TDA Progress Report 42-111

1992 ...
495089 20 p

November 15, 1992

N93-18917

p. 16

Demonstration of a Joint U.S.–Russian Very Long Baseline Interferometry Tracking Capability

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This article discusses results of the first very long baseline interferometric (VLBI) measurements between antennas of the NASA DSN and the Russian three-station spacecraft tracking network. The VLBI systems of the U.S. and Russian tracking networks are described, and their compatibility for joint U.S.–Russian measurements is discussed. The results of a series of VLBI measurements involving Deep Space Stations and Russian tracking antennas are presented. The purpose of these first observations is to establish the compatibility of the two VLBI recording systems and verify that data recorded on these systems can be successfully correlated. The delay and delay rate observables produced by correlation of the recorded data are then used to estimate the locations of the Russian tracking stations relative to the Deep Space Stations. These first experiments, carried out at 1.7 GHz, are precursors to a future series of observations at 2 and 8 GHz, which will provide far more accurate station location estimates. The capability of the VLBI systems for joint U.S.–Russian spacecraft navigation measurements is also discussed.

I. Introduction

NASA's DSN has cooperated with Soviet (Russian) tracking stations in performing spacecraft navigation for several missions, including the Soviet VEGA (Pathfinder mission) and PHOBOS missions. Because of incompatibilities in the antenna receiving systems and uncertainties in the locations of the Soviet tracking stations relative to the DSN stations, the Soviet and DSN tracking data were analyzed independently. Recent upgrades to three tracking stations in Russia, at Evpatoria, Ussuriisk, and Bear Lakes, have now made it possible to carry out joint VLBI measurements with antennas of the DSN.

There are several potential benefits that will result from joint spacecraft VLBI measurements between DSN and Russian antennas. The increased number of stations and their geographical locations relative to the DSN stations (see Fig. 1) greatly increase the common spacecraft visibility window. An example of this is illustrated in Fig. 2 where the common visibility period of a source at various declinations is plotted for several baselines. As is evident from this figure, the addition of the Ussuriisk station significantly increases the visibility period for sources within 20 deg of the ecliptic plane, and with DSS 14 and DSS 43 would allow observations with a three-station network. The addition of more and longer baselines would also improve the accuracy of the VLBI measurements. From an operational viewpoint, the additional antennas would decrease the demands on any single antenna for tracking time and provide greater flexibility in scheduling interferometric observations. These same benefits would also apply to differenced range and Doppler observations. Several preliminary observations have now been completed to verify the compatibility of receiving and recording systems at the Russian and DSN stations.

II. VLBI System Parameters

This section provides a brief description of the VLBI system in place at the DSN sites and the equivalent system under development at the Russian sites.

A. NASA DSN VLBI System[1]

The NASA DSN VLBI system consists of 70-m and 34-m antennas at three Deep Space Communication Complexes located at Goldstone, California; Canberra, Australia; and Madrid, Spain (see Table 1). In addition to the antennas and their receiving systems, there are two VLBI correlators, a tracking network control center, and a system for direct data transmission to JPL. The characteristics of the receiving systems are given in Table 2.

Figure 3 shows a block diagram of the DSN VLBI receiving system. Each terminal includes two subsystems: narrow-channel bandwidth (NCB) and wide-channel bandwidth (WCB). The NCB system is used for operational spacecraft tracking and for rapid calibration of Earth orientation. The limited data rate (500 kbits/sec) of the NCB system allows rapid transfer of the data to JPL via a ground communications system where the data can be processed in 12 hours or less for such time-critical applications as planetary approach maneuvers. The WCB system, on the other hand, takes advantage of greatly increased data rates and spanned bandwidths to provide much higher accuracy and sensitivity. Data rates of up to 112 Mbits/sec are recorded to wide-band video tape, which is then shipped to JPL for further processing. The WCB system is used for developing an inertial reference frame defined by the angular positions of distant, extragalactic radio sources (e.g., quasars) and for monitoring long-term motions of the DSN stations in this reference frame. The NCB and WCB systems each have their own VLBI correlator. The Block I correlator, located in JPL's Space Flight Operations Facility (SFOF), processes the NCB data transmitted to JPL via a ground communications system. The Block II correlator, located on the Caltech campus, is used to process data recorded with the WCB system. It can correlate data recorded in either of two standard radio astronomy formats: Mark III, used with the WCB system, or Mark II, an older format with a narrower bandwidth, which is still in common use at many sites. Table 3 summarizes the characteristics of the NCB and WCB subsystems.

B. Russian VLBI Navigation System [1]

The Russian VLBI navigation system, known as "ORION," consists of three deep space tracking stations located in the territory of the former Soviet Union: Evpatoria (Ukraine), Ussuriisk (Russia), and Bear Lakes (Russia) (see Table 1). As in the case of the DSN, there is also a VLBI correlator, a tracking network control center, a data distribution and delivery system, and an orbit determination center.

During 1992, the 70-m antennas at Evpatoria and Ussuriisk and the 64-m antenna at Bear Lakes will be equipped with 2- and 8-GHz receivers. The 1.7-GHz receivers will continue to be available in antennas at Ussuriisk and Bear Lakes. The parameters of the receiving systems are given in Table 4. Figure 4 shows a block diagram of the Russian VLBI navigation receiving terminal. Each terminal includes two subsystems: navigation and calibration. The navigation subsystem is designed exclusively for spacecraft navigation and is based on the principle of frequency bandwidth synthesis (BWS) with time-multiplexed channels [2]. The calibration subsystem is intended for calibration of the interferometer, including measurement of baseline lengths and Earth orientation parameters, positions of reference radio sources, and clock synchronization.

The 2- and 8-GHz systems will have bandwidths of 2215–2375 MHz and 8370–8530 MHz, respectively. The intermediate frequency (IF) signal, with a bandwidth of 160 MHz (375–535 MHz), is split into two signals with frequency bandwidths of 375–465 MHz and 445–535 MHz. These two signal paths are then downconverted separately

[1] *Deep Space Network/Flight Interface Design Handbook* [illegible]

cies of 478 and 432 MHz in steps of 10 Hz. A summary of the navigation subsystem is given in Table 5.

When in the navigation mode, signals from the spacecraft and reference sources will be recorded in the Mark II format using a 3-channel, time-multiplexed BWS system. Measurements made in the calibration mode will use the Very Long Baseline Array (VLBA) recording system provided by NASA for use in the Radioastron and other missions. Tapes recorded with this system are compatible with the Mark III system tapes and can be correlated on the JPL/Caltech Block II VLBI correlator.

Each tracking station in the ORION network will use a high-quality hydrogen maser frequency standard with a stability of 10^{-14} to 10^{-15} for integration times up to 1000 sec. Clock synchronization will be performed with the Global Positioning System (GPS) or Global Orbiting Navigation Satellite System (GLONASS) receivers located at each station.

Data recorded during the calibration observing sessions in the VLBA format will be processed at the JPL/Caltech Block II correlator. Data recorded in the navigational

For the Soviet VEGA and PHOBOS missions, the Soviet and U.S. antennas used 1.7-GHz receivers. However, there are no plans to put 1.7-GHz transmitters on future spacecraft, and this frequency will no longer be used for VLBI navigation. For this reason the 1.7-GHz receiver at the Evpatoria antenna was removed in the Fall of 1991.

B. VLBI Navigation Systems

The DSN uses the NCB system (see Sec. II.A) for operational spacecraft VLBI measurements. Data recorded with this system, however, are not compatible with the Russian VLBI systems now in place. At the present time, only VLBI data recorded with the DSN WCB system can be correlated with data recorded at Russian sites in either the Mark II or VLBA format.

C. Data Delivery

The means of transmitting the radio metric data to a central processing facility will depend upon the requirements for mission navigation. During planetary encounters, navigation data must be processed rapidly (1–2 days) in order to provide mission controllers with the information needed for orbit corrections. At JPL this is accom-

Russian and DSN stations were completed for the purpose of measuring the locations of the Russian stations in the reference frame of the DSN (see Section IV). An antenna located at Hobart, Tasmania, also participated in several of these measurements.

F. Coordination of Joint U.S.–Russian VLBI Measurements

By its very nature, VLBI requires close cooperation between the often widely separated antennas participating in the measurements. Scheduling of joint U.S.–Russian spacecraft VLBI observations will require coordination between the DSN and ORION network control groups. A common set of experimental parameters must be generated and transmitted to all stations participating in a spacecraft VLBI measurement. These parameters include the sequence of spacecraft and radio source observations, source coordinates for both the spacecraft and radio sources to be observed, and the configuration of the frequency channels of the VLBI recording systems. Generation of the frequency and spacecraft antenna pointing information requires knowledge of the spacecraft trajectory from the Russian or U.S. orbit determination centers. All observations would have to be scheduled well in advance to assure that the network facilities would be available and to avoid conflicts with the requirements of other missions. A reliable and rapid means of communication between Russian and DSN network control centers should be established.

IV. The First Joint DSN–Russian VLBI Experiments

During 1991, five VLBI experiments were performed to test the compatibility of the DSN and Russian VLBI systems and to obtain improved estimates of the Russian station locations relative to the DSN sites. A summary of these measurements is contained in Table 6. In these first experiments, data were recorded at 1.7 GHz in a single 2-MHz channel at each station. Because of the narrow bandwidth in these measurements, the expected accuracy of the estimated station locations was several meters. Additionally, the effect of the ionosphere on the 1.7-GHz signals was expected to introduce a significant systematic error into these results.

The compatibility of the recording systems (bandwidths, sampling rates, recorders, recording media, and data formats) is fundamental to any VLBI measurement. During these first measurements, the Russian stations recorded data on VHS tapes in the Mark II format. Data at the DSN stations were recorded with the Mark III system operating in mode D (single-channel recording). One of the most important results of these first tests was to demonstrate that data recorded in these configurations could be successfully cross-correlated at the JPL/Caltech Block II VLBI correlator.

The second major result of these tests was the estimation of the locations of the Russian tracking antennas from the delay and delay rate observables obtained from correlation of the VLBI data. This information is critical to the success of future joint U.S.–Russian spacecraft VLBI measurements and orbiting VLBI (OVLBI) where station location accuracy is an important component of the error budget. Accurate station locations for the Russian antennas in the DSN reference frame will also benefit the navigation accuracy for Doppler tracking. Future experiments at 8 GHz will significantly improve on the station location estimates provided by these initial 1.7-GHz measurements.

A. VLBI Data Processing

Processing of VLBI data proceeds in several steps beginning with the correlation of the recorded data streams from each station to produce the complex fringes, followed by extraction of the delay and delay rate observables from the fringe phase and amplitude, and finally estimation of the VLBI delay model parameters from the delay and delay rate observables. The following sections describe in some detail each of these steps for the five U.S.–Russian VLBI measurements completed in 1991.

B. Correlation of Recorded Data Streams

Each of the five VLBI measurement sessions consists of a series of repeated observations of several different radio sources. The typical duration of each observation ranged from 20 to 40 minutes. Except for the DSN sites, the data were recorded in a Mark II–compatible format. At the DSN sites, the data were recorded with a Mark III system operating in mode D, in which a single 2-MHz channel of data was recorded in successive tracks of the 28-track Mark III video tape recorder. The correlation of the raw VLBI data was performed with the JPL/Caltech Block II VLBI Correlator.

The magnitude of the correlation SNR of the interferometric fringes is a function of several experimental parameters. A correlation SNR of at least 4.5 was considered necessary in order to estimate meaningful values for delay and delay rate observables from the complex fringes. The correlation SNR is related to the experimental parameters by

$$SNR = 2.05 \times 10^{-4} \gamma S D_1 D_2 \sqrt{\frac{e_1 e_2 B T}{T_{sys_1} T_{sys_2}}} \qquad (1)$$

where γ is the ratio of the correlated flux density to the total source flux density, S is the source strength in janskys, D_1 and D_2 are the antenna diameters in meters, e_1 and e_2 are the antenna efficiencies (0–1), B is the bandwidth in hertz (2 MHz), T is the integration time in seconds, and T_{sys_1} and T_{sys_2} are the antenna system temperatures in kelvins. A low value for the correlation SNR could result from a weak source (S), resolution of an extended source ($\gamma < 1$), an insufficient integration time (T) or some problem in the recording system hardware.

In general, the quality of the recording systems was adequate to allow fringe detection ($SNR > 4.5$) on most baselines. Where fringes could not be detected, the causes were usually obvious problems in the recording hardware or instabilities in the station frequency standards of such [illegible] that adequate signal averaging was not pos-

D. Estimation of Station Locations

Once the delay and delay rate observables have been extracted from the correlator output, they are input to the parameter estimation software, "MODEST" [4], which can be used to estimate all parameters of the interferometric delay model. For these purposes, the interest is primarily in estimating the locations of the antennas at Bear Lakes, Evpatoria, and Ussuriisk. The other parameters of the delay model are held fixed at values obtained from independent sources. Radio source coordinates and DSN and Hobart station locations were obtained from the International Earth Rotation Service (IERS) 1990 Annual Report [5], and Earth orientation parameters (UT1–UTC, polar motion, and nutation corrections) were obtained from the IERS series 90-C-04.[2] This ensured that the Russian station location estimates would be in the IERS terrestrial reference frame. The particular reference frame used is somewhat arbitrary, but the IERS provides a well-defined, documented set of conventions for Earth orientation parameters, station locations, and radio source positions.

a χ^2 per degree of freedom equal to 1. This required that the random errors on the delay observable be increased by an additional 1.0×10^{-9} to 6.0×10^{-8} sec and the delay rate observables increased by 1.0×10^{-12} sec/sec.

Simultaneous analysis of all five VLBI measurements yielded station location estimates with formal errors of 1 to 2 m in the X and Y (equatorial) components, and about 5 m in the Z (Earth rotation axis) direction (see Table 7). The much larger formal errors in the Z components are due to the fact that this coordinate is not sensitive to the delay rate observable and is, therefore, determined solely from the less-precise single-channel delay observable.

Because these observations were carried out at 1.7 GHz, the results are expected to be quite sensitive to ionospheric effects. Indeed, it was found that the values of the estimated station locations changed by several meters when the Bent model ionospheric calibrations were scaled by 35 percent about the nominal values in the various experiments. The systematic errors listed in Table 7 are the changes in the station location estimates resulting from these scalings. Varying the tropospheric calibrations was found to have little effect on the station location estimates.

The dominant error sources in the station location estimates are random and instrumental phase errors in the delay observable and ionospheric calibration errors in both the delay and delay rate observables. Both random and instrumental phase errors will be much improved in future multiple-frequency channel observations, and the ionospheric errors will be much reduced in future 8-GHz observations, or effectively eliminated in dual-frequency band (2- and 8-GHz) observations.

V. Plans for Future Observations

In 1992, U.S.–Russian VLBI tests emphasized observations at 2 and 8 GHz using both the 3-channel bandwidth synthesis system (see Section II.B) of the Russian ORION system and Mark III compatible systems. The main purposes of these observations are

(1) to complete a full test of the compatibility of the time multiplexed bandwidth synthesis system at the Russian stations with the Mark III system at the DSN stations.

(2) to use the results of these 2- and 8-GHz measurements to improve the estimates of the Russian station locations to an accuracy of 5 cm.

On March 12, 1992, a VLBI measurement was completed that involved Ussuriisk, Canberra (DSS 43), the 9-m antenna at Kauai, Hawaii, and the 26-m antenna at Gilmore Creek, Alaska. In this measurement, data were recorded in a Mark III–compatible format at 8 GHz at all sites. At Ussuriisk this was accomplished through the use of a U.S.–supplied VLBA recording system on temporary loan from the National Radio Astronomy Observatory (NRAO). Data from this measurement will be correlated at the Mark III Haystack Correlator with the post-correlation analysis and geodetic parameter estimation completed at the Goddard Space Flight Center (GSFC) and JPL. The results of this first 8-GHz experiment will improve the estimates of the Ussuriisk location by an order of magnitude over the 1.7-GHz results. Future experiments with the two other Russian sites await the installation of 2- and 8-GHz receivers and the completion of the other components of the ORION VLBI recording system.

VI. Conclusions

Five VLBI measurements involving three Russian and two DSN tracking stations have been completed and the data have been processed to provide estimates of the locations of the Russian antennas in the DSN reference frame with an accuracy of 5 to 15 m in each coordinate. These first experiments have demonstrated the compatibility of the receiving and recording systems of the two tracking networks and have shown that VLBI data from the two networks can be successfully correlated to produce delay and delay rate observables. Future experiments at other wavelengths will improve the accuracy of the station locations estimated from the data in the first series of experiments and may also include VLBI measurements of U.S. spacecraft.

Acknowledgments

The authors thank Dave Jauncey for valuable assistance in conducting the DSN observations in Australia, K. Pobedonoscev and Y. Gorshenkov at the Moscow Power Institute, Peter McCulloch and Edward King from Hobart University (Tasmania) for cooperation in the joint VLBI measurements, and Don Green and Herb Royden of JPL for supplying and explaining the ionospheric calibrations.

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[5] *International Earth Rotation Service, Annual Report for 1990*, Observatoire de Paris, France, 1991.

[6] S. K. Llewellyn and R. B. Bent, *Documentation and description of the Bent ionospheric model*, Rep. AD-772 733, available from National Technical Information Service, Springfield, Virginia, 1973.

Table 1. Locations of Deep Space Station Antennas for U.S. and Russian networks.

Site	Antenna	Latitude	E. longitude	Diameter, m
Goldstone	DSS 14	35 25 33.3	243 06 40.6	70
	DSS 15	35 25 18.8	243 06 49.1	34
Canberra	DSS 43	−35 24 14.4	148 58 58.1	70
	DSS 45	−35 24 00.1	148 58 35.2	34
Madrid	DSS 63	40 25 56.6	355 45 11.0	70
	DSS 65	40 25 42.1	355 44 59.7	34
Evpatoria	DSS 52	45 11 22.0	33 11 19.0	70
Ussuriisk	DSS 47	44 00 57.0	131 45 22.0	70
Moscow	Bear Lakes	55 51 57.0	37 57 17.0	64
Hobart[a]	–	−42 48 13.0	147 26 26.0	26

[a] The 26-m antenna at Hobart, operated by the University of Tasmania, participated in these measurements, but is not part of either the Russian or the U.S. tracking network.

Table 2. Characteristics of receiving systems at DSN stations.

Antenna	Receiver	Bandwidth, MHz	System temperature, K	Polarization	Amplifier[a]
70-m	X-band	8400–8500	21	RCP[b]/LCP[c]	TWM
	S-band	2265–2305	23	RCP/LCP	TWM
	L-band	1628–1708	35	LCP[d]	FET
34-m	X-band	8400–8500	20	RCP/LCP	TWM
		8200–8600	36	RCP/LCP	HEMT
	S-band	2200–2305	38	RCP/LCP	HEMT

[a] TWM = traveling wave maser, HEMT = high-electron mobility transistor, FET = field effect transistor.

[b] RCP = right circular polarization.

[c] LCP = left circular polarization.

[d] RCP is available by performing a mechanical adjustment in the L-band receiver.

Table 3. Characteristics of DSN narrowband and wideband VLBI recording systems.

System parameter	NCB system	WCB system
Channel configuration	4 S-band, 8 X-band	14 independent channels
Channel bandwidth	250, 125, 62.5, 31.25 KHz	4, 2 MHz
Channel local oscillator	10-Hz resolution	10-KHz resolution
Sampling mode	Time-multiplexed sampling of channels, 0 to 60-sec dwell time	All channels recorded continuously
Sampling rate	500, 250, 125, 62.5 KHz	8, 4 MHz
Quantization	1 bit	1 bit
Recording medium	Disk or 9-track tape	1-in. 28-track video tape
Data transmission	Direct, via satellite relay	Shipment of tapes to JPL
Data correlation	JPL Block I VLBI correlator	Caltech/JPL Block II VLBI processor

Table 4. Characteristics of receiving systems at Russian stations.

Receiver	Bandwidth, MHz	System temperature, K	Polarization	Amplifier[a]
X-band	8370–8530[b]	45	RCP/LCP	FET
	8395–8445		RCP/LCP	FET
S-band	2270–2300[b]		RCP/LCP	FET
	2215–2375[b]		RCP/LCP	FET
L-band	1662-1692	55	LCP	

[a] FET = field effect transistor.

[b] To be installed in 1992.

Table 5. Characteristics of Russian VLBI navigation system.

System parameter	Specification
Channel configuration	3 independent channels
Channel bandwidth	0–2 MHz
Channel local oscillator	10-Hz resolution
Sampling mode	Multiplexed, 0.2-sec dwell
Sampling rate	4 MHz
Quantization	1 bit
Recording medium	VHS tapes, Mark II format
Data transmission	Shipment of tapes to correlator
Data correlation	JPL/Caltech Block II VLBI processor/ Russian ORION processor

Table 6. Summary of 1.7-GHz VLBI measurements.

Date	Start time, hr:min	Stop time, hr:min	Baseline	Length, km	Number of sources detected	Number of sources observed
March 27, 1991	00:00	12:00	Hobart–Evpatoria	11,715.9	0	5
			Hobart–Ussuriisk	8813.0	9	9
			Evpatoria–Ussuriisk	6896.2	0	5
June 19–20, 1991	20:55	08:45	Hobart–Evpatoria	11,715.9	4	6
			Hobart–Ussuriisk	8813.0	3	9
			Hobart–Bear Lakes	11,730.1	0	6
			Evpatoria–Ussuriisk	6896.2	3	6
			Evpatoria–Bear Lakes	1232.3	0	6
			Ussuriisk–Bear Lakes	6072.9	0	6
June 22, 1991	06:40	10:00	DSS 63–Evpatoria	3049.2	5	5
			DSS 63–Ussuriisk	8773.9	0	4
			DSS 63–Bear Lakes	3459.9	5	5
			Evpatoria–Ussuriisk	6896.2	4	4
			Evpatoria–Bear Lakes	1232.2	5	5
			Ussuriisk–Bear Lakes	6072.9	4	4
October 17, 1991	12:30	18:50	DSS 43–Ussuriisk	8238.5	0	6
October 21, 1991	13:15	22:05	DSS 43–Ussuriisk	8238.5	0	8
			DSS 43–Hobart	831.8	7	8
			Ussuriisk–Hobart	8813.0	5	8

Table 7. Estimates of Russian tracking station locations.

Station	Estimates of Cartesian station locations and uncertainties, m								
	X	σ_f^a	σ_{ion}^b	Y	σ_f^a	σ_{ion}^b	Z	σ_f^a	σ_{ion}^b
Bear Lakes	2828548.1	1.4	0.4	2206063.7	1.4	2.8	5256401.7	5.4	3.2
Evpatoria	3768306.9	1.7	3.5	2464683.0	1.3	2.6	4502254.5	4.7	3.6
Ussuriisk	−3059724.4	1.6	0.3	3427253.3	1.5	0.7	4409476.2	4.8	6.4

[a] Formal errors from parameter estimation software.

[b] Systematic error from ionospheric effects.

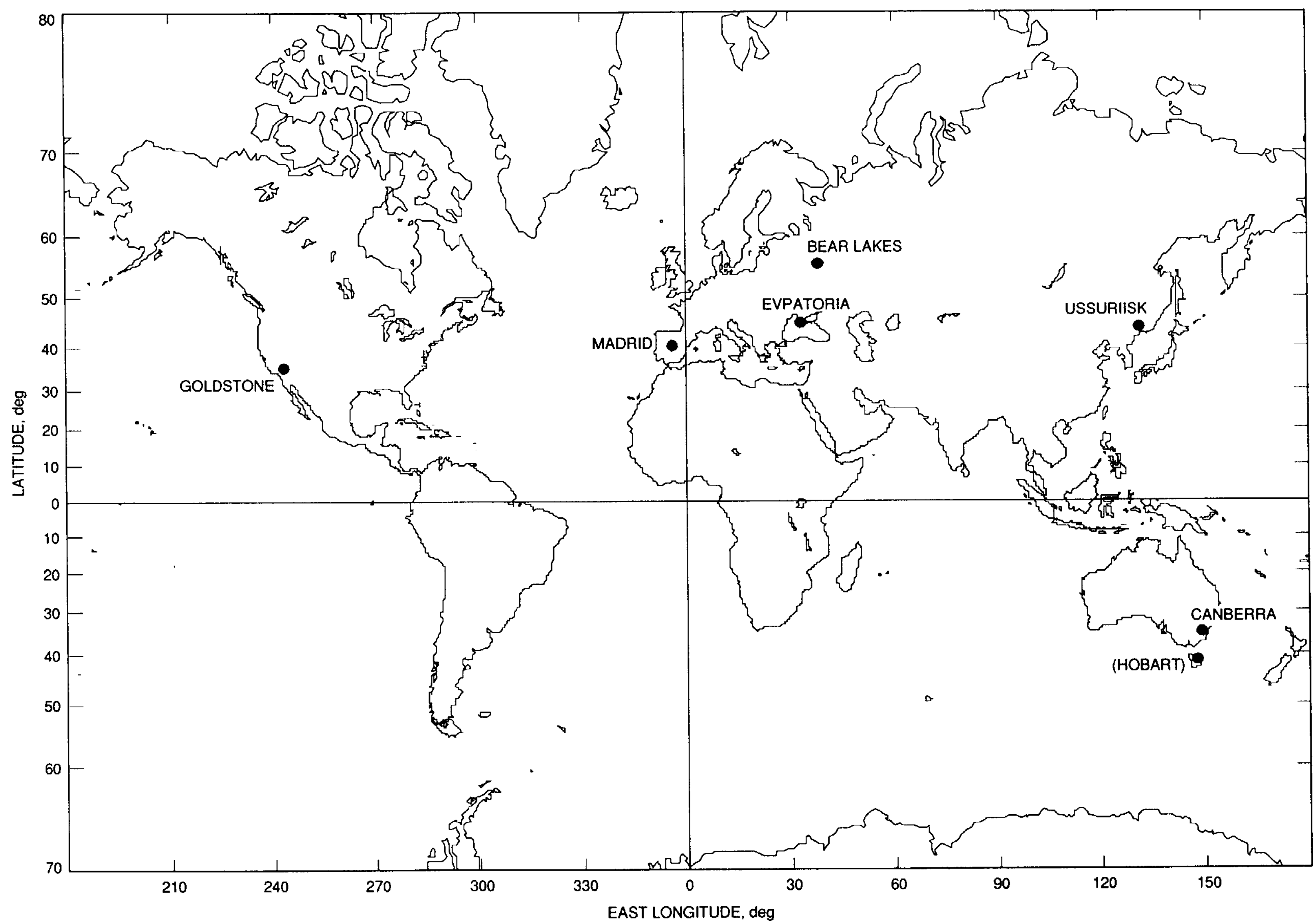

Fig. 1. Location of Deep Space Stations and Russian tracking stations. The 26-m antenna at Hobart, Tasmania, participated in the VLBI measurements described in this article, but it is not part of either the Russian or U.S. tracking network.

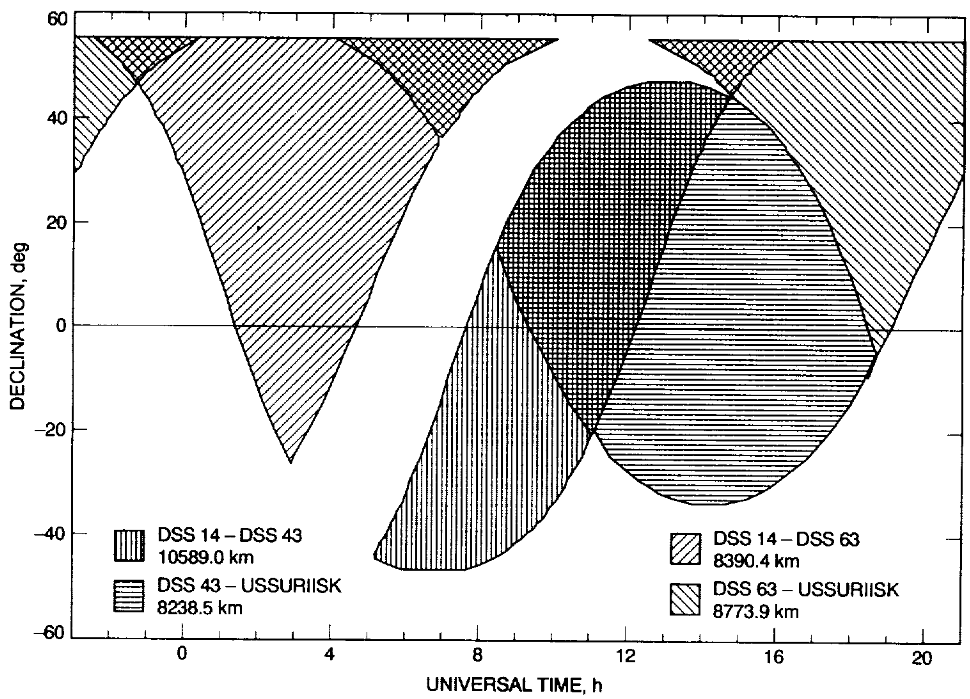

Fig. 2. Common visibility periods of a source with right ascension 0 h 0 min 0 sec, at a range of declinations on 4 different baselines.

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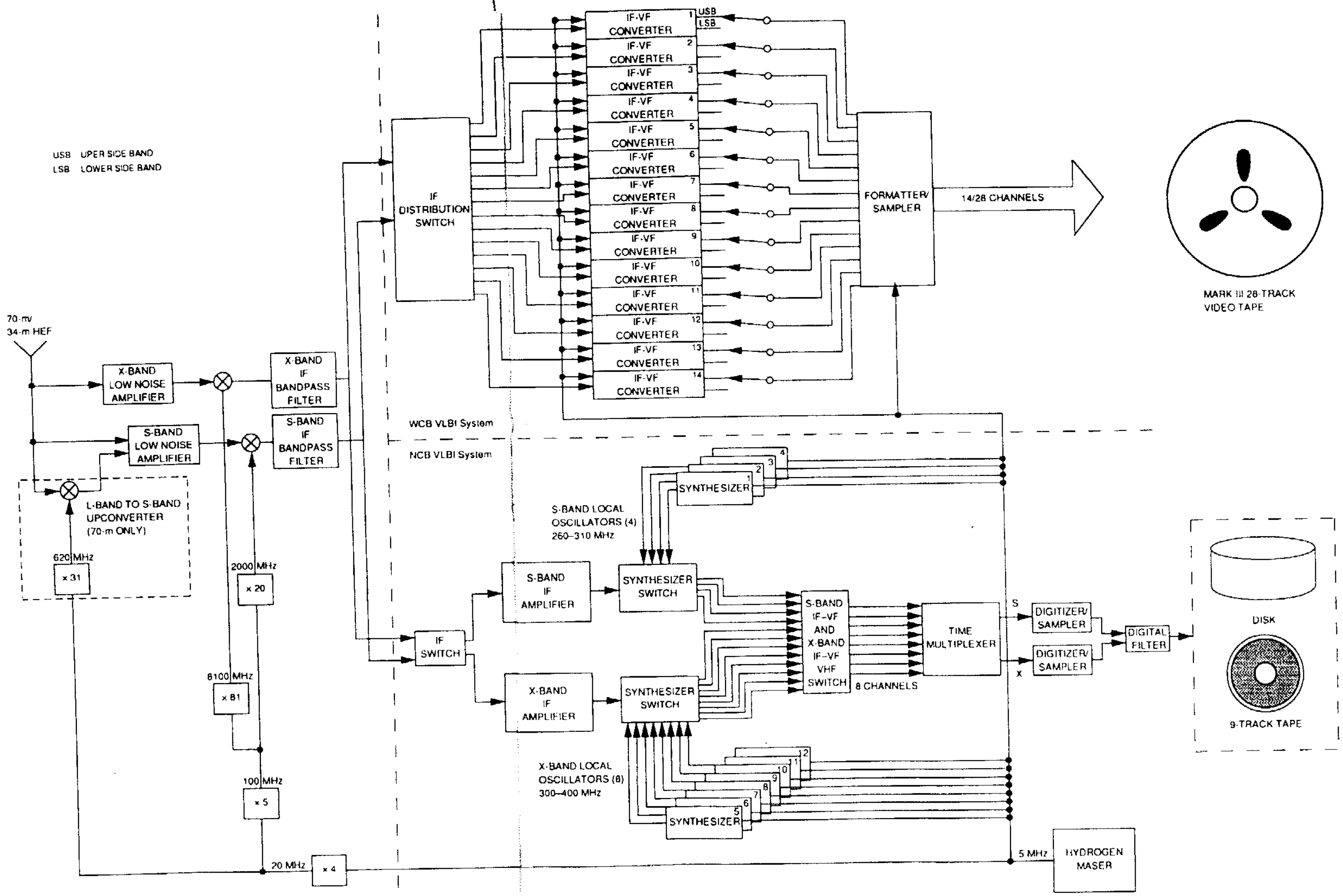

Fig. 3. Block diagram of the DSN VLBI system.

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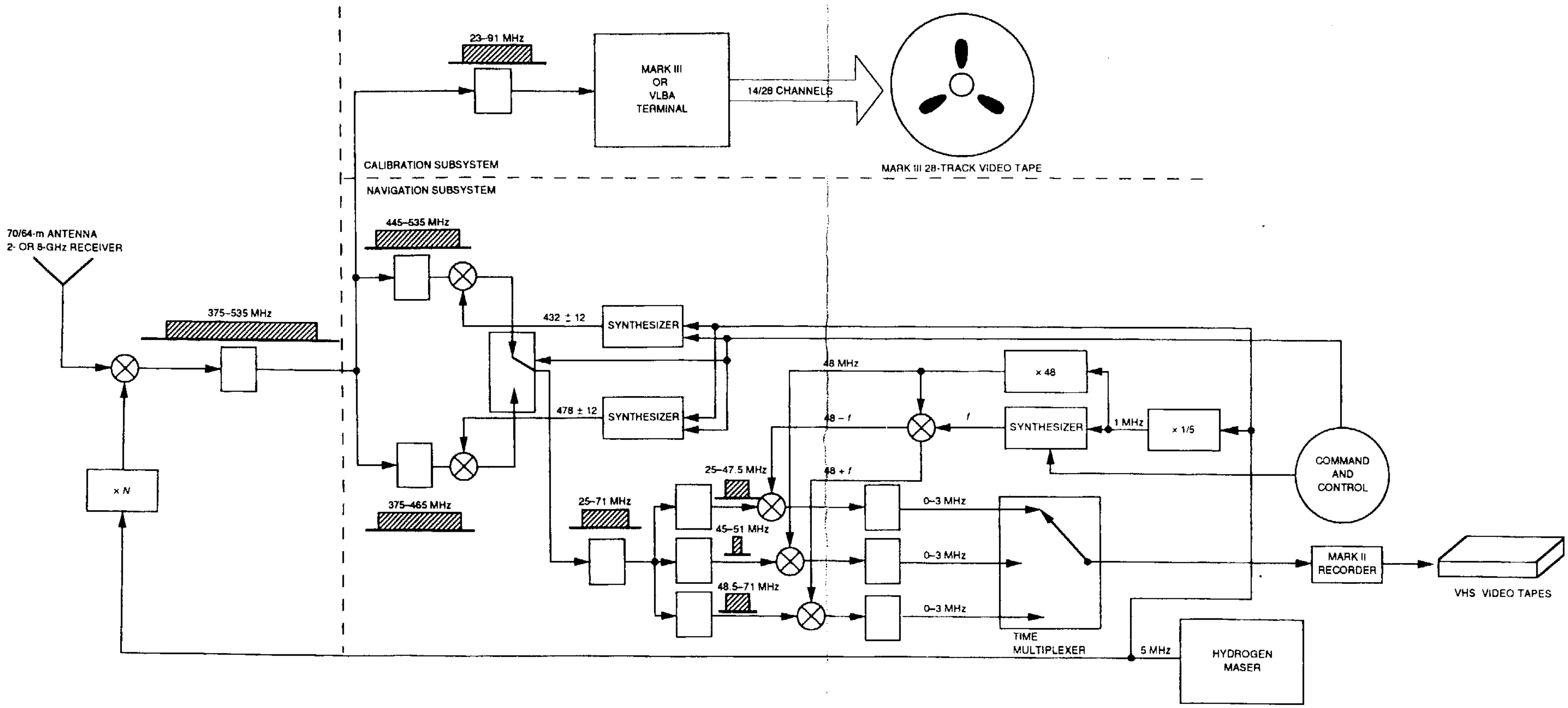

Fig. 4. Block diagram of the Russian ORION VLBI system.