters. The main activities by VIE in 2017 and 2018 are related to the further development of the Vienna VLBI and Satellite Software (VieVS), for example, with respect to the implementation of the vgosDB format. Furthermore, we have developed a new scheduling software VieSched++ as part of VieVS and we have submitted solutions for the ICRF-3, the most recent realization of the International Celestial Reference Frame.

1 General Information

The Department of Geodesy and Geoinformation in the Faculty of Mathematics and Geoinformation of TU Wien is divided into seven Research Divisions. One of those, the Research Division Higher Geodesy (HG) with about twenty members, is focusing on satellite geodesy and geodetic VLBI.

The Federal Office of Metrology and Surveying (Bundesamt für Eich- und Vermessungswesen, BEV) is the body responsible for official surveying, geoinformation and weights and measures (metrology) in Austria. Currently, it belongs to the Federal Ministry on Digital and Economic Affairs. The Department of Control Survey at BEV is divided into several sections, such as on reference systems or geophysics and precise levelling. VLBI staff at BEV is attached to those two sections.

1. Technische Universität Wien
2. Bundesamt für Eich- und Vermessungswesen

VIE Analysis Center

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2 Staff

Personnel at TU Wien and BEV associated with the IVS Special Analysis Center in Vienna and their main research fields and activities are summarized in Table 1. The staff members at TU Wien are partly paid by TU Wien and partly funded by the Austrian Science Fund (FWF) within several projects listed in the acknowledgements.

Figure 1 shows some of the current members of VIE together with former members at the excursion to Ny-Ålesund held as part of the IVS General Meeting 2018.

3 Current Status and Activities

3.1 Global Reference Frames and Earth Orientation

Although not yet an operational Analysis Center of the IVS, we routinely analyze all IVS 24-hour sessions and submit SINEX files for the R1 and R4 sessions to the IVS Combination Center at BKG. Based on the cooperation with BEV, we are planning to become an operational Analysis Center in the near future.

Fig. 1 Current and former members of the IVS Analysis Center VIE at the excursion to Ny-Ålesund in June 2018 held during the IVS General Meeting 2018. From left to right: Johannes Böhm, David Mayer, Jakob Gruber, Matthias Schartner, Andreas Hellerschmied, Maria Karbon (now at Observatoire de Paris), and Benedikt Soja (now at NASA JPL).

Table 1 Staff members ordered alphabetically with the main tasks related to VLBI.

Johannes Böhm	Reference frames, Chair of HG
Sigrid Böhm	VieVS admin, Earth orientation
Jakob Gruber	Correlation, vgosDB in VieVS
Andreas Hellerschmied	Operational VLBI processing, VLBI to satellites
Hana Krásná	Reference frames, VLBI global solutions
Daniel Landskron	Troposphere delay models
David Mayer	Operational VLBI processing, celestial reference frames
Markus Mikschi	Support for correlation activities
Matthias Schartner	Development of VieSched++, scheduling VLBI sessions, ringlaser
Helene Wolf	Scheduling VLBI observations to satellites

In 2017 and 2018, we have contributed to the ICRF-3 Working Group of the International Astronomical Union (IAU) by regularly submitting CRF solutions determined with VieVS (Mayer, 2019 [6]) (compare Figure 2). Special emphasis was put on the determination of galactic aberration from the history of VLBI observations and on the impact of different analysis strategies, such as different tropospheric delay models or the application of different datum stations. Mayer (2019 [6]) has also carried out detailed comparisons against celestial reference frames from the ESA Gaia mission.

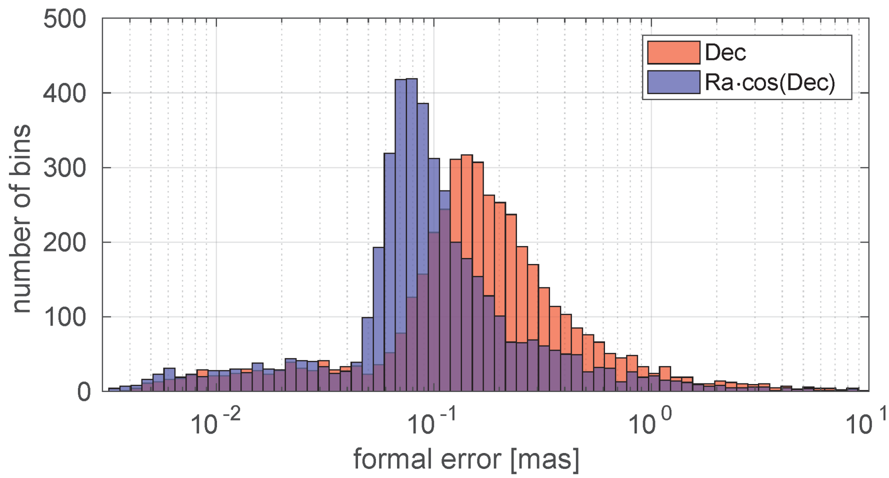

Fig. 2 Distribution of the formal uncertainties in the Vienna solution to the ICRF-3 ([6]). Please note that the errors are not scaled.

3.2 Tropospheric Delays

We are providing the parameters of the Vienna Mapping Functions (VMF) to the scientific community, both from analysis data as well as from forecast data of the European Centre for Medium-range Weather Forecasts. It should be mentioned that we moved the provision of the coefficients from the server *http://ggosatm.hg.tuwien.ac.at/* to the new server *http://vmf.geo.tuwien.ac.at/*. There, we are not only providing parameters of VMF1, but also of the recently developed VMF3 (Landskron and Böhm, 2017 [4]) and the corresponding horizontal gradients model GRAD (Landskron and Böhm, 2018 [5]). Besides the troposphere delay models we also provide a complete database of ray-traced delays for each geodetic VLBI observation since 1980. The software VieVS can apply these ray-traced delays directly in VLBI analysis. An individual ray-tracing tool enables creating ray-traced delays also for GNSS and DORIS stations. Additionally, the code of our ray-tracing software RADIATE (Hofmeister and Böhm, 2017 [3]) has been made freely available via GitHub at *https://github.com/TUW-VieVS/RADIATE*, providing users with even more flexibility in creating their own ray-traced delays. For the future, we plan to compute all models for optical wavelengths as well, so that they can be used for the analysis of SLR observations, too.

3.3 Development of VieVS

VieVS stands now for Vienna VLBI and Satellite Software (Böhm et al., 2018 [1]) and is the umbrella brand for our software activities at the Research Division HG. It does not only comprise the VLBI modules but also the ray-tracing module, upcoming SLR and GNSS-PPP modules, or the new scheduling tool VieSched++ written in C++ (Schartner and Böhm, 2019 [8]). The VLBI module is capable of using and analyzing files in the vgosDB format. VieSched++ has already been successfully tested for various session types, e.g., INT3 or T2 sessions. It is based on a multi-scheduling approach, i.e., a large number of schedules is generated and the best one is selected based on Monte-Carlo simulations.

We want to highlight here that we are now providing VieVS via Github: https://github.com/TUW-VieVS. As in previous years, we are going to organize VieVS Days at TU Wien from 15 to 17 October 2019 where participants have the chance to get to know VLBI analysis with VieVS as well as the scheduling of geodetic and astrometric VLBI sessions.

3.4 VLBI Observations to Satellites

In 2017 and 2018, we have completed and summarized our work on VLBI observations to satellites. The observations to GNSS satellites are documented by Plank et

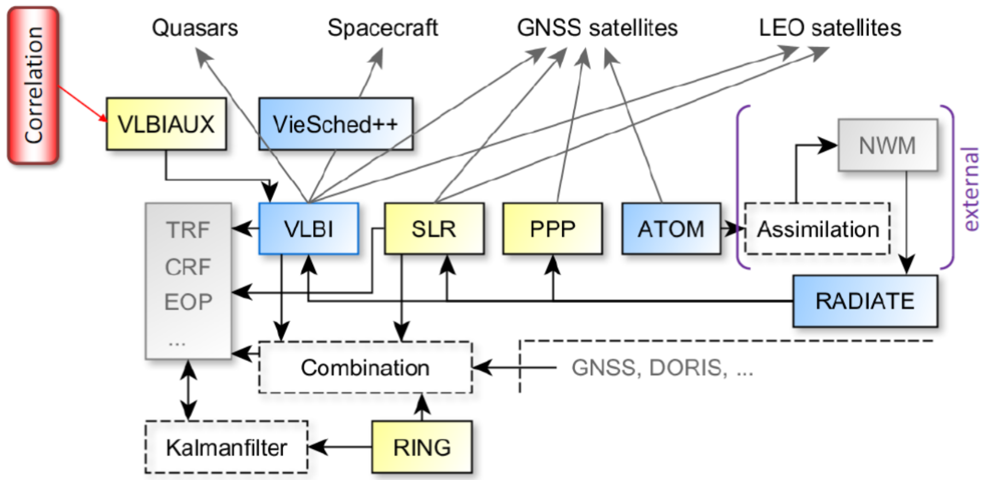

Fig. 3 Planned future developments of the Vienna VLBI and Satellite Software (VieVS). The boxes in blue are already quite mature and distributed via Github, whereas the boxes in yellow are under development.

al. (2017 [7]) and the observations to APOD by Hellerschmied et al. (2018 [2]). With both experiments, we reach an accuracy of a few nanoseconds for the observed delays. At the moment, we are working on the implementation of satellite observations in the new VieSched++ scheduling tool.

4 Future Plans

We plan to become an operational IVS Analysis Center in the near future. Since we also host an IVS Correlation Center, we plan to close the gap between the correlation output and the analysis of VLBI observations with the VLBI module of VieVS. In other words, we will add the ambiguity resolution and the ionosphere calibration to the VieVS package.

Acknowledgements

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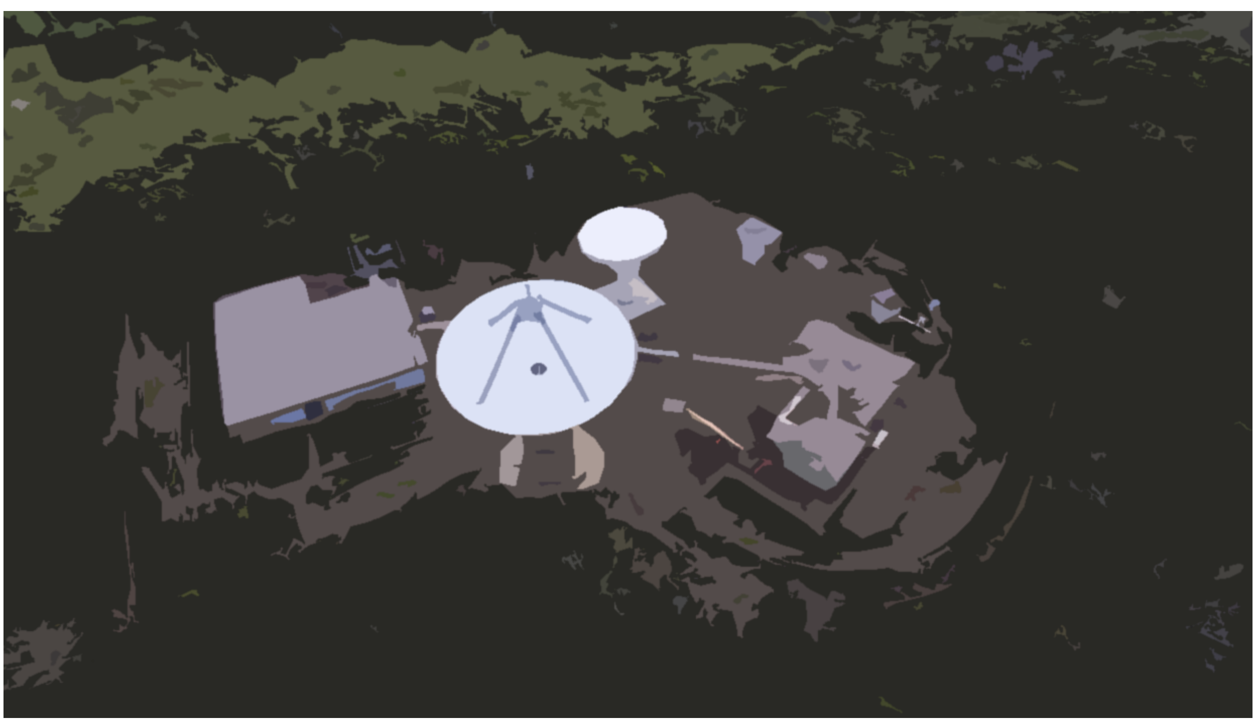
TECHNOLOGY DEVELOPMENT CENTERS



GSFC IVS Technology Development Center

Ed Himwich, John Gipson, Dave Horsley, Mario Bérubé

Abstract This report summarizes the activities of the GSFC Technology Development Center (TDC) and describes plans for the future. The GSFC TDC develops station software including the Field System (FS), Monitoring and Archiving System (MAS), IVS session Web pages, and scheduling software (*sked*); hardware including tools for station timing and meteorology; scheduling algorithms; and operational procedures. It provides a pool of individuals to assist with station implementation, check-out, upgrades, and training.

1 General Information

The GSFC IVS Technology Development Center (TDC) develops hardware, software, algorithms, and operational procedures. It provides manpower for station visits for training and upgrades. Other technology development areas at GSFC are covered by other IVS components such as the GSFC Analysis Center. The current staff of the GSFC TDC consists of John Gipson, Ed Himwich, Dave Horsley, and Mario Bérubé. The remainder of this report covers the status of the main areas supported by the TDC.

2 Field System

The GSFC TDC is responsible for the development, maintenance, and documentation of the Field System (FS) software package. The FS provides equipment control at VLBI stations. It interprets the `.snp` schedule and `.prc` procedure files (both as prepared by *drudg* from the `.skd` schedule). The FS controls the antenna, data acquisition hardware, and related ancillary equipment needed for making VLBI measurements. All major VLBI data acquisition backends are supported. The FS is customizable to allow it to control station specific equipment. It is used at almost all of the IVS Network Stations (more than 35) and also at many stations that perform VLBI only for astronomical observations. The only major VLBI facilities not using the FS are the LBO and VERA.

There are two major branches of the FS currently: the "main" branch, which is used for most operational observing, and the "VGOS" branch, which is used in the operational test observations at VGOS stations. During this period, there was one major release of the FS (9.13.0) for the main branch. Full details can be found in the FS release notes. The VGOS branch had two minor updates (9.12.12 and 9.12.13).

2.1 Main Branch Changes

In the main branch of the FS the most significant changes were:

- A display server was added as an option. If enabled, this separates the core of the FS from the user interface and makes it possible to run multiple independent instances of the user interface. This allows, for example, both local and remote interfaces to run at the same time—the latter typically via an *ssh* connection. Since the user interfaces run independently of the core of the FS, they

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can be started and stopped without affecting the operation of the FS. One advantage of this is that closing a window can now not accidentally kill the FS. This also includes implementation of a publication/subscription model for FS log display and error report output.
- Support for two VSI outputs for DDC racks that include a FiLa10G was added. This also includes support for output on either VSI1 or VSI2 for modes that have different track mappings between the two VSI outputs.
- Improved support for configuration of recording modes for VDIF recorders running *jive5ab* was added. These changes include full 64-bit integer support (exact) for recording bit rates for all possible recording rates supported by *jive5ab*.
- The VEX parser was updated to accept units for rates in the `clock_early` statements.
- Support was added for user radiometry devices that cannot have a "zero" level measured.
- Support for NMEA standard wind sensors was added.

2.2 VGOS Branch Changes

In the VGOS branch of the FS the most significant changes were:

- Support for a preliminary version of the Display Server (see above in the main branch changes) and eventually the full version was added.
- Support for DBBC3 BBC and IF device set-up and monitoring was added. This includes support for Tsys, pointing measurements (with *fivpt*), and SEFD measurements (with *onoff*). Currently, this does not include time setting and monitoring or VDIF output format control.

2.3 Plans for Next Year

Several other improvements are expected in future releases, including:

- Support for continuous calibration with the DBBC PFB personality.
- Support for chopper-wheel and hot/cold load calibration methods.
- A complete update to the documentation and conversion to a more modern format that will be easier to use and maintain.
- Conversion of the FORTRAN source code to use the *gfortran* compiler, which will enable use of the source level debugger, *gdb*, for development and field debugging.
- Support for 64-bit Linux OSs.
- *Chekr* support for Mark 5A and Mark 5B systems.
- FS Linux 10, based on Debian *Stretch*.
- Support for periodic firing of the noise diode during observations.
- Completion of the VEX2 standard and implementation of it.
- Further unification of the Patriot 12-m (GGAO) and ISI 12-m (Kokee Park and McDonald) antenna interface code. This will allow a common code base to be used for the two very similiar Antenna Control Units (ACUs).

3 Monitor and Archiving System (MAS)

The GSFC TDC is also responsible for development, maintenance, and documentation of the Monitoring and Archiving System (MAS) software package—formerly named TIG after its components: Telegraf, InfluxDB, and Grafana—and hardware specification. The MAS provides a system for collecting, storing, processing, and visualizing time-series data collected from various components of a VLBI station. The software suite is comprised of several open-source packages along with some custom software specific for VLBI stations. The system is capable of collecting data from the Field System and PC diagnostic subsystems as well as certain meteorological devices, back-ends, and antennas. The suite can easily be expanded to include site-specific data. Currently the system is deployed at the NASA managed stations, and the hardware specification and software are available to the community.

The most significant changes were:

- The MAS was expanded to include an operating system and hardware configuration guideline. The suite was developed to monitor more station components of both general and site specific functionality.

4 IVS Session Pages

The GSFC TDC is responsible for development and maintenance of the IVS session pages. The pages display the master schedule and session files in a human friendly format.

The most significant changes of the IVS session pages were:

- The IVS session pages were updated to be generated using a more modern, Python-based framework.

5 *sked* and *drudg*

The GSFC TDC is responsible for the development, maintenance, and documentation of *sked* and *drudg*. These two programs are very closely related, and they operate as a pair for the preparation of the detailed observing schedule for a VLBI session and its proper execution in the field. In the normal data flow for geodetic schedules, first *sked* is run at the Operation Centers to generate the `.skd` file that contains the full network observing schedule. Then stations use the `.skd` file as input to *drudg* for making the control files and procedures for their station. Catalogs are used to define the equipment, stations, sources, and observing modes which are selected when writing a schedule with *sked*.

Changes to *sked* and *drudg* are driven by changes in equipment and by feedback from the users. The following summarizes some of the important changes to these programs during 2017–2018 and plans for the future. This list includes only the most important bugs which were found and fixed over this period. A more complete summary of the changes can be found in the *change_log.txt* files associated with *sked* and *drudg*.

5.1 *sked* Changes and Bug Fixes

Enhancements:

- Skeleton support for TWIN telescopes. We put in the bookkeeping for *sked* to recognize that a station is part of a pair of TWINS, but we have not modified the scheduling algorithms yet.
- Removal of numerous (although not all) tape related information. For example, *sked* will no longer write out the obsolete HEAD_POS or PASS_ORDER information.
- Modification so that bandwidth can vary from station to station.
- Modification so that *sked* can now compile under *gfortran*. In the process, numerous sleeping bugs were fixed.
- Second personality. Previously supported DBBC equipment as only the DDC personality. Now *sked* supports DBBC_DDC and DBBC_PFB.

Important bug fixes:

- If there was a problem with Cable-Wrap, *sked* would write out the wrong station.
- In tag-along mode, *sked* was not calculating the SNR correctly.

5.2 *drudg* Changes

The most significant changes in *drudg* were:

- Ad-hoc support for *sched* “staggered start mode” was added. In this mode, scans start at different times for different stations and the data valid time is when the antenna is expected to reach the source. This mode violates the observation time-line that *drudg* assumes, so it is not possible to fully support this mode. But, the added support eliminates useless data recording while slewing, takes calibration data after the antenna is expected to be onsource, and marks the data valid after the calibration is finished. These changes were accomplished with a minimum loss of data due to calibration (10 seconds or less).
- Support for modes that use VSI2.
- Reporting an error for a VEX file if a station is in a scan but was not defined previously. This occurred with a schedule that was modified ‘by hand.’
- Numerous minor changes to support changes in the SNAP language.
- Better debugging information if *drudg* cannot find an allowed mode for DBBCs.

5.3 Catalog Changes

The *sked* catalogs were updated during 2017–2018 to reflect the new stations coming on line: RAEGSMAR, NYAL13S, NYALE13N, ONSA13NE, and ONSA13SW. The catalogs were also updated to reflect equipment changes, as more and more stations switched to digital equipment and as new kinds of digital equipment came into use.

5.4 Plans for Next Year

Plans for next year include the following:

- Make VEX/VEX2 the native format for *sked*: no more `.skd` files.

IAA Technology Development Center Report for 2017–2018

Evgeny Nosov, Evgeny Khvostov, Alexander Vytnov

Abstract In 2018, the IAA finished the construction of a new 13-meter radio telescope (RT-13) at the Svetloe observatory. The main activity of the IAA Technology Development Center was focused on equipping the new antenna with a VGOS-compatible signal chain and a clock and frequency distribution system. The presented report briefly gives an overview of this activity.

1 General Information

In 2015 two multi-band, fast rotating antennas with a mirror diameter of about 13.2-m (RT-13) were installed at the Zelenchukskaya and Badary stations [1]. The inaugural ceremony of the third RT-13 radio telescope at the Svetloe observatory was held on September 19, 2018. Each RT-13 radio telescope is equipped with a specially designed receiver system. The main feature of this system is the cryogenic receiver unit that includes a cooled tri-band feed and low-noise amplifier. Such a design makes it possible to achieve high sensitivity and to receive weak noise signals of cosmic origin. As well, the feed design allows us to receive signals in three frequency bands: S (2.2—2.6 GHz), X (7.0—9.5 GHz), and Ka (28—34 GHz) in both circular polarizations simultaneously [2].

Institute of Applied Astronomy (IAA RAS)

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2 Wideband Receiver

The UWB (ultra-wideband) receiving system designed in the IAA RAS is purposed for implementation at the “Quasar” VLBI Network RT-13 radio telescopes [3]. The UWB receiving system operates in 3–16 GHz band on dual linear orthogonal polarizations. It is fully compatible with RT-13 mechanical, cryogenic, and electric interfaces. It is supposed that the UWB system can replace the Tri-band system and be replaced by it on demand.

The UWB system operates the following way. The radiation from a source, focused by the dish and the subreflector, comes through the radio-transparent cover of the cryo unit to the focal center of the QRFH feed, where it is separated into vertical and horizontal linear polarizations. Two signals, mixed with calibration signals at the direct coupler, are amplified with cryogenic LNAs, and every signal is divided four ways by the splitter unit. The splitter unit also includes room temperature pre-amplifiers. Dual-channel FCUs use up-down conversion to select from the input range 3–16 GHz, 1 GHz band, to the BRAS system [4] bandwidth (1–2 GHz).

3 Multifunctional Digital Backend (MDBE)

The MDBE is intended for equipping all radio telescopes of the “Quasar” VLBI network with a unified, both legacy- and VGOS-compatible, digital backend. The system consists of up to 12 DPS units, connected by backplane with the Synchronization and Control Unit (Figure 1). Each DSP unit digitizes an input IF signal by using the 4096 MHz sampling frequency, performs necessary digital processing in the FPGA, and outputs the data through a 40 Gpbs or 10 Gbps fiber optical link. Table 1 presents the basic parameters of the MDBE.

Table 1 Basic parameters of MDBE.

Number of IF inputs (DSP units)	up to 12
Input frequency range	0.5–2048 MHz
Sampling frequency	4096 MHz
Synchronization	5/10/100 MHz 1 PPS (two inputs) 1 PPS monitor
Outputs per DSP unit	1x10 Gbps (SFP+) 1x40 Gbps (QSFP)
Output format	VDIF in raw Ethernet frames VDIF in UDP packets
Calibration features	PCAL extractor & analyzer Inner delay variation control Noise calibration
Control interface	10/100/1000 Ethernet (Fiber or copper)
Basic VLBI modes	Wideband channels: 2048, 1024, or 512 MHz DDCs mode: 8, 16, or 32 MHz
Size	19” 3U case + 1U fan unit

Like the previous backend, the BRAS [4], the MDBE will be located in the focal cabin of the antenna, near to the receiver. As there is no direct access to the system for the staff while observing is in progress, the MDBE provides full remote control of the system and signals. The control features include measuring voltages, currents, fan speed, and temperatures in key points of the system. Each DSP unit logs signal power, statistics of 2-bit output data, the extracted PCAL signal (in the time domain), estimation of its group delay, and phases and amplitudes of the tones. MDBE has an embedded calibration system that allows it to control the phase/delay stability of the clock synthesizer and ADCs.

Currently the design stage is finished, and the first sample of the MDBE is in production. Figure 2 presents the view of the DSP unit without a radiator and a front panel. The radiator (not shown in the figure) covers the board to effectively remove the heat produced by the FPGA, the ADC, and other parts. It also divides the board into a few partitions to shield sensitive ADC parts from a noisy digital environment. The clock generator (Figure 3), which is a part of the Synchronization and Control Unit, also has been produced and is undergoing testing.

The first field test of the MDBE is planned for the end of 2019 at the RT-13 at Svetloe. It will work in BRAS-compatible mode, producing four 512 MHz channels. We plan to equip all three RT-13 antennas with eight channel MDBEs in 2020. The firmware implementing the digital downconverter (DDC) mode has to be ready until the summer of 2020. From that time, the antenna at Svetloe will be able to participate in international VGOS observing.

4 Clock and Frequency Distribution System

The frequency and time distribution equipment with the phase calibration system is located in the RT-13 elevation cabin. The frequency distribution system transmits the 100 MHz reference frequency signal from the H-maser to consumers via a fiber-optic communication line. The equipment measures the electrical lengths of the reference frequency path from the H-maser simultaneously to the BRAS (to the MDBE in the future) and the PCAL generator. The resolution of the delay meter is 1 ps.

5 Future Plans

Currently we perform regular observations with the three RT-13s four to five times per day in S/X and S/X/Ka bands. We register up to four channels with 512 MHz bandwidth and a total data rate of 8 Gbps. The average recorded data rate is 8 TB per day in 24/7 mode. In 2020 we plan to participate in international VGOS observing by using the RT-13 at Svetloe.

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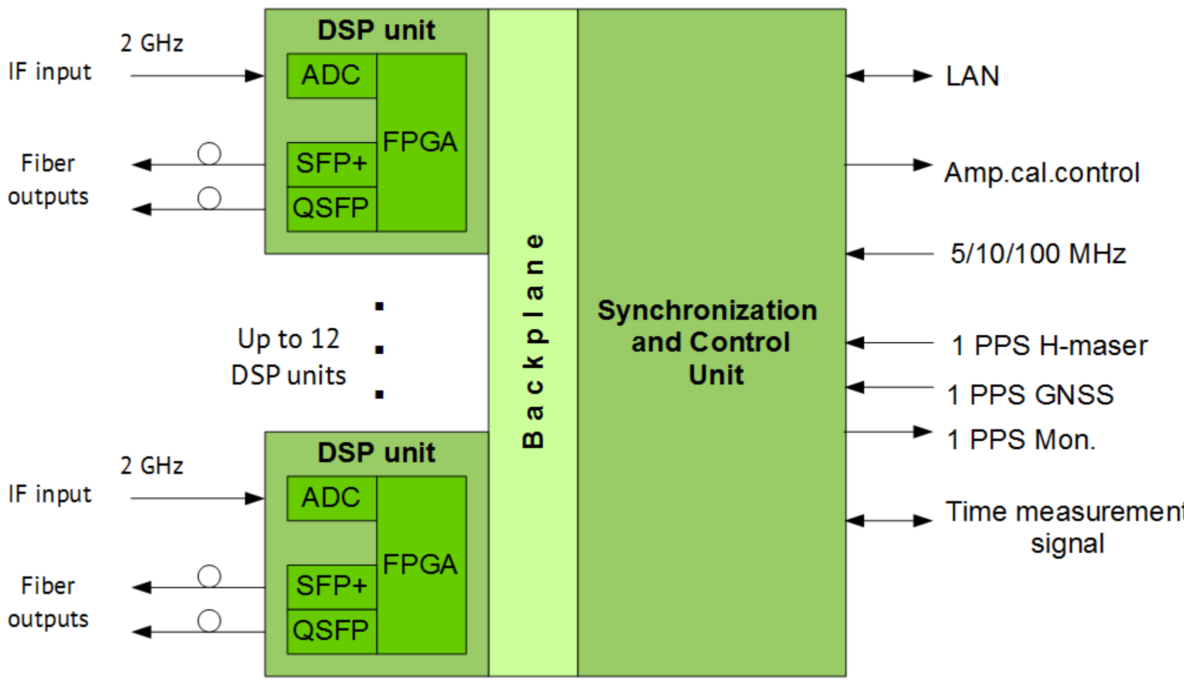

Fig. 1 MDBE structure.

Fig. 2 DSP unit without radiator, front-end board, and front panel.

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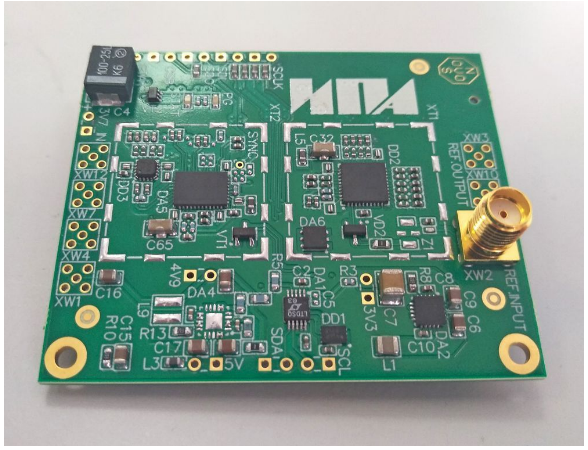

Fig. 3 Clock synthesizer without shields.

NICT Technology Development Center 2017+2018 Biennial Report

Kazuhiro Takefuji, Hideki Ujihara

Abstract The National Institute of Information and Communications Technology (NICT) is developing and testing VLBI technologies and conducts observations with this new equipment. This report gives an overview of the Technology Development Center (TDC) at NICT and summarizes recent activities.

1 NICT as IVS-TDC and Staff Members

The National Institute of Information and Communications Technology (NICT) publishes the newsletter "IVS NICT-TDC News (former IVS CRL-TDC News)" at least once a year in order to inform about the development of VLBI related technology as an IVS Technology Development Center. The newsletter is available at the following URL: `http://www2.nict.go.jp/sts/stmg/ivstdc/news-index.html`. Table 1 lists the staff members at NICT who are contributing to the Technology Development Center.

Table 1 Staff members of NICT TDC as of January 2017 (alphabetical).

HASEGAWA, Shingo	KAWAI, Eiji
MIYAUCHI, Yuka	SEKIDO, Mamoru
TAKEFUJI, Kazuhiro	TSUTSUMI, Masanori
UJIHARA, Hideki	

Kashima Space Technology Center, National Institute of Information and Communications Technology

NICT Technology Development Center

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2 General Information

We have been developing a broadband VLBI system called GALA-V, which has to meet the VGOS (VLBI Global Observing System) requirements among others, and also upgrading Cassegrain optics antennas such as our 34-m radio telescope and compact telescopes for the project of Time and Frequency transfer.

3 The 2.4-m Diameter Compact Antenna Installed in Medicina for Time & Frequency Transfer by VLBI

In March 2018, the 2.4-m diameter compact telescope installed at NMIJ at Tsukuba was moved to Kashima so maintenance could be performed. Then, all instruments were packed and transferred to the Medicina observatory in Bologna in May 2018. We visited Bologna to install the compact antenna in summer 2018. After we spent one week, the antenna was successfully installed, and we got first fringes between Ishioka and Medicina during our visit (Figure 1).

4 Broadband VLBI on Italy and Japan Baseline

We have conducted VLBI experiments for optical clock comparison on an Italy–Japan intercontinental baseline. A reference signal generated by the Yb optical lattice clock at INRIM in Torino is provided to Medicina by a stabilized optical fiber link. The

Fig. 1 Memorial picture when the 2.4-m diameter compact telescope was successfully installed at Medicina observatory.

Sr lattice clock has been operated at the NICT headquarters. These two optical lattice clock signals were compared by a series of VLBI experiments via VLBI network observations with transportable 2.4-m diameter broadband VLBI stations at the Medicina radio astronomy observatory of INAF in Italy and the NICT headquarters at Koganei, Japan and the 34-m radio telescope at Kashima. Hydrogen masers are used as reference signal for the VLBI observations, and the behavior of these masers as a fly-wheel for maintaining clocks is monitored at each end with optical clocks, which were operated intermittently. The VLBI link of the frequency transfer will be compared with the GPS link as an alternative technique.

Since October 2018, we have conducted standard geodetic VLBI experiments, where multiple radio sources in different parts of the sky are observed alternately. We chose about 20 compact quasars, whose flux densities are mostly over 1 Jy, from the radio catalogs in a single session. NINJA feeds originally developed for broadband, which are capable of observing in a 3.2 to 14.4 GHz frequency range, are mounted at the two 2.4-m diameter VLBI antennas and the Kashima 34-m antenna. A single linear receiver is equipped at these small VLBI stations and dual linear polarization at the 34-m VLBI station.

The initial observation was made at the 5.5 GHz, 8.0 GHz, 10.0 GHz, and 12.8 GHz radio frequencies with 1-GHz bandwidth each. A high speed RF-direct sampling technique, which digitizes the radio signal at 16 GHz sampling, enables stable group delay measurements in a broad frequency range. About 60 TB of observation data at Medicina was transferred on average at 5 Gbps to Kashima in two days for each session via high speed research networks by using jive5ab. Over the next four days, we correlated a total of 240 TB with the GICO3 software correlator. For post processing, two linear polarization datasets (V-V and H-V) are combined with compensation for the delay and the phase differences (shown in the left panel of Figure 2). Signals over the broad frequency range are synthesized by wideband bandwidth synthesis with correction of the ionospheric delay. The right panel of Figure 2 shows the measured ΔTEC effect during the session.

5 Holographic Measurement of Kashima 34-m RT by Applying VLBI Technology

Holographic measurements are performed by applying the correlation between a reference antenna and a target antenna. Normally the direction of the reference antenna is toward a stationary orbit satellite, and the target antenna drives in a zigzag motion toward the satellite so that it covers a beam pattern map of the target antenna. The two dimensional beam pattern after correlation has a Fourier relationship between the illumination pattern and the displacement distribution of the target surface. Thus, a wider angle observation makes a finer result.

The repair work of the main mirror of the Kashima 34-meter telescope in summer 2018 was anticipated to shift the main mirror and degrade the sensitivity. Actually, our staff reported a change of a few cm during the repair work. We developed the holographic measurement with applying the VLBI technology (see Figure 3) and performed it before and after the repair work. Data reduction of the holographic measurement was performed as follows:

1. Acquiring data by K5/VSSP32 at 16-Msps, 8-bits.
2. Correlating the 8-bit data by GICO3 and outputting the data every 10 ms.
3. By comparing the antenna log and the correlation output, representing the correlation output in the Az and El domain.
4. Performing a two dimensional Fourier transform with rough removal of the phase offset and the phase slope.

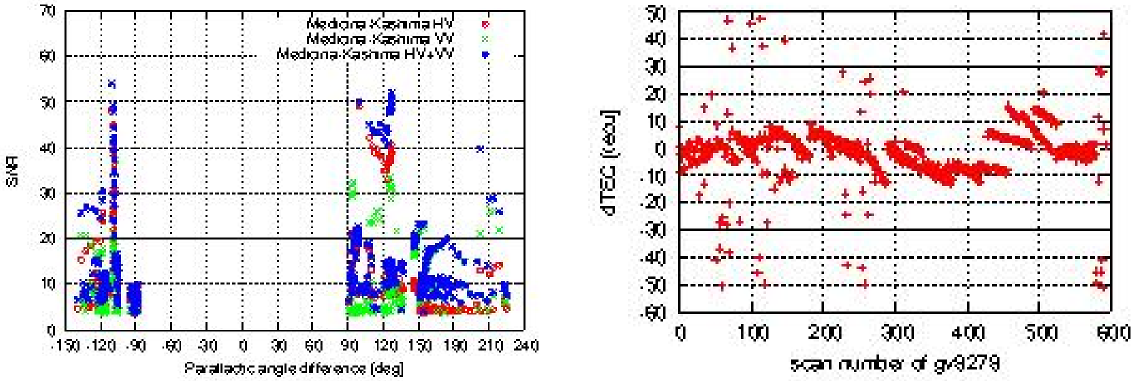

Fig. 2 Left: red circles show the Hpol-Vpol correlation results for the Kashima and Medicina baseline, and green crosses are for the Vpol-Vpol results. After two polarization pairs were synthesized, the SNRs shown as blue asterisks improved. Right: ionospheric effect by wide bandwidth synthesis clearly appears with a large variation on the Italy and Japan baseline in a 30-hour session.

5. Performing the least squares method to remove the phase offset accurately.
6. Calculating the displacement value at each bolt position on the antenna surface.
7. Let's adjust the surface!

Figure 4 shows the measurement system. Here, signals from two antennas are transferred to the observation room, and we record the data by K5/VSSP32 after a single down-conversion is done. After the repair work was completed, we iteratively adjusted the main surface based on the holographic measurements. The results are shown in Figures 5 and 6. The RMS just after the repair work was completed was 1.5 mm, and the RMS after the adjustment of the surface was 0.3 mm.

Fig. 3 Reference antenna and Kashima 34-m RT during the holographic measurement.

6 Wideband Feed Development

6.1 Kashima 34-m Antenna

The NINJA feed for the 34-m antenna was replaced by a newly developed feed. The distinguishing feature of this feed is shorter length and less weight than the previous one (Figure 7). Before replacing the old feed, the far-field patterns of the new one were measured by a near field scanner in the radio shielded room at METLAB at Kyoto University. Also, the aperture efficiency after installation at the 34-m RT is 30–40% and nearly flat at upper frequencies with ripples over 3.2–14.4 GHz. The ripples will be improved by reducing the return loss of the OMT and anti-reflection coating of the lenses in future development.

6.2 MARBLEs: The 2.4-m Diameter Antenna

MARBLE1 was moved to the Medicina radio observatory in Italy for intensive experiments of VLBI T&F transfer with Japan. Both MARBLE1 and MARBLE2 were refurbished with rigid and light weight CFRP pipes as a pillar to keep their mirrors at ±1mm ac-

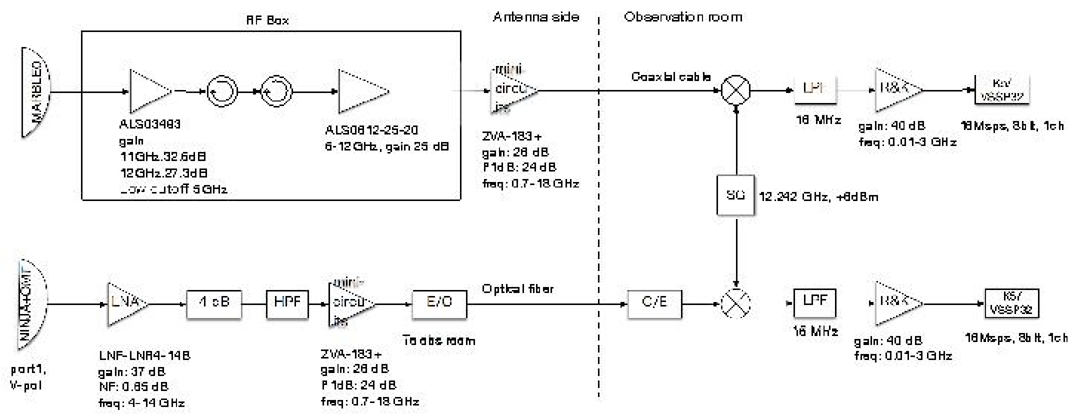

Fig. 4 System diagram of the holography measurement.

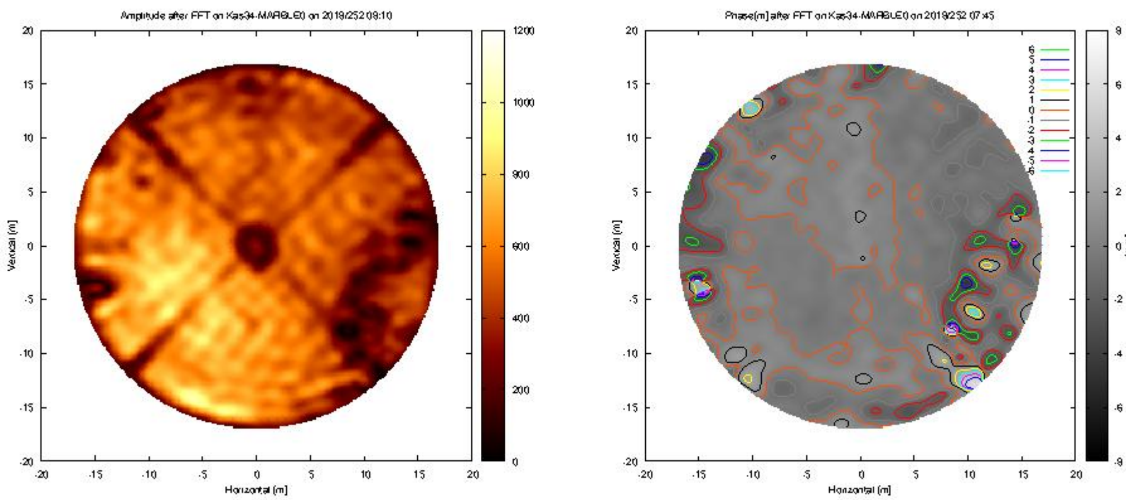

Fig. 5 Left: obtained illumination pattern. The cross in the figure was caused by four pillars that support the secondary mirror. Right: displacement distribution (right) of the Kashima 34-meter telescope just after the repair work was completed. Some messy regions due to the repair work and the 30 years of aging can be found in both figures.

curacy, and the NINJA feeds were replaced with new OMTs and lenses (Figure 8). RF over the fiber system of MARBLE1 was also replaced to improve stability before shipment to Bologna in May 2018.

6.3 Ortho Mode Transducer (OMT)

Extremely strong RFI under 3 GHz had made an inter-modulated noise and pushed up the noise temperature of our Gala-V system. Thus, dedicated OMTs with sharpened skirts under 3.2 GHz to cut such RFI were developed, and they replaced the previous OMTs of NINJA feeds in the 34-m antenna and the MARBLEs.

7 Future Development Plans

Development of a new water vapor measurement system with a 20–60 GHz wideband feed and preliminary research for a 1.5–15.5 GHz wideband second focus feed for the BRAND project were started.

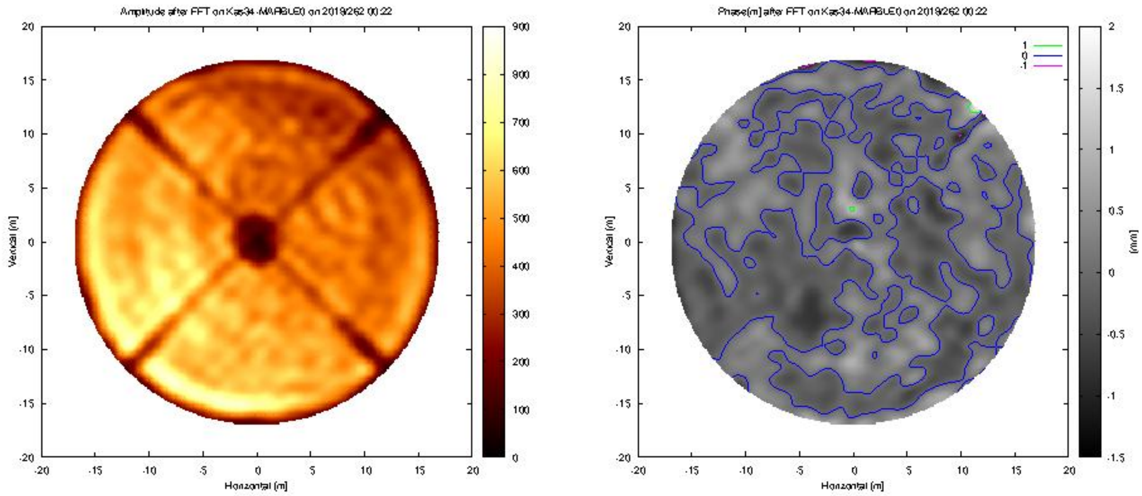

Fig. 6 Same as Figure 5 but after the careful surface adjustment was completed.

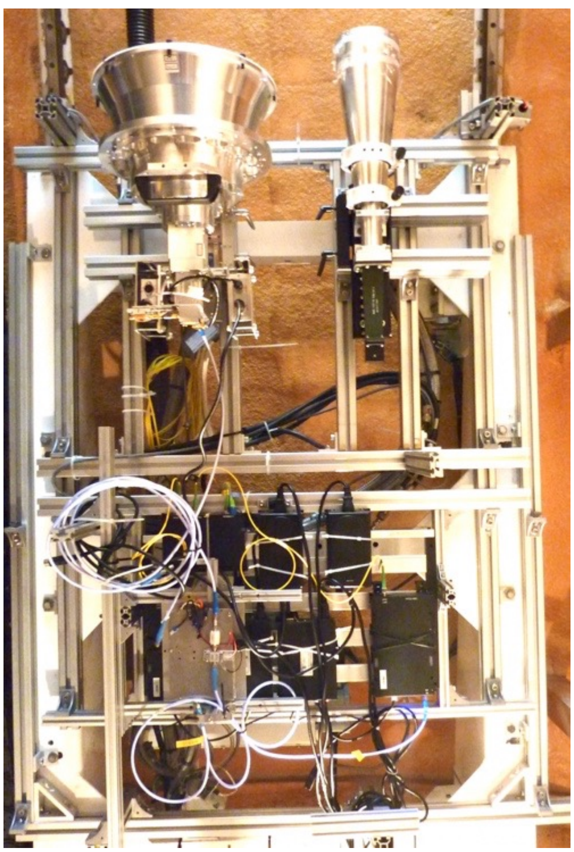

Fig. 7 The new compact NINJA feed installed on the left stage of the receiver carriage in the feed cone of the Kashima 34-m antenna. IGUANA-H is placed on the right.

Fig. 8 Refurbished MARBLE1 at Kashima before shipment to Bologna.

Onsala Space Observatory – IVS Technology Development Center Activities during 2017–2018

Rüdiger Haas, Gunnar Elgered, Leif Helldner, Karl-Åke Johansson, Lars Petterson, Jonas Flygare, Ulf Kylenfall, Magnus Dahlgren, Miroslav Pantaleev

Abstract We give a brief overview of the technical development related to geodetic VLBI done during 2017 and 2018 at the Onsala Space Observatory.

1 General Information

The technical development work for geodetic VLBI at the Onsala Space Observatory (OSO) was mainly dedicated to commissioning the Onsala twin telescopes (OTT). Additional technical development concerned a new broadband feed horn and activities related to water vapor radiometry and the tide gauge station.

The main activities are summarized as follows and discussed in more detail in the subsequent sections:

- Installation and testing of the OTT DBBC3s.
- Testing the OTT CDMS systems.
- Temperature monitoring system in the OTT towers.
- Broadband feed horn.
- Water vapor radiometry.
- Tide gauge station.

Chalmers University of Technology, Department of Space, Earth and Environment, Onsala Space Observatory

OSO Technology Development Center

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2 Installation, Testing, and Fine-tuning the DBBC3s

The two DBBC3s for OTT were delivered in March 2017 and successively installed and tested. In the following weeks and months, extensive tests were performed and improvements made in close cooperation with Gino Tuccari and Sven Dornbusch. Several upgrades of the DBBC3 hardware and software were done, and in 2018 Ed Himwich included full support of the DBBC3 in the VLBI Field System. VGOS observations were started in September 2017, and by the end of 2018 the OTT VGOS systems worked quasi-operationally. As an example, Figure 1 depicts spectra that are produced immediately after each scan in VGOS sessions and displayed on the OTT VLBI FS computers. There are spectra for all 64 channels, each one with 32-MHz bandwidth, covering the current VGOS frequency and polarization setup, as well as sampler statistics. The graphs are displayed for each scan during a VGOS session, as well as stored, and thus allow an online quality control of the ongoing session as well as a post-session identification of potential problems due to, for instance, radio frequency interference (RFI) or other problems.

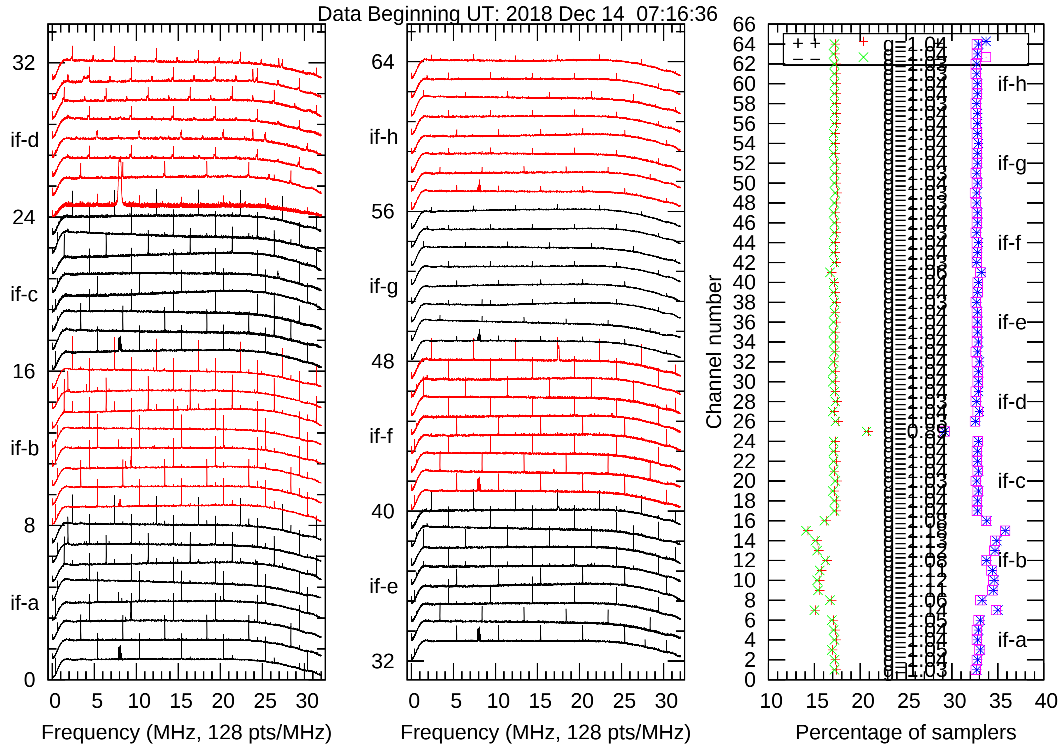

Fig. 1 Spectra of all 64 channels recorded during a VGOS scan. Black and red lines indicate H- and V-polarization, respectively. Phase-cal tones every 5 MHz are visible in all channels, but the amplitudes decrease for the higher frequencies. The sampler statistics are shown in the right graph. Disturbance due to RFI is clearly visible in the first 16 channels (if-a and if-b), which cover 3.0–3.5 GHz.

3 Testing and Fine-tuning the Cable-delay and Phase-cal Systems

Two CDMS (cable delay measuring systems) were purchased from Haystack Observatory, one for each of the OTT. Because the distance between the CDMS ground units in the maser room and the antenna units on the OTT is about 1 km, we use a fiber-based system. This solution is unique and is not used by any other observatory. As an example, Figure 2 depicts the two-way delay measurements recorded by the two systems during a VGOS test session at the end of 2018. While the data for OE show a clear relation to temperature and have an RMS of 7 ps only, the data for OW are much more noisy with an RMS of 27 ps. This indicated that the OW CDMS system was defective. It was sent for repairs to Haystack in early 2019.

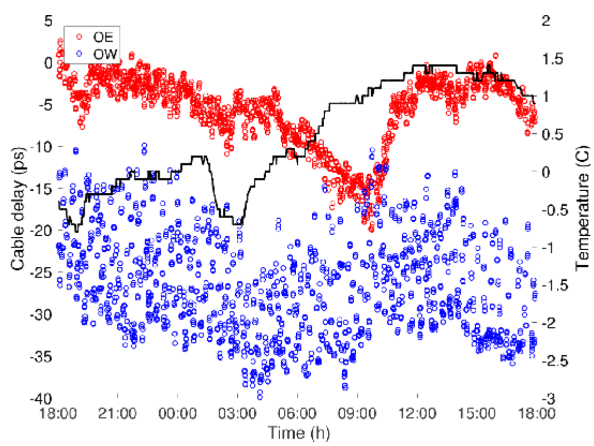

Fig. 2 Cable measurements performed with the two CDMS systems during VGOS session VT847. While the data for OE (red) show a clear relation to outside air temperature (black line, right scale) and have an RMS of 7 ps only, the data for OW (blue) are much more noisy with an RMS of 27 ps.

4 A Temperature Monitoring System for the OTT Towers

The concrete towers of the OTT were equipped with a number of temperature sensors at different levels. The two lower levels, L1 and L2, have sensors in four different azimuth directions, while the upper level, L3, has only one sensor. Temperatures are recorded with five minute temporal resolution. There are also dedicated sensors in different depths to give temperature profiles in the concrete tower. This kind of data will be used in the future to model the temperature-induced deformation of the telescope towers. As an example, Figure 3 depicts tower temperatures recorded for OTT-N during a cold and a warm day in 2018.

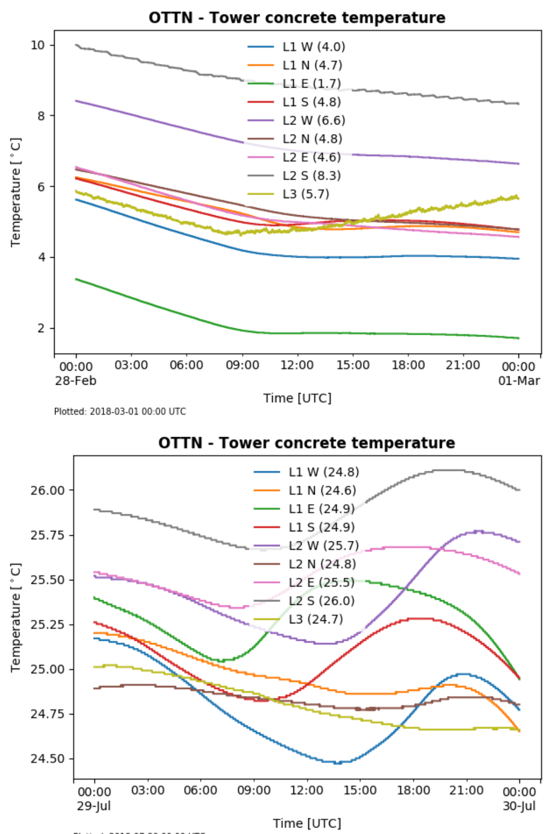

Fig. 3 Temperatures recorded in the OTT-N concrete tower on 1 March (upper plot) and 30 July (lower plot), which were the coldest and warmest days in 2018. There are temperature sensors on three levels, L1, L2, and L3, where the first two levels have sensors in four different azimuth directions. Similar plots are available for OTT-S.

5 Broadband Feed Horn

An ultra-wideband (UWB) feed horn for Band B of the Square Kilometre Array (SKA) project was designed for the frequency range 4.6–24 GHz [1]. The system performance of this UWB horn was simulated also for the OTT [2]. The results show that this horn is very well suited for the OTT. It could thus be an interesting option for VGOS in case the lower frequency band of VGOS in the future gets unusable due to RFI by, for instance, 5G mobile telephony.

6 Water Vapor Radiometry

The water vapor radiometers (WVRs) Astrid and Konrad have been operating at the observatory for approximately four and two decades, respectively. In order to secure possible future studies of the signal propagation delays caused by the wet atmosphere, the observatory has agreed to host a new prototype WVR. It is called Orwvar and has been developed by the company Omnisys Inc. in Gothenburg for the European Space Agency (ESA). Initial comparison measurements were carried out during the summer 2018 (see Figure 4). Currently we are investigating the possibility to operate Orwvar at the observatory as a long-term loan from ESA, who is the formal owner of the instrument.

7 Tide Gauge Station

The tide gauge station at the observatory has produced official data within the framework of the national observational sea level network, operated by the Swedish Meteorological and Hydrological Institute (SMHI) since mid 2015. A general description of the station was presented at the EVGA meeting in Las Palmas 2019 [3]. Motivated by the concern about the need for very accurate sea level data, at the millimeter level, the use of the very best sensors is required. During the time of operation, the root-mean-square (RMS) difference between a laser sensor and the prime sensor (the Campbell CS476, a 26-GHz radar sensor) has been about 3–4 mm. There are reasons to believe that a systematic error of the radar sensor is signal multipath in the well. In order to assess this assumption, a high

Fig. 4 The three WVRs on the 13th of July 2018. Seen from the left to the right are: Konrad, Orwvar, and Astrid. The main GNSS station ONSA is also seen, just to the right of Orwvar.

frequency radar (VEGAPULS64 operating in the 76–80 GHz frequency range) was bought. The main difference between the two radar sensors is the beam angles. The opening angle (full-width half maximum) of the VEGAPULS64 and the CS476 is 3° and 8°, respectively. The electronic laboratory staff has not been able to detect any radiation transmitted through the concrete wall, i.e., the radars do not cause any RFI affecting the radio astronomy observations.

As an example, we present the status of a comparison of the two radar sensors and a laser sensor for the time period from 19 October to 31 December 2018. The time series are presented in Figure 5. All three of these sensors are mounted in the concrete well. We note that the large variations are determined by the local weather conditions, whereas the tidal signal is approximately 20 cm peak-to-peak. Pairwise comparisons between the sensors result in biases, as well as standard deviations (SD), of a few millimeters.

8 Outlook and Future Plans

The plan for the upcoming two years is to stabilize and optimize the OTT system for VGOS operations. This includes also a calibration of the systems.

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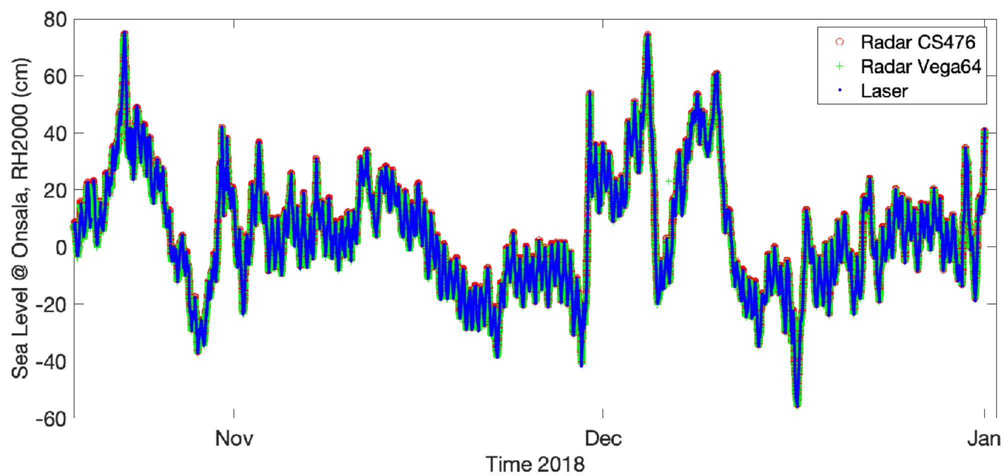

Fig. 5 Sea level recorded at Onsala.

Observatory of Yebes Technological Development Center 2017–2018 Biennial Report

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Abstract We present the main technical developments of the Observatory of Yebes (IGN) from years 2017 and 2018 related to geodetic VLBI.

1 General Information

The Observatory of Yebes was declared a Technological Development Center for the IVS in 2015. Its main contributions lay in the area of receivers covering low noise amplifiers, passive devices and cryogenics, microwave receivers, modules for receiver calibration, antenna control software, RFI measurements, and topographic measurements for the local tie.

The Observatory of Yebes also runs two radiotelescopes, 13.2-m and 40-m in diameter, respectively, which are integrated into the IVS. The first one regularly runs VGOS observations, and the second one has run legacy IVS observations since 2008. The details are explained by González et al. (2019) in this same volume. The 13.2-m radiotelescope belongs to the RAEGE (Red Atlántica de Estaciones Geodinámicas y Espaciales), and it is the first operative radiotelescope of the four foreseen within that network (Yebes, Santa María, Gran Canaria, and Flores). The Observatory of Yebes also manages two GNSS receivers: one integrated into the international network and a second one into the Spanish national one. It also runs two gravimeters, an absolute one and a relative superconductor one. We are also planning the installation of an SLR station in the next five years, which would convert the Observatory of Yebes into a GGOS core station. Around the 40-m and 13.2-m radiotelescopes and the associated equipment and instrumentation, a team of engineers and astronomers have developed and continue developing technology for radioastronomy which is used for our telescopes and for other institutes around the world. To achieve such a goal, the observatory hosts several laboratories and workshops with precision machines where these developments take place.

In the following sections we describe the most relevant activities and technical developments accomplished during 2017 and 2018. Most of these continue during 2019.

Observatory of Yebes, IGN

IGN Yebes Technology Development Center

IVS 2017+2018 Biennial Report

2 VGOS Broadband Receivers

The Observatory of Yebes received the mission to design and build three cryogenic VGOS broadband receivers: two for the Norwegian Mapping Authority (NMA) and one for the Finnish Geospatial Research Institute (FGI). These broadband receivers are cooled using a two stage cryostat (15 and 50 K) and operate between 2 and 14 GHz. They have cryogenic low noise amplifiers designed and built at the Observatory of Yebes and deliver a receiver temperature below 25 K along the whole band measured in an RFI-free lab environment. They provide two linear orthogonal polarizations simultaneously.

Two of them will be delivered by the second half of 2019, one to NMA and one to FGI, respectively. Figure 1 shows the schematics of one such receiver in which we can see its different modules. After the cryostat, the signal is split into two sub-bands: 2.1 – 5.6 GHz and 3.6 – 11.6 GHz following Haystack's approach to avoid the saturation of the optical fiber amplifiers from strong signals in the lower part of the band. The signals, once amplified, filtered, and transported through optical fiber links to the backends room, are directed towards two identical DBBC3 RF interface modules designed and built at Yebes. These modules split the signals from both polarizations into four frequency sub-bands ready to be injected into the DBBC3. The filtering and conditioning module for the DBBC3 does not use tunable LOs, and, in case the observing bands change, they can be adapted by replacing the band pass filters with new ones.

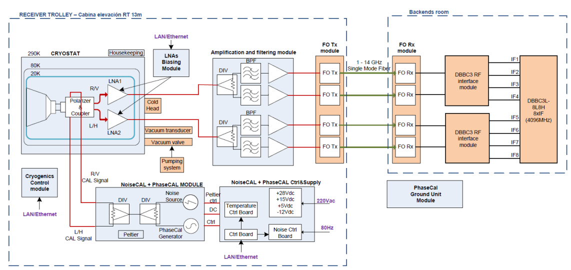

Fig. 1 Schematics of the VGOS broad band receiver for NMA and FGI.

Figure 2 shows the receiver temperature measured in both linear polarizations along the band. The peaks at low frequencies are due to RFI associated with WiFi, UMTS, Bluetooth, WiMax, and other sources of noise.

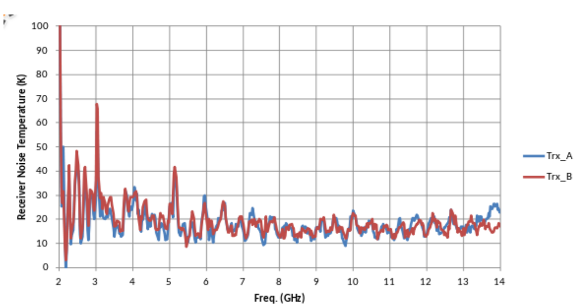

Fig. 2 Receiver temperature for the FGI broadband receiver along the band. The peaks at low freuencies come from RFI.

The receivers use a cryogenics and vacuum control system which has been overhauled from a previous version used in the Yebes VGOS receiver. This new version has a remote ethernet connection to the Local Area Network that allows remote monitoring and control of both pumps (rotatory and turbomolecular), the cryogenic temperature, the vacuum sensors, the electrovalve, and the heat resistors and regenerators. This remote monitoring and control eases the operation of the receiver, adds stability, and provides a complete time log of the cryogenics. It is integrated into the control system of the telescope and can be used by third party software.

3 Tri-band Receiver for Ny-Ålesund

The NMA runs two twin VGOS radio telescopes at Ny-Ålesund station which were inaugurated during the last IVS General Meeting in June 2018. In order to test these radiotelescopes, NMA borrowed from the Observatory of Yebes one tri-band receiver which simultaneously works in the bands: 2.2–2.7 GHz, 7.5–9 GHz, and 28–32 GHz. The receiver was mounted first in one antenna and then in the second one to test the telescopes and determine the pointing and focusing model. The SEFD and the efficiency at X-band were estimated. Both telescopes were using the Yebes control software and the Yebes pipeline and reduction software. Receiver temperatures are below 25 K at S-, X-, and Ka-band in all cases.

4 QRFH Revisited

The Observatory of Yebes has worked in the optimization of the QRFH design from JPL used in the VGOS radiotelescopes. The Yebes design resembles the original design but has slightly changed the profile and the connectors (coaxial ones). The antenna works between 2.3 and 14 GHz in dual linear polarization. The schematics allow it to be manufactured easily. The efficiency is silghtly better than the original design, above 0.55 along the whole band, but the reflection is slightly worse (see Figure 3).

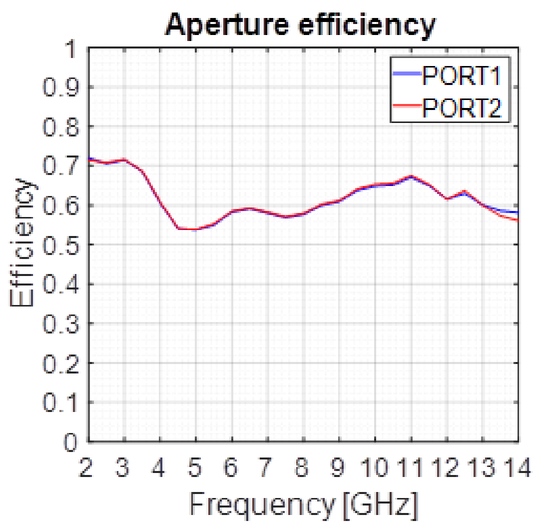

Fig. 3 Efficiency of the QRFH along the frequency band.

5 Linear to Circular Polarization: Hybrids and Software

One of the main drawbacks of the broadband receivers is the need to use linear polarization. This has prevented an easy simultaneous operation with the IVS legacy observations which only use Left Circular Polarization (LCP). The usage of linear polarization generates new problems to be taken into account like variable polarization coming from the paralactic angle which differs at the different radiotelescopes on the Earth. Sources may be totally or partially polarized, and because their paralactic angle changes with time, it is necessary to observe in both polarizations to recover the whole signal. Furthermore, instrumental effects should also be taken into account. The conversion from linear to circular polarization can be done either by software or by hardware.

The Observatory of Yebes has developed a solution based on cryogenic 3dB/90 degrees multi-octave stripline hybrids which can be used to obtain both circular polarization signals from linear polarization ones. The usage of such devices at cryogenic temperatures (15 K) only increases 1.5 K on average the noise temperature of the LNAs. This solution guarantees cross polarization below 25 dB, an axial ratio below 1 dB, an amplitude unbalance below 0.9 dB, and a phase unbalance lower than 3 degrees. To achieve such specifications the length of the lines has to be controlled with great accuracy, but this is achievable using special connectors. Figure 4 shows the hybrids' performance along the frequency band. This solution has not been implemented on a receiver yet, but the BRAND project from Radionet is considering it as a first option.

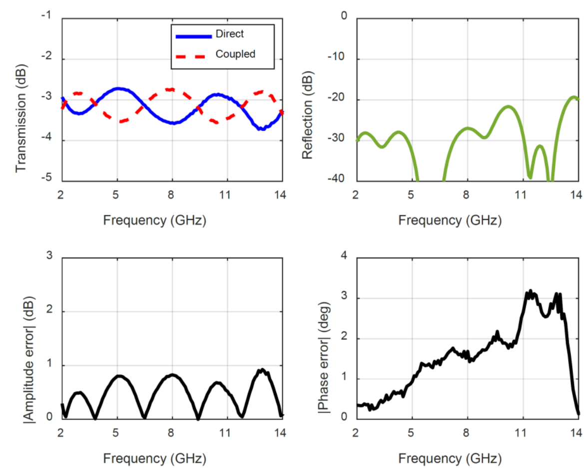

Fig. 4 Hybrid performance: transmission, reflection, amplitude error, and phase error, along the frequency band.

The alternative approach to convert linear to circular polarization is by software using PolConvert software by I. Martá-Vidal. This task is part of the effort started by the EU-VGOS project which aims to create a pipeline that performs the correlation, polarization conversion, instrumental polarization calibration, and fringe fitting along the whole band to estimate the dispersive effects of the ionosphere. The goal is to obtain the final observable: the broadband delay for each scan and baseline from which the length of the baselines is estimated. EU-VGOS observes regularly with the European antennas from Onsala, Wettzell, and Yebes to test this pipeline currently under development.

6 Ultra Low Noise Wide Band Amplifiers

We have developed two kinds of low noise cryogenic ultra wide band amplifiers in the band between 2 and 14 GHz. The first option is a compact, light single ended amplifier which is usable in a much larger band, between 0.5 and 18 GHz. The average noise temperature is 6.1 K and the gain 33.9 dB, with an input IRL of -1.5 dB and an ORL of -16.9 dB. The consumption is 36 mW. This amplifier has a large input reflection, and an alternative solution was investigated using a balanced amplifier.

The balanced amplifier uses 3dB/90 degree hybrids, and the results are excellent. The penalty for using the hybrids is very low. The noise temperature increases only 1.5 K on average, up to 7.6 K, and the gain stays at 33.8 dB, but the IRL drops to -21 dB and the ORL to -23 dB. We have developed two versions, one for the 2-14 GHz band and another for the 1.5-15 GHz band (BRAND receiver).

The behavior of both amplifiers are shown in Figures 5 and 6 for an easy comparison.

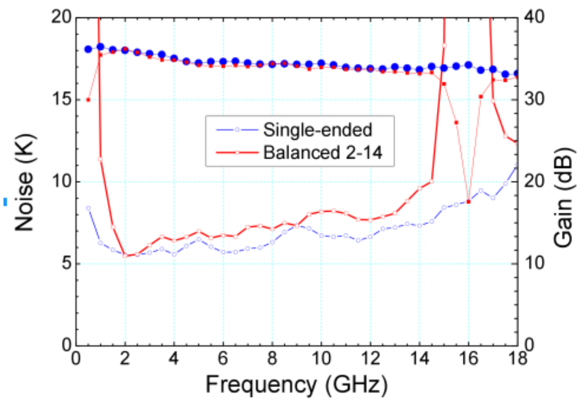

Fig. 5 Noise temperature and gain of single ended and balanced amplifiers.

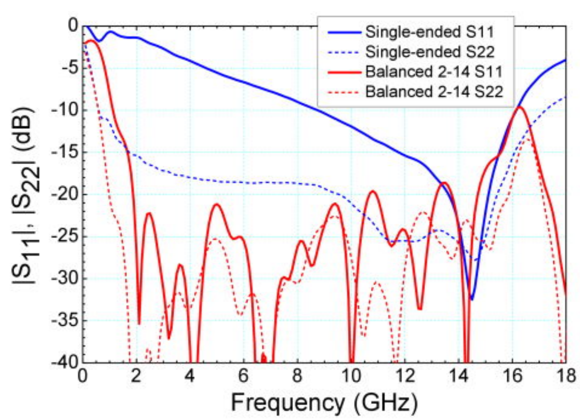

Fig. 6 S parameters for single ended and balanced amplifiers.

7 Phase Cal Developments

The phase cal system for VLBI is composed of two subsystems: the antenna unit, which injects phase cal tones used for calibration of the instrumental phase along the observing band, and the cable delay measurement system, which estimates the variable delay in the signal caused by the cables between the receiver and the VLBI backends. This system devised by A. Rogers is very powerful, and it is in use at the IVS radiotelescopes.

We have optimized the antenna unit system by providing extra features. The noise and phase unit at Yebes is installed at the receiver trolley, very close to the cryostat. It uses short semirigid coaxial cables to decrease the variability caused by temperature variations in the receiver cabin. The system generates pulses 10 MHz apart and works between 2 and 14 GHz. The pulse generator is based on Hittite ultrafast logic gates, a similar approach as at Haystack. The noise cal can be switched at a 80 Hz rate. The whole unit is shielded, and it is temperature stabilized using a Peltier cooler and passive insulation. The control of the Peltier is done with a PR59 control module from Laird Technologies and the noise cal with a PCB designed and built at the Observatory of Yebes. The final control and monitoring of the pulses, noise cal, and the Peltier is done with a Raspberry Pi using Python scripts. Yebes labs has built nine units for BKG, AGGO, NMA, FGI, and Yebes and is integrating this system into the VGOS receivers in construction for NMA and FGI.

The Cable Delay Measurement System (CDMS) is based on the legacy design, but it has been adapted in a single PCB to simplify its usage. A new CDMS is being developed and is still undergoing tests; it does not require a frequency counter. The system compares the 5 MHz reference signal from the generator module with the 5 MHz signal coming from the antenna unit installed in the receiver trolley. Both signals are phase compared in a phase detector, whose DC output is read by a 24-bit ADC. The achieved RMS is < 5 ps, which corresponds to < 0.003 degrees in phase. This system yields higher sensitivity and lower phase noise. It is currently being tested at the 13.2-m Yebes antenna and will be extended to other telescopes once it is validated.

8 RFI Measurements

After several tests to avoid a Tsys increase due to RFI, the configuration shown in Figure 7 was adopted. A 3 GHz high-pass filter was installed at the dewar's output. In addtion, a PIN diode power limiter (+6 dBm) was installed at each optic fiber link input, in order to protect them from damage due to strong RFI which is present and could enter the receiver during antenna maintenance 0-deg elevation. With this configuration, we managed to reduce Tsys from 70 K down to 50 K.

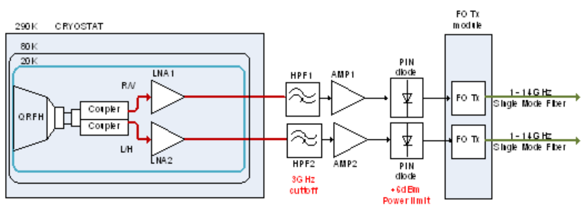

Fig. 7 Yebes VGOS receiver configuration.

In addition, a line of research on high temperature superconducting filters (HTS) began at Yebes labs (Huang et al., 2018). The initial project was a sharp HTS filter for the legacy S-band, which is the worst one in terms of RFI. The specifications for this filter were very selective in order to reject high power radiolinks close to this band:

- Center frequency: 2295 MHz
- Bandwidth: 2215 - 2375 MHz
- Max insertion loss: 0.1dB @ 20 Kelvin
- Rejection $>$ 60 dB at 2115 $<=$ f $<=$ 2180 MHz
- Rejection $>$ 30 dB at f $>$ 2400 MHz
- Max VSWR in/out: 1.4:1
- In/Out impedance: 50 ohms
- Temperature of operation: 20 Kelvin.
- Input connector: coaxial SMA-female
- Output connector: coaxial SMA-male

After this, the simulation of an HTS filter for VGOS is underway with promising results. The current configuration considered for VGOS is a band-pass filter (2–14 GHz) with one notch at a pre-defined frequency.

Finally, it has to be mentioned that a new RFI monitoring station has started operations on the roof of the laboratory building. It allows the monitoring of RFI from 1 to 40 GHz.

9 Large Future Plans

Two large and ambitious goals for the Observatory of Yebes are planned for the next four years using European funds from regional development. The first one is the construction of a future Satellite Laser Ranging station at Yebes. In the next months we will make a study of the requirements for the telescope and ancillary equipment and the software. Once this is decided, the acquisition of the equipment will take place, and later the building that hosts the telescope will be erected.

The second goal consists of the extension of the current building of laboratories and workshops. The new building, whose civil work will start shortly, will host several laboratories, including a clean room and workshops to host precision milling machines and lathes as well as metrology equipment.

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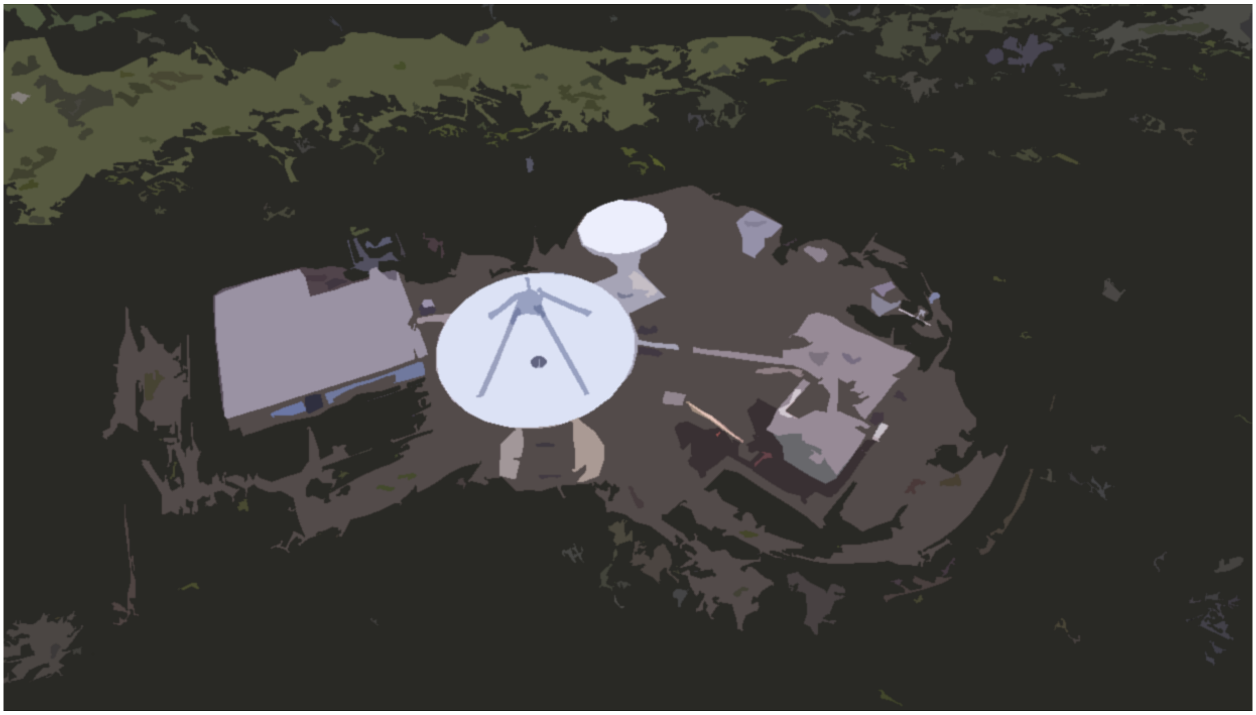
IVS Information



IVS Terms of Reference

1 Summary

1.1 Charter

The International VLBI Service for Geodesy and Astrometry (IVS) is an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components. IVS provides a service which supports geodetic and astrometric work on reference systems, Earth science research, and operational activities. IVS is a Service of the International Association of Geodesy (IAG) and of the International Astronomical Union (IAU).

1.2 Objectives

IVS fulfills its charter through the following objectives:

1. foster and carry out VLBI programs. This is accomplished through close coordination of the participating organizations to provide high-quality VLBI data and products.
2. promote research and development activities in all aspects of the geodetic and astrometric VLBI technique.
3. advance the education and training of VLBI participants through workshops, reports, and other means.
4. support the integration of new components into IVS.
5. interact with the community of users of VLBI products. IVS represents VLBI in the Global Geodetic Observing System (GGOS) of the IAG and interacts closely with the International Earth Rotation and Reference Systems Service (IERS).

In support of these objectives, IVS coordinates VLBI observing programs, sets performance standards for VLBI stations, establishes conventions for VLBI data formats and data products, issues recommendations for VLBI data analysis software, sets standards for VLBI analysis documentation, and institutes appropriate VLBI product delivery methods to ensure suitable product quality and timeliness. IVS coordinates its activities with the astronomical community because of the dual use of many VLBI facilities and technologies for both astronomy and astrometry/geodesy.

1.3 Data Products

VLBI data products contribute uniquely to these important activities:

- defining and maintaining the celestial reference frame,
- monitoring universal time (UT1), and
- monitoring the coordinates of the celestial pole (nutation and precession).

These results are the foundation of many scientific and practical applications requiring the use of an accurate quasi-inertial reference frame, such as high-precision positioning, navigation, and timing. In addition IVS provides a variety of VLBI products with differing applications, timeliness, detail, and temporal resolution, such as:

- all components of Earth orientation parameters,
- terrestrial reference frame,
- baseline lengths, and
- tropospheric parameters.

All VLBI data and products are publicly available in appropriate formats from IVS Data Centers.

1.4 Research

The IVS data and products are used for research in many areas of geodesy, geophysics, and astronomy, such as:

- UT1 and polar motion excitation over periods of hours to decades,
- solid Earth interior research (e.g., mantle rheology, anelasticity, libration, and core modes),
- characterization of celestial reference frame sources and improvements to the frame,
- tidal variations (solid Earth, oceanic, and atmospheric),
- improvements in the terrestrial reference frame, especially in the scale,
- climate studies (e.g., sea level change, deglaciation, and water vapor),
- regional and global geodynamics, and
- general relativity.

To support these activities, there are ongoing research efforts to improve and extend the VLBI technique in areas such as:

- instrumentation, data acquisition, and correlation,
- data analysis techniques,
- spacecraft tracking and navigation (Earth-orbiting and interplanetary), and
- combination of VLBI data and results with other techniques.

2 Permanent Components

IVS acquires, correlates, and analyzes VLBI data to produce geodetic, astrometric, and other results that are archived and publicized. IVS accomplishes its objectives through the following permanent components:

- Network Stations,
- Operation Centers,
- Correlators,
- Analysis Centers,
- Data Centers,
- Technology Development Centers, and
- Coordinating Center.

2.1 Network Stations

The IVS observing network consists of high performance VLBI stations.

- Stations may either be dedicated to geodesy or have multiple uses (including astronomical observations or satellite tracking applications).
- Stations comply with performance standards for data quality and operational reliability specified by the Directing Board.
- Stations provide local tie information, timing and meteorological data to the IVS Data Centers.
- VLBI data acquisition sessions are conducted by groups of Network Stations that may be distributed either globally or over a geographical region.

2.2 Operation Centers

The IVS Operation Centers coordinate the routine operations of specific networks. Operation Center activities include:

- planning network observing programs,
- supporting the network stations in improving their performance,
- generating the detailed observing schedules for use in data acquisition sessions by IVS Network Stations, and
- posting the observing schedule to an IVS Data Center for distribution and archiving.

IVS Operation Centers follow guidelines from the Coordinating Center for timeliness and schedule file formats.

2.3 Correlators

The IVS Correlators process raw VLBI data. Their other tasks are to:

- provide timely feedback to the Network Stations about data quality,
- jointly maintain the geodetic/astrometric community's media pool and transport,
- manage electronic data transfer,
- make processed data available to the Data Centers, and
- regularly compare processing techniques, models, and outputs to ensure that data from different Correlators are identical.

2.4 Analysis Centers

The IVS coordinates VLBI data analysis to provide high-quality products for its users. The analyses are performed by:

- Operational Analysis Center,
- Associate Analysis Centers,
- Special Analysis Centers for Specific Observing Sessions, and
- Combination Centers.

All Analysis Centers maintain and/or develop appropriate VLBI analysis software.

Operational Analysis Centers are committed to producing results to the specifications of the IVS Analysis Coordinator and always on schedule to meet IVS requirements. In addition, Operational Analysis Centers may produce Earth orientation parameters, station coordinates, and source positions in regular intervals.

Operational Analysis Centers place their final results in IVS Data Centers for dissemination to researchers and other users. They adhere to IVS recommendations for the creation of high-quality products and their timely archiving and distribution. Any deviations that an Operational Analysis Center makes from IVS recommendations are properly documented. Operational Analysis Centers provide timely feedback about station performance. In addition to these regular services, Operational Analysis Centers may also perform any task of an Associate Analysis Center.

Associate Analysis Centers are committed to regularly submit specialized products using complete series or subsets of VLBI observing sessions. The analysis is performed for specific purposes as recognized by the Directing Board, such as exploitation of VLBI data for new types of results, investigations of regional phenomena, reference frame maintenance, or special determinations of Earth orientation parameters. The Associate Analysis Centers place their final results in IVS Data Centers for dissemination to researchers and other users. They adhere to IVS recommendations for the creation of high-quality products and their timely archiving and distribution. Any deviations that an Associate Analysis Center makes from IVS recommendations are properly documented.

Special Analysis Centers for Specific Observing Sessions have responsibility for ongoing series-related investigations of one or more existing session types. They perform detailed and comparative analyses of each session of a series within a reasonable time after correlation. In addition, they report deficits and technical complications to the observing sites, the correlators, and to the schedulers as well as to the IVS Network and Analysis Coordinators.

Combination Centers are committed to produce combination results from the individual submissions of the Operational Analysis Centers as official IVS products. For this purpose they monitor the quality of the submissions. The official IVS products include, but are not limited to, EOP time series derived from session-based results for 24-hour network sessions and one-hour Intensive sessions. Combination Centers also contribute to the generation of the official IVS input to International Terrestrial Reference Frame (ITRF) computations. The combination work is done in a timely fashion and in close cooperation with the IVS Analysis Coordinator.

2.5 Data Centers

The IVS Data Centers are repositories for VLBI observing schedules, station log files, data and products. Data Centers may mirror other Data Centers to make the distribution and maintenance of data more efficient and reliable.

- Data Centers are the primary means of distributing VLBI products to users.

- Data Centers work closely with the Coordinating Center and with the Analysis Centers to ensure that all the information and data required by IVS components are quickly and reliably available.

  Data Centers provide the following functions:

- receive and archive schedule files from Operation Centers,
- receive and archive log files and ancillary data files from the Network Stations,
- receive and archive data products from the Analysis Centers, and
- provide access and public availability to IVS data products for all users.

2.6 Technology Development Centers

The IVS Technology Development Centers contribute to the development of new VLBI technology for improvement of the VLBI technique. They:

- investigate new equipment and approaches,
- develop, test, and document new hardware, firmware, and software for operations,
- assist with deployment, installation, and training for any new approved technology, and
- maintain and support operational equipment.

2.7 Coordinating Center

The IVS Coordinating Center is responsible for coordination of both the day-to-day and the long-term activities of IVS, consistent with the directives and policies established by the Directing Board. Specifically, the Coordinating Center monitors, coordinates, and supports the activities of the Network Stations, Operation Centers, Correlators, Data Centers, Analysis Centers, and Technology Development Centers. The Coordinating Center works closely with the Technology Coordinator, the Network Coordinator, and the Analysis Coordinator to coordinate IVS activities.

The primary functions of the Coordinating Center are to:

- coordinate observing programs approved by the Directing Board,
- create and maintain the master schedule of observing sessions in coordination with IVS Network Stations and astronomical observing programs,
- foster communications among all components of the IVS,
- coordinate the best use of community resources,
- develop standard procedures for IVS components,
- organize training in VLBI techniques,
- organize workshops and meetings, including IVS technical meetings,
- produce and publish reports of activities of IVS components,
- maintain the IVS information system and archive all documents, standards, specifications, manuals, reports, and publications,
- coordinate IVS outreach and educational activities,
- provide liaison with the IAU, IAG, GGOS, IERS, and other organizations, and
- provide the Secretariat of the Directing Board.

2.8 Becoming a Permanent Component

IVS will accept proposals at any time to become a permanent component. Such proposals will be reviewed for approval by the Directing Board.

3 Coordinators

Specific IVS activities regarding network data quality, products, and technology are accomplished through the functions performed by three coordinators: a Network Coordinator, an Analysis Coordinator, and a Technology Coordinator.

3.1 Network Coordinator

The IVS Network Coordinator is selected by the Directing Board from responses to an open solicitation to all IVS components. The Network Coordinator represents the IVS Network Stations on the Directing Board and works closely with the Coordinating Center. The Network Coordinator is responsible for stimulating the maintenance of a high quality level in the station operation and data delivery. The Network Coordinator performs the following functions:

- monitors adherence to standards in the network operation,
- participates in the quality control of the data acquisition performance of the network stations,
- tracks data quality and data flow problems and suggests actions to improve the level of performance, and
- coordinates software development for station control and monitoring.

The Network Coordinator works closely with the geodetic and astronomical communities who are using the same network stations for observations. The Network Coordinator takes a leading role in ensuring the visibility and representation of the network stations.

3.2 Analysis Coordinator

The IVS Analysis Coordinator is selected by the Directing Board from responses to an open solicitation to the IVS Analysis Centers. The Analysis Coordinator is responsible for coordinating the analysis activities of IVS and for stimulating VLBI product development and delivery. The Analysis Coordinator performs the following functions:

- fosters comparisons of results from different VLBI analysis software packages and different analysis strategies,
- encourages documentation of analysis and combination software,
- participates in comparisons of results from different space geodetic techniques,
- monitors Analysis Centers' products for high quality results and for adherence to IVS standards and IERS Conventions,
- ensures that IVS analysis and combination products from all Analysis Centers are archived and are available to the scientific community, and
- supervises the formation of the official IVS products specified by the IVS Directing Board.

The Analysis Coordinator plays a leadership role in the development of methods for generation and distribution of VLBI products so that the products reach the users in a timely manner. The Analysis Coordinator interacts with GGOS and the IERS and promotes the use of VLBI products by the broader scientific community. The Analysis Coordinator works closely with the astronomical communities who are using some of the same analysis methods and software.

3.3 Technology Coordinator

The IVS Technology Coordinator is selected by the Directing Board from responses to an open solicitation to the IVS Technology Development Centers. The Technology Coordinator performs the following functions:

- stimulates advancement of the VLBI technique,
- maintains awareness of all current VLBI technologies and ongoing development,
- coordinates development of new technology among all IVS Technology Development Centers,
- encourages technical compatibility with the astronomical community,
- encourages and oversees development of VLBI-related technical standards,
- coordinates the distribution of and access to technical documents and standards, and
- helps promulgate new technologies to the IVS community.

The Technology Coordinator works closely with the astronomical community, both to maintain technical compatibility between the geodetic and astronomical communities and to take advantage of technology development activities in the astronomical community.

4 Directing Board

4.1 Roles and Responsibilities

The Directing Board sets objectives, determines policies, adopts standards, and sets the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Directing Board may determine appropriate actions to ensure the quality of the IVS products.

The Directing Board will receive and review proposals for non-IVS research programs that request IVS resources.

4.2 Membership

The Directing Board consists of representatives of the IVS components, members at-large, appointed members, and ex officio members. The members are:

Representatives of IVS Components (see below):

- Correlators and Operation Centers representative (1)
- Analysis and Data Centers representatives (2)
- Networks representatives (2)
- Technology Development Centers representative (1)

Elected by the Directing Board upon recommendation from the Coordinating Center (see below):

- Members at large (3)

Selected by Directing Board upon review of proposals from IVS Member Organizations:

- Coordinating Center Director
- Network Coordinator
- Analysis Coordinator
- Technology Coordinator

Appointed members:

- IAU representative
- IAG representative
- IERS representative

Through a reciprocity agreement between IVS and IERS, the IVS serves as the VLBI Technique Center for IERS, and as such its designated representative(s) serve on the IERS Directing Board. In turn, the IERS Directing Board designates a representative to the IVS Directing Board. This arrangement is to assure full cooperation between the two services.

Total number: 16

The members appointed by IAU, IAG, and IERS are not subject to institutional restrictions.

The six members who are the representatives of the IVS components are elected by the IVS Associate Members. All elected members serve staggered four-year terms once renewable.

At-large members are intended to ensure representation on the Directing Board of each of the components of IVS and to balance representation from as many countries and institutions and IVS interests as possible. At-large members serve two-year terms once renewable.

A Directing Board member who departs before the end of his/her term is replaced by a person selected by the Directing Board. The new member will serve until the next official elections. The position will then be filled for a full term.

An individual can only serve two consecutive full terms on the Board in any of the representative and at-large positions. Partial terms are not counted to this limit. After serving two consecutive full terms, an individual becomes eligible again for a position on the Board following a two-year absence.

The three Coordinators are selected by the Directing Board on the basis of proposals from IVS Member Organizations. On a two-thirds vote the Directing Board may call for new proposals for any Coordinator when it determines that a new Coordinator is required. Coordinators are encouraged to give at least six months notice before resigning.

4.3 Elections

Election of Board members from the IVS components shall be conducted by a committee of three Directing Board members, the chair of which is appointed by the chair of the Directing Board. The committee solicits nominations for each representative from the relevant IVS components. For each position, the candidate who receives the largest number of votes from the Associate Members will be elected. In case of a tie the Directing Board will make the decision.

4.4 Chair

The chair is one of the Directing Board members and is elected by the Board for a term of four years with the possibility of reelection for one additional term. The chair is the official representative of IVS to external organizations.

4.5 Decisions

Most decisions by the Directing Board are made by consensus or by simple majority vote of the members present. In case of a tie, the chair decides how to proceed. If a two-thirds quorum is not present, the vote shall be held later by electronic mail. A two-thirds vote of all Board members is required to modify the Terms of Reference, to change the chair, or to replace any of the members before their normal term expires.

4.6 Meetings

The Directing Board meets at least annually, or more frequently if meetings are called by the chair or at the request of at least three Board members. The Board will conduct periodic reviews of the IVS organization and its mandate, functions, and components.

5 Definitions

5.1 Member Organizations

Organizations that support one or more IVS components are IVS Member Organizations. Individuals associated with IVS Member Organizations may become IVS Associate Members.

5.2 Affiliated Organizations

Organizations that cooperate with IVS on issues of common interest, but do not support an IVS component, are IVS Affiliated Organizations. Affiliated Organizations express an interest in establishing and maintaining a strong working association with IVS to mutual benefit. Individuals affiliated with IVS Affiliated Organizations may become IVS Corresponding Members.

5.3 Associate Members

Individuals associated with organizations that support an IVS component may become IVS Associate Members. Associate Members take part in the election of the incoming members of the Directing Board representing the IVS components.

5.4 Corresponding Members

IVS Corresponding Members are individuals who express interest in receiving IVS publications, wish to participate in workshops or scientific meetings organized by IVS, or generally are interested in IVS activities. Ex officio Corresponding Members are the following:

- IAG Secretary General
- Chair of GGOS
- President of IAG Commission 1 – Reference Frames
- President of IAG Commission 3 - Earth Rotation and Geodynamics
- President of IAU Division I – Fundamental Astronomy
- President of IAU Commission 8 – Astrometry
- President of IAU Commission 19 – Rotation of the Earth
- President of IAU Commission 31 – Time
- President of IAU Commission 40 – Radio Astronomy
- President of URSI Commission 52 – Relativity in Fundamental Astronomy
- President of URSI Commission J – Radio Astronomy

Individuals are accepted as IVS Corresponding Members upon request to the Coordinating Center.

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Links to Additional IVS Information

This page provides links to information about the individuals and groups that support IVS. Member organizations are organizations that support one or more permanent components. Permanent components are groups that formally commit to provide support in one of six categories: coordination of network operations (Operation Centers), collection of VLBI data (Network Stations), processing of raw data (Correlators), archival and distribution of data and products (Data Centers), analysis of data and generation of products (Analysis Centers), and development of new technology (Technology Development Centers).

Associate Members are individuals that are associated with a member organization and have been granted Associate Member status. Associate Members generally support IVS by participating in the activities of one or more components.

Affiliated organizations cooperate with IVS on matters of common interest but do not support a component.

Information Category	Link
Associate Members	
(listed alphabetically by last name)	ivscc.gsfc.nasa.gov/about/org/members/assoc_name.pdf
(listed alphabetically by their organization's country)	ivscc.gsfc.nasa.gov/about/org/members/assoc_org.pdf
Permanent Components	
Network Stations	https://ivscc.gsfc.nasa.gov/about/org/components/ns-list.html
Operation Centers	https://ivscc.gsfc.nasa.gov/about/org/components/oc-list.html
Correlators	https://ivscc.gsfc.nasa.gov/about/org/components/co-list.html
Data Centers	https://ivscc.gsfc.nasa.gov/about/org/components/dc-list.html
Analysis Centers	https://ivscc.gsfc.nasa.gov/about/org/components/ac-list.html
Technology Development Centers	https://ivscc.gsfc.nasa.gov/about/org/components/td-list.html
Member Organizations	https://ivscc.gsfc.nasa.gov/about/org/members/memberorgs.html
Affiliated Organizations	https://ivscc.gsfc.nasa.gov/about/org/members/affilmemberorgs.html