VLBI2010: An Overview

Bill Petrachenko

Natural Resources Canada (NRCan)

e-mail: `Bill.Petrachenko@nrcan.gc.ca`

Abstract

The first concrete actions toward a next generation system for geodetic VLBI began in 2003 when the IVS initiated Working Group 3 to investigate requirements for a new system. The working group set out ambitious performance goals and sketched out initial recommendations for the system. Starting in 2006, developments continued under the leadership of the VLBI2010 Committee (V2C) in two main areas: Monte Carlo simulators were developed to evaluate proposed system changes according to their impact on IVS final products, and a proof-of-concept effort sponsored by NASA was initiated to develop next generation systems and verify the concepts behind VLBI2010. In 2009, the V2C produced a progress report that summarized the conclusions of the Monte Carlo work and outlined recommendations for the next generation system in terms of systems, analysis, operations, and network configuration. At the time of writing: two complete VLBI2010 signal paths have been completed and data is being produced; a number of VLBI2010 antenna projects are under way; and a VLBI2010 Project Executive Group (V2PEG) has been initiated to provide strategic leadership.

1. Introduction

The current VLBI system was conceived and constructed mostly in the 1960s and 1970s. Aging antennas, increasing radio frequency interference (RFI) problems, obsolete electronics, and high operating costs have made it increasingly difficult to sustain required levels of accuracy, reliability, and timeliness. In September 2003 the IVS, recognizing the limitations of existing VLBI infrastructure and the increasingly demanding requirements of space geodesy, established Working Group 3 (WG3): VLBI2010 to investigate options for modernization [1].

Guided by emerging space geodesy science and operational needs [9] [10], WG3 established challenging goals for the next generation VLBI system:

- 1 mm position and 0.1 mm/year velocity accuracy on global scales,

- continuous measurements for time series of station positions and EOP,

- posting of initial geodetic results less than 24 hours after observations are complete.

In its final report [4], WG3 proposed strategies to move toward the unprecedented 1 mm position accuracy target and broad recommendations for a next generation system based on the use of smaller ($\sim$12m) fast-slewing automated antennas.

In order to encourage the realization of the recommendations of WG3, the IVS, in September 2005, established the VLBI2010 Committee (V2C) as a permanent body of the IVS. The V2C takes an integrated view of VLBI and evaluates the effectiveness of proposed system changes based on the degree to which they improve the final products. The V2C work goes hand-in-hand with the gradual establishment of the Global Geodetic Observing System (GGOS) [8] of the International Association of Geodesy (IAG).

2. Monte Carlo Simulators

Making rational design decisions for VLBI2010 requires a realistic understanding of the impacts of new operating modes on final products. To fill this gap, Monte Carlo simulators were developed [3] [5] [11]. The concept of a Monte Carlo simulator involves the generation of several sets (typically 25 for the VLBI2010 studies) of artificial input data, with each set driven by different random numbers. All data sets are then processed as if they were from real sessions, and the ensemble of output products is analyzed statistically to produce estimates of the bias and standard deviation of those products.

The simulators have been used to study the effects of the dominant VLBI random error processes (related to the atmosphere, the reference clocks, and the delay measurement noise) and the benefit of new approaches to reduce them, such as decreasing the source-switching interval and improving analysis and scheduling strategies. Of particular merit is the strategy to reduce the source-switching interval which results in a nearly proportionate improvement in station position accuracy [7]. Regardless of the strategy employed, the simulators confirm that the dominant VLBI error source is the atmosphere.

3. System Considerations

Based on the Monte Carlo studies, high priority is placed on finding strategies for reducing the source-switching interval. This entails decreasing both the on-source time and the time required to slew between sources. From these two somewhat competing goals, recommendations for the VLBI2010 antennas are emerging, e.g., use either a single 12-m diameter antenna with very high slew rates (e.g., $12°$/s in azimuth and $4°$/s in elevation) (see Figure 1) or a pair of 12-m diameter antennas, each with more moderate slew rates (e.g., $5°$/s in azimuth and $1.5°$/s in elevation [6]).
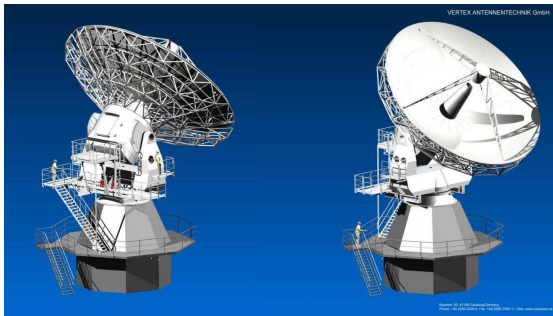

Figure 1. An artist's conception of the VLBI2010 antenna designed by Vertex Antennentechnik GMBH. A pair of these fully VLBI2010 compliant antennas is being installed at the Geodetic Observatory Wettzell in Germany.
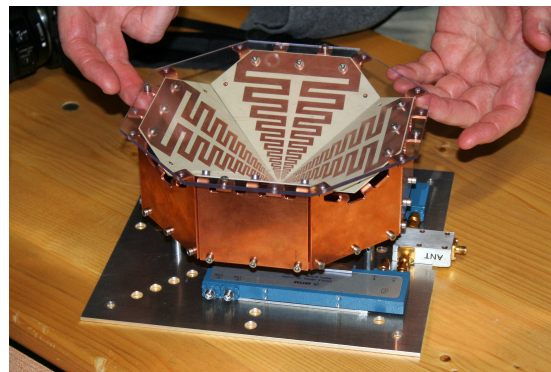

Figure 2. Prototype of a broadband 2-14 GHz "Eleven" feed for VLBI2010. The feed is being developed at Chalmers University of Technology in Sweden.

In order to shorten the on-source observing time, a new approach is being developed in which several widely spaced frequency bands are used to unambiguously resolve the interferometer phase.

The new observable is being referred to as the broadband delay (bbd). To do this, a four-band system is recommended that uses a broadband feed to span the entire frequency range from 2 to 14 GHz (see Figure 2). In order to be able to detect an adequate number of radio sources, a total instantaneous data rate as high as 32 Gbps and a sustained data storage or transmission rate of 8 Gbps are necessary. The system development effort for VLBI2010 involves nearly a complete reworking of the current S/X system. Since the bbd technique is new and untested, NASA is funding a proof-of-concept development effort to verify that it works and to gain experience with the new VLBI2010 systems.

It is also recognized that reducing systematic errors plays a critical role in improving VLBI accuracy. For minimizing electronic biases, updated calibration systems and processes are being developed. For errors due to source structure, the application of corrections based on images derived directly from the VLBI2010 observations is under study. For antenna deformations, conventional surveying techniques continue to be refined, while the use of a small reference antenna for generating deformation models and establishing site ties is also under consideration [2].

4. Network Considerations

It is recommended that a globally distributed network of at least 16 VLBI2010 antennas observe every day to determine Earth Orientation Parameters (EOP), and that other antennas be added as needed for the maintenance of the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). A subset of antennas with access to high-speed fiber networks is also required to enable daily delivery of initial IVS products in less than 24 hours. For the observation of faint radio sources for densification of the ICRF, at least four large radio telescopes per hemisphere are also recommended. High priority is placed on increasing the number of stations in the southern hemisphere.

5. Operational Considerations

In order to increase reliability and to reduce the cost of operations, enhanced automation will be introduced both at the stations and in the analysis process. Stations will be monitored centrally to ensure compatible operating modes, to update schedules as required, and to notify station staff when problems occur.

Since IVS products must be delivered without interruption, a transition period to VLBI2010 operations is required in which there will be a mix of antennas with current and next-generation receiving systems. For this period a compatibility mode of operation has been identified. To preserve continuity in particular with respect to the strength of stable long-term time series of station positions, baseline lengths, and troposphere parameters, among other things, several existing radio telescopes are expected to continue VLBI observations for many years to come.

6. Status at the Beginning of 2010

Sponsored by NASA, full progenitor VLBI2010 signal paths have been implemented on two antennas, the 18-m antenna at the Haystack Observatory in Westford, Massachusetts, and the 5-m MV-3 antenna at the NASA Goddard Space Flight Center (GSFC) in Maryland, a baseline of 597 km. With the new systems, fringes are now routinely detected. As an example, in Figures 3 and

4, phase delays are displayed from a seven minute scan of 4C39.25 taken on day 314 of 2009. In Figure 3 the scan is broken down into 10-s segments, each with an SNR of about 28. Integer cycles of phase are resolved independently for each 10-s segment using the bbd technique. There are no apparent phase resolution errors. Rms delay scatter is a few ps relative to a 30-ps p-p systematic signal. In Figure 4, when the segments are reduced to 8-s each, SNR becomes about 24 and two of the segments can be seen to have phase resolution errors. This implies that, for this system, phase resolution with about 2-sigma confidence can be achieved at an SNR of about 25. This is a very encouraging first step. When the proof-of-concept system is brought to full VLBI2010 compliance (i.e., an increase of bandwidth from 512 to 1024 GHz per band, and an increase in frequency range from 3.5-8.5 GHz to 2.2-14 GHz), it has been calculated that phase resolution with 4- to 5-sigma confidence can be achieved at the VLBI2010 target SNR of 15 to 20.
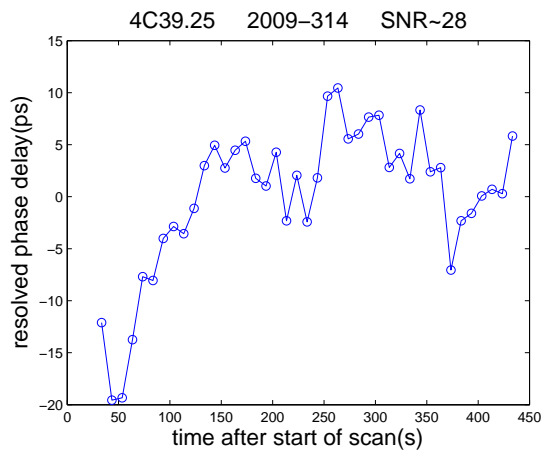

Figure 3. Phase delays for a 450-s scan of 4C39.25 taken on day 314 of 2009. The scan is divided into 10-s segments, each with an SNR of about 28. Cycles of phase were resolved independently for each segment using the bbd technique.
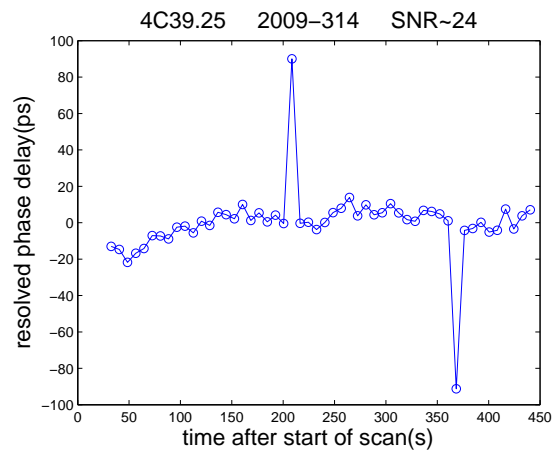
Figure 4. Phase delays for a 450-s scan of 4C39.25 taken on day 314 of 2009. The scan is divided into 8-s segments, each with an SNR of about 24. Cycles of phase were resolved independently for each segment using the bbd technique.

Worldwide, about ten VLBI2010 antennas have been funded and are currently in various stages of implementation. New antennas are coming up in Australia, Korea, New Zealand, Germany, Spain, Portugal, and the USA. The IVS has been approached by several other countries regarding VLBI2010, and a number of proposals for new sites are in various stages of preparation and approval.

Beyond the NASA development effort, organizations in other countries are involved in system developments potentially applicable to VLBI2010. These include Australia, China, Finland, Germany, Italy, Japan, Norway, Sweden, and possibly others.

The VLBI2010 concept also needs strategic and political support to be realized. In March 2009 a small VLBI2010 Project Executive Group (V2PEG) was established to move to the next level of defining development and deployment schedules and soliciting contributions.

7. Acknowledgements

The work on the definition, design, and prototyping of VLBI2010 was supported by many IVS members and components. All of them are gratefully acknowledged. I would also like to acknowledge specific writing contributions from D. Behrend, B.E. Corey, A.E. Niell, and H. Schuh.

References

[1] Behrend D., Böhm J., Charlot P., Clark T., Corey B., Gipson J., Haas R., Koyama Y., MacMillan D., Malkin Z., Niell A., Nilsson T., Petrachenko B., Rogers A., Tuccari G. (2009). Recent Progress in the VLBI2010 Development. In: *Observing our Changing Earth*, ed. by M. Sideris, IAG Symposia, Vol. 133, pp. 833-840.

[2] Ichikawa, R., Ishii A., Takiguchi H., Kuboki H., Kimura M., Nakajima J., Koyama Y., Kondo T., Machida M., Kurihara S., Kokado K., Matsuzaka S. (2008). Development of a Compact VLBI System for Providing over 10-km Baseline Calibration. In: *"Measuring the Future", Proceedings of the Fifth IVS General Meeting*, ed. by A. Finkelstein and D. Behrend, Nauka, St. Petersburg, ISBN 978-5-02-025332-2, pp. 400-404.

[3] MacMillan D. (2008). Simulation Analysis of the Geodetic Performance of Networks of VLBI Stations. In: *"Measuring the Future", Proceedings of the Fifth IVS General Meeting*, ed. by A. Finkelstein and D. Behrend, Nauka, St. Petersberg, ISBN 978-5-02-025332-2, pp. 416-420.

[4] Niell A., Whitney A., Petrachenko B., Schlüter W., Vandenberg N., Hase H., Koyama Y., Ma C., Schuh H., Tuccari G. (2006). VLBI2010: Current and future requirements of geodetic VLBI systems. In: *International VLBI Service for Geodesy and Astrometry 2005 Annual Report*, ed. by D. Behrend and K. Baver, NASA/TP-2006-214136, pp. 13-40.

[5] Nilsson T., Haas R. (2008). Modelling Tropospheric Delays with Atmospheric Turbulence Models. In: *"Measuring the Future", Proceedings of the Fifth IVS General Meeting*, ed. by A. Finkelstein and D. Behrend, Nauka, St. Petersburg, ISBN 978-5-02-025332-2, pp. 361-370.

[6] Petrachenko B., Böhm J., MacMillan D., Pany A., Searle A., Wresnik J. (2008). VLBI2010 Antenna Slew Rate Study. In: *"Measuring the Future", Proceedings of the Fifth IVS General Meeting*, ed. by A. Finkelstein and D. Behrend, Nauka, St. Petersberg, ISBN 978-5-02-025332-2 pp. 410-415.

[7] Petrachenko B., Niell A., Behrend D., Corey B., Böhm J., Charlot P., Collioud A., Gipson J., Haas R., Hobiger T., Koyama Y., MacMillan D., Malkin Z., Nilsson T., Pany A., Tuccari G., Whitney A., Wresnik J. (2009). Design Aspects of the VLBI2010 System - Progress Report of the VLBI2010 Committee, NASA/TM-2009-214180, 58 pp.

[8] Plag H-P., Gross, R., Rothacher, M. (2009), Global Geodetic Observing System for Geohazards and Global Change. *Geosciences, BRGM's journal for a sustainable Earth*, **9**, 96-103.

[9] Plag H-P., Pearlman M. (Eds.) (2009). Global Geodetic Observing System Meeting the Requirements of a Global Society on a Changing Planet in 2020, *Springer-Verlag*, ISBN 978-3-642-02686-7, doi: 10.1007/978-3-642-02687-4

[10] Schuh H., Charlot P., Hase H., Himwich E., Kingham K., Klatt C., Ma C., Malkin Z., Niell A., Nothnagel A., Schlüter W., Takashima K., Vandenberg N. (2002). IVS Working Group 2 for Product Specification and Observing Programs. In: *International VLBI Service for Geodesy and Astrometry 2001 Annual Report*, ed. by N. Vandenberg and K. Baver, NASA/TP-2002-21000181, pp. 13-45.

[11] Wresnik J., Böhm J., Pany A., Schuh H. (2008). VLBI2010 simulations at IGG Vienna. In: *"Measuring the Future", Proceedings of the Fifth IVS General Meeting*, ed. by A. Finkelstein and D. Behrend, Nauka, St. Petersberg, ISBN 978-5-02-025332-2, pp. 421-426.