DSN Very Long Baseline Interferometry System Mark IV-88

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This article presents a functional description of the Deep Space Network Very Long Baseline Interferometry system as it will exist at the end of 1988.

I. Introduction

Very Long Baseline Interferometry (VLBI), in its simplest form, uses two radio telescopes to synthesize a radio telescope with an angular resolution equal to that of a telescope whose diameter equals the separation of the two telescopes. The DSN makes use of this very high angular resolution to produce precision navigational data for spacecraft in deep space. VLBI data is also used to produce source coordinates for radio reference sources and platform parameters, which include the relative antenna positions on the surface of the Earth and the instantaneous rotations of the Earth's surface relative to its mean position. The VLBI system also supports a variety of astronomical and geodetic programs.

II. VLBI Description

A schematic representation of a VLBI observation is shown in Fig. 1. When the signals from the two antennas are correlated against each other, with a variable relative delay, the actual delay is given by the relative delay which maximizes the degree of correlation. This time delay is the VLBI observable. If the baseline vector is known, the angle of arrival of the radio waves and hence the source's angular position can be computed. A priori knowledge of the observational parameters is, in general, not well enough known to unambiguously determine the absolute phase of the measured delay. Measurements at several frequencies allow the group delay to be computed from the slope of phase versus frequency. Measurements from the frequency channels with the smallest frequency separation have ambiguities which can be resolved from a priori knowledge. The channels with wider frequency separation are used to progressively improve the precision of the delay determination. This technique is called bandwidth synthesis. For a complete description of VLBI, see [1]–[4].

VLBI accuracy is reduced by errors in knowledge of the baseline length and its orientation in relation to the instantaneous spin axis of the Earth, station clock drift, and unmodeled media delays. In the case of navigation, these errors can be greatly reduced by observing a reference radio source that is angularly near a spacecraft. Such an observational scenario is shown in Fig. 2. By differencing the delay measured from the Extragalactic Radio Source (EGRS) observation with the delay measured from the observation of the spacecraft, one can determine the angular separation of the EGRS and the spacecraft in the direction perpendicular to the baseline. The differencing process eliminates any errors that are common to both observations. Reducing the angular and time separation of the observations increases the amount of commonality of the error sources and therefore reduces the common mode errors. This procedure is called delta-differential one-way range (delta-DOR). It is analogous to differencing one-way ranging delays between two stations (DOR) and then differencing these ranges between two sources. If delay measurements are made over some time interval, they can be differenced to produce a data type called delta-differential one-way doppler (delta-DOD). This gives an angular rate in the plane of the sky rather than an angular position and is analogous to doubly differenced doppler data. The generic term for the differenced VLBI data is delta-VLBI.

A penalty of using an EGRS as a reference is that angular positions and rates relative to the EGRS are produced rather than absolute positions and rates. In order to make use of this data for navigation, the EGRS position must be accurately known from other measurements. VLBI observations can determine relative station locations with an accuracy of 5 to 10 centimeters and source positions to an accuracy better than 30 nanoradians by repeated observations of many sources with varying observing geometries. An ongoing program (Catalog Maintenance and Enhancement) in the DSN continues to improve the positional accuracy of a catalog of more than 100 EGRSs while adding sources for new projects when necessary.

Another program supported by the DSN, called TEMPO (Time and Earth Motion Precision Observations), makes weekly VLBI observations that provide detailed knowledge of the short term fluctuations in the angular position of the Earth's crust relative to its mean position. The quantities measured (platform parameters) are the variations in rotation/time (UT1 – UTC) and the variations in the position of the spin axis (polar motion). These platform parameters are used in the Orbit Determination Program for the reduction of delta-VLBI data as well as all other radiometric data types. The TEMPO observations also produce information about the relative time offset and rate offset between the precision clocks at the DSCC and aid in maintaining clock synchronization and syntonization (relative frequency).

III. Key Characteristics

There are three distinct VLBI configurations currently implemented within the DSN. This section will describe the key characteristics of the two new configurations and will conclude with a brief note about the third, which is being replaced by the other two.

A. Narrow Channel Bandwidth (NCB) VLBI

NCB VLBI (also known as Block I VLBI) is used to produce most of the spacecraft navigation data (delta-VLBI data) and weekly EGRS measurements for determination of the platform parameters (TEMPO project). The name is derived from the use of relatively narrow bandwidth individual channels. Table 1 shows the key parameters of the NCB configuration. The sensitivity of the NCB VLBI system to both narrowband (spacecraft) and wideband (EGRS) signals is shown in Table 2.

Because the recording rate is only 500 kbits/sec, the data can be recorded directly on a high capacity disk, and playback of the data can begin while the observations are still in progress. This is important for those applications with tight time constraints on the delivery of the processed VLBI data.

The VLBI observables are of little value until they are converted to angular positions and rates of a spacecraft or other source. The achievable accuracy depends on this conversion and is also affected by external variables such as delays in the transmission media. Figures 3 and 4 show estimated VLBI error budgets for spacecraft angular delay and rate measurements under typical conditions.

The TEMPO project (also known as Clock Sync) observes from 16 to 20 EGRSs once a week on each DSN baseline (California to Spain and California to Australia) for a total of about 8000 seconds of data. The Earth rotation parameters that are produced from this data are accurate to 30 cm (1 sigma) in each component. The primary factors limiting the accuracy are the spanned bandwidth and SNR in the narrow channels.

B. Wide Channel Bandwidth (WCB) VLBI

WCB VLBI is used primarily for producing the EGRS position catalog required for analysis of the delta-VLBI navigation data. Because of the greater sensitivity and precision, relative to NCB, the WCB configuration is used for radio astronomy and geophysical studies associated with tectonic plate motion and deformation. In some cases (e.g., the Phobos Project), when it is necessary to use a very weak EGRS and the NCB sensitivity is too low, WCB VLBI can be used for delta-VLBI observations. WCB VLBI is also known as Block II VLBI. The WCB digital hardware at the station is the same as the Mark III hardware in use by the astronomical and geophysical communities. The computer and software that control the hardware are different from those used by Mark III. The data format produced by WCB VLBI is identical to the Mark III data.

Key characteristics of the WCB configuration are shown in Table 1. The increased spanned bandwidth and data volume, due to increased channel bandwidth and simultaneous channel recording, give WCB VLBI much higher sensitivity than the NCB VLBI, as is shown in Table 2. For projects not requiring a fast turnaround time, the increased sensitivity of WCB VLBI allows the use of the 34-meter HEF subnet rather than the 70-meter subnet, which is usually required for NCB VLBI. Because of the volume of data generated, it is not possible to transmit the data to the correlator electronically. The need to mail tapes from the overseas stations limits the minimum time required to produce reduced data to 1 to 2 weeks.

C. Block 0 VLBI

The first VLBI configuration implemented in the DSN was known as Block 0. It is identical to Mark II VLBI used at astronomical observatories around the world. Like NCB and WCB VLBI, Block 0 can accept data from two frequency bands. The IF that is used is centered at 50 MHz and comes from either Block IV or dedicated VLBI receivers. It has up to 8 channels, each of which is 2 MHz wide, and with a maximum frequency separation of 40 MHz. The channels are time multiplexed, and the data is recorded on standard videocassettes. Although NCB VLBI is less sensitive than the Block 0, it can be automatically controlled by predicts, can play the data back electronically, and has better phase response. This has led to the exclusive use of the NCB configuration for delta-VLBI and TEMPO activities. The Block 0 configuration will be retained during testing of WCB VLBI but will not be used for taking operational data after 1989.

IV. System Functional Description

In this section the VLBI system will be described in more detail. In the first part of this section the Deep Space Communications Complex (DSCC) portion of the system will be presented, and in the second part the Network Operations Control Center (NOCC), JPL/CIT Correlator, and postcorrelation processing portions of the system will be described. Figure 5 shows a block diagram of the VLBI system. The flow of the actual VLBI data (processed RF signal) is shown with wide arrows, while control, status, and calibration data flow is shown with small arrows.

A. DSCC System

The VLBI system can use either the 34-m HEF or the 70-m antenna at each complex and can accept inputs from two frequency bands. Currently only 2.3-GHz (S-band) and 8.4-GHz (X-band) signals can be received simultaneously. Dual frequency observations allow corrections to be made for the effects of charged particles in the transmission media. The 1.7-GHz (L-band) signal at the 70-m antenna, which is upconverted to S-band, can also be used. Either left or right circular polarization may be used; however, the same polarization must be used by each of the antennas being employed. Table 3 shows the details of the radio frequency signals which the VLBI system can process. Because the phase of the RF signal is the end product of the VLBI system, the signal path is calibrated by injecting calibration tones into the RF feed prior to the low noise amplifiers. Variations in the phase of these signals are applied as corrections to the observed radio source phase. Operation of the Phase Calibration Generators (PCGs) is controlled by the Spectrum Processing Assembly (SPA) by means of messages sent to the Frequency and Timing Subsystem (FTS) controller.

The RF signals are downconverted to a 300-MHz IF using phase stable local oscillators operating at the fixed frequencies of 2.0 (S-band) and 8.1 GHz (X-band). Signals at L-band are first upconverted to S-band using a 620-MHz local oscillator and then sent to the S-band downconverter.

For NCB VLBI, an IF selector switch in the Signal Processing Center (SPC) sends the desired IF signals to a VLBI receiver (NVR). The receiver downconverts the IF signals to video frequency in up to twelve time-multiplexed channels. The output of the receiver is then digitized and sampled, single sideband converted, and digitally filtered. This digital processing occurs within the Data Channel Filter (DCF). Digital rather than analog processing is required in order to meet the phase ripple and out-of-band rejection specifications placed on the NCB VLBI configuration. The bandpass of the filter can be set to one of four values. After the bandpass filtering, the signal is passed to the Spectrum Processing Assembly for formatting and recording. Under some conditions (e.g., low Sun–Earth–probe angles), the phase of the RF signal may fluctuate enough during the minimum NCB channel multiplexing time that the correct RF cycle cannot be determined from data point to data point. If only a single channel is being recorded in each frequency band, as is the case for delta-DOD, a band combiner can be used to eliminate the time multiplexing of the channels. The band combiner simply sums the signals from two channels, and only the sum is recorded. The individual signals can be recovered later, in the correlation process, although the system noise temperature is approximately doubled.

For WCB VLBI, all of the IF signals are routed from the IF selector to the Data Acquisition Terminal (DAT), which is the processor and recording assembly for WCB VLBI. Switching within the DAT selects the IF channels corresponding to the desired antenna and frequency band. Fourteen video converters within the DAT produce filtered, clipped (one-bit digitized), single sideband downconverted video signals. Both upper and lower sidebands are generated for a total of 28 2-MHz channels. There are provisions for a range of filters within the video converters (see Table 1), but at this time only the 2-MHz bandpass filters are implemented. All 28 channels can be recorded simultaneously or, if a smaller number is recorded, multiple recordings can be made on the same tape.

The Digital Tone Extractor (DTE) monitors the phase calibration tones for phase drift and jitter. Predicts loaded into the SPA contain standards and limits for the amplitude, drift, and jitter of the phase calibration tones. The DTE output is used during precalibration at the station as part of a system coherence test and as a monitor during the remainder of the pass. The SPA supplies the DTE with a model which is correlated with the video frequency signals from the DCF or the DAT to produce relative phase measurements.

The Spectrum Processing Assembly (SPA) controls all parts of the SPC portion of the VLBI system through predicts and provides monitor data to the DSCC Monitor and Control (DMC) system. The DMC provides the SPA with monitor data from the FTS, the Media Calibration Subsystem (DMD), and the Precision Power Monitor (PPM). Due to timing constraints, pointing angle information is sent directly to the SPA. Monitor data from the VLBI assemblies (DAT, DCF, DTE, SPA), the receiver, and the subsystems just mentioned are reformatted by the SPA and sent via the Digital Communication Subsystem to the Network Operations Control Center (NOCC). The predicts (configuration and standard and limit information) which control and configure the DSCC VLBI system are sent from the NOCC to the SPA via the DMC. The SPA has the ability to support separate WCB and NCB VLBI activities simultaneously. Once the VLBI data is acquired it is sent electronically to the NOCC (in the case of NCB data), or tapes are mailed back to JPL (in the case of Block 0 or WCB data).

B. NOCC System

The NOCC contains the facilities for generating the required predicts, monitoring of VLBI operations in real time, correlating the VLBI data, and providing postcorrelation processing. Figure 5 shows the subsystems within the NOCC.

The NOCC Support Subsystem (NSS) provides antenna pointing predicts for VLBI activities, VLBI configuration parameters used at the DSCC, and the standards and limits used for monitoring system performance. DSCC configuration and performance data is returned to the NOCC Radio Science/VLBI real-time monitor (NRV) during a VLBI activity. The displayed data are monitored by the Network Operations Control Team and Operations and Engineering Analysis for correct operation. The NOCC VLBI Processor (NVP) receives the VLBI and monitor data directly from the Digital Communications Subsystem via wideband data lines and records it on disk. The NVP consists of several independent computers, two hardware correlators, and disk storage capacity for approximately one week of VLBI data. The NVP CPUs provide models and VLBI data to the correlators and receive the results of the correlation process which are phase as a function of time. A complete description of the correlation process is contained in [2]-[4]. Postcorrelation software in the NVP further edits the phase data, applies phase calibration corrections, compresses it to phase points at specified intervals, produces phase rate data, and sends the results to the DSN Navigation Subsystem (NAV). NAV reformats the processed VLBI data and forwards it to the appropriate project along with other radio metric data.

The WCB VLBI videotapes are mailed to the JPL/CIT Block II correlator for processing. This correlator handles much higher data rates than the NCB correlator and multiple simultaneous baselines. Block 0 data is also processed on this correlator. Once it is correlated, the data is brought to the NVP for postcorrelation processing. This correlated data, after editing and calibration, is used as input to a parameter estimation program which produces station location and source position estimates. This program is also used to process NCB VLBI data for TEMPO to produce corrections to Universal Time and the Earth's pole position. The models used in the parameter estimation program are described in [5].

References

[1] A. E. E. Rogers, "Very Long Baseline Interferometry With Large Effective Bandwidth for Phase-delay Measurements," *Radio Science*, vol. 5, no. 10, pp. 1239–1248, October 1970.

[2] J. B. Thomas, *An Analysis of Long Baseline Radio Interferometry*, JPL Technical Report 32-1526, vol. VII, Jet Propulsion Laboratory, Pasadena, California, pp. 37–50, February 15, 1972.

[3] J. B. Thomas, *An Analysis of Long Baseline Radio Interferometry, Part II*, JPL Technical Report 32-1526, vol. VIII, Jet Propulsion Laboratory, Pasadena, California, pp. 29–38, April 15, 1972.

[4] J. B. Thomas, *An Analysis of Long Baseline Radio Interferometry, Part III*, JPL Technical Report 32-1526, vol. XVI, Jet Propulsion Laboratory, Pasadena, California, pp. 47–64, June 15, 1973.

[5] O. J. Sovers and J. L. Fanselow, *Observation Model and Parameter Partials for the JPL VLBI Parameter Estimation Software "MASTERFIT"-1987*, JPL Publication 83-89, Rev. 3, Jet Propulsion Laboratory, Pasadena, California, December 1987.

Table 1. Key system characteristics

Function	NCB system	WCB system
Number of simultaneous frequency bands	2	2
Spanned bandwidth	40 MHz (S) 100 MHz (X)	100 MHz (S) 400 MHz (X)
Number of channels	12	14
Channel multiplex time	0.2 sec (minimum)	N/A
Channel bandwidth	31.25, 62.5, 125, 250 kHz	2.0, 4.0 MHz*
Channel frequency resolution	10 Hz	10 kHz
Data rate (maximum)	500 kbit/sec	112 Mbit/sec
Recording media	High capacity disk or 9-track tape	Video tape
Storage capacity	2 Gbit/disk (2 disks), 0.9 Gbit/tape	100 Gbit/tape
Playback rate	120 kbit/sec	Tape shipment

*Expandable to include 0.125, 0.250, 0.5, and 1.0 MHz.

Table 2. System sensitivity

Quantity	NCB system	WCB system
Minimum detectable EGRS flux* (5-minute integration)	0.15 jansky	0.005 jansky
Minimum detectable spacecraft signal* (1-second integration)	−168 dBm	−171 dBm

*Assuming two 70-meter antennas operating at an SNT of 30 K.

Table 3. RF reception characteristics

Parameter	Antenna	
	34-meter HEF	70-meter
Frequency range, MHz		
L-band	N/A	1620–1685
S-band (HEMT)	2200–2305	N/A
S-band (maser)	N/A	2265–2305
X-band (HEMT)	8200–8600	N/A
X-band (maser)	8400–8500	8400–8500
System noise temperature, kelvins, zenith		
L-band		35
S-band (cryo-HEMT)	43	
S-band (maser)		15
X-band (cryo-HEMT)	50*	
X-band (maser)	21	21
Polarization		
L-band		LCP
S- and X-band	RCP or LCP	RCP or LCP

*Predicted value.

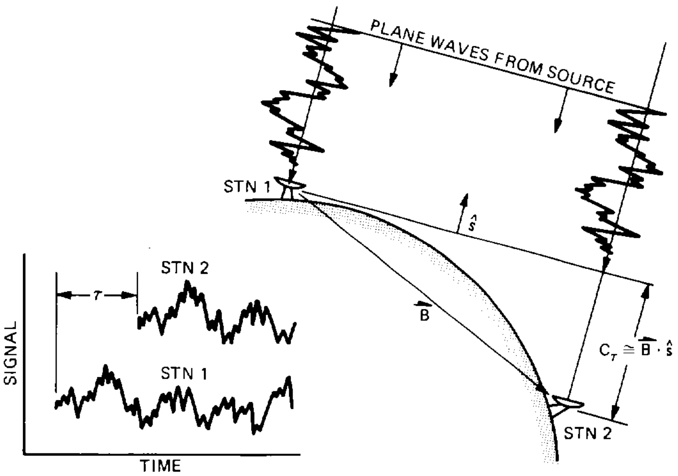


Fig. 1. Schematic representation of a VLBI observation showing the measured delay, τ, which is given by the dot product of the baseline vector, *B*, and the unit vector to the source

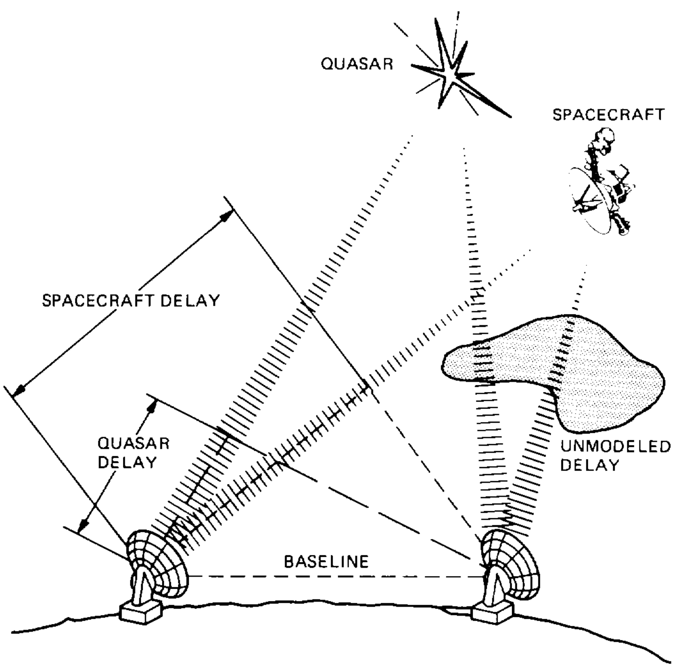


Fig. 2. Schematic of a ΔVLBI observation. Unmodeled media delays or baseline errors occur in the observation of both the Extragalactic Radio Source (EGRS) and the spacecraft. These effects are greatly reduced by differencing the delay observations.

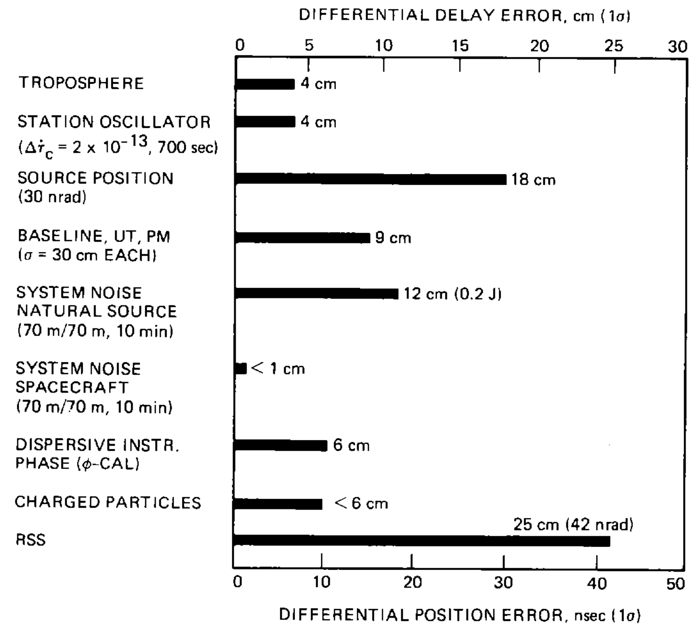


Fig. 3. Delta-DOR angular position error budget for the Galileo Project. A spacecraft-to-EGRS angular separation of 10 degrees, 600-second observations on each source, and 700 seconds between the EGRS and spacecraft observations are assumed.

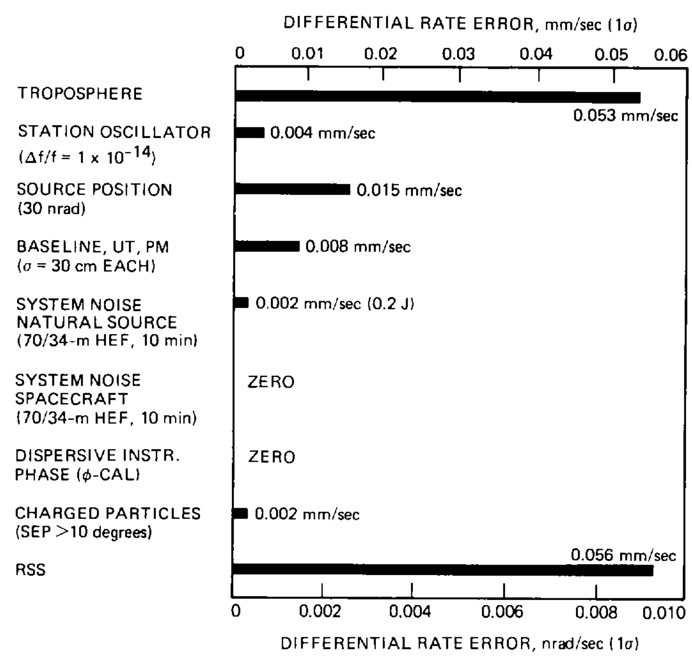
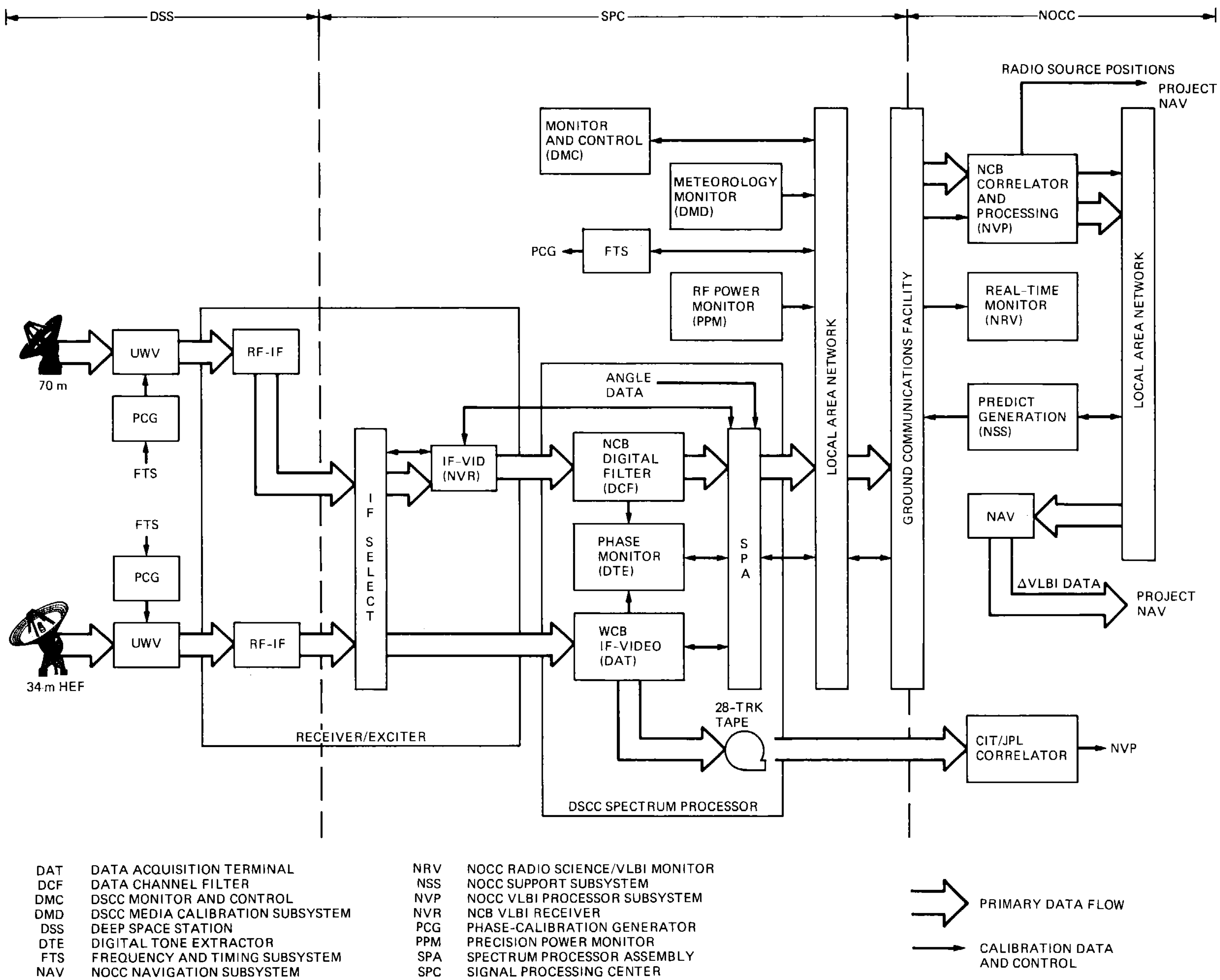


Fig. 4. Delta-DOD angular rate error budget for the Magellan Project. An average elevation angle of 15 degrees is assumed along with a Sun–Earth–probe (SEP) angle greater than 10 degrees, a spacecraft-to-EGRS separation of 10 degrees, and an integration time of 600 seconds. The ΔDOD accuracy is dominated by unmodeled fluctuations in the troposphere.



DAT DATA ACQUISITION TERMINAL
DCF DATA CHANNEL FILTER
DMC DSCC MONITOR AND CONTROL
DMD DSCC MEDIA CALIBRATION SUBSYSTEM
DSS DEEP SPACE STATION
DTE DIGITAL TONE EXTRACTOR
FTS FREQUENCY AND TIMING SUBSYSTEM
NAV NOCC NAVIGATION SUBSYSTEM
NOCC NETWORK OPERATIONS CONTROL CENTER

NRV NOCC RADIO SCIENCE/VLBI MONITOR
NSS NOCC SUPPORT SUBSYSTEM
NVP NOCC VLBI PROCESSOR SUBSYSTEM
NVR NCB VLBI RECEIVER
PCG PHASE-CALIBRATION GENERATOR
PPM PRECISION POWER MONITOR
SPA SPECTRUM PROCESSOR ASSEMBLY
SPC SIGNAL PROCESSING CENTER
UWV MICROWAVE SUBSYSTEM

Fig. 5. VLBI system block diagram