

# 211, Rev. A

## Wideband Very-Long Baseline Interferometry

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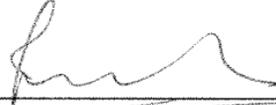
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### *Change Log*

<b>Rev</b>	<b>Issue Date</b>	<b>Prepared By</b>	<b>Paragraphs Affected</b>	<b>Change Summary</b>
Initial	8/25/2006	Kurt Liewer	All	All
A	4/15/2011	Kurt Liewer	Section 2, 2.1, 2.3 Figure 2, 2.3.3, 2.3.5, and 2.4	<ul style="list-style-type: none"><li>• Removed references to Mark III VLBI DAT</li><li>• Replaced all instances of "radio telescope" to "antenna"</li><li>• Added text noting new DAT system will be replacing old in 2013.</li><li>• Removed EAC references</li><li>• Noted termination of Mark-IV tape support</li><li>• Updated Figure 2 to reflect changes in the system</li></ul>

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## ***1 Introduction***

### ***1.1 Purpose***

This module provides an introduction to the Very-Long Baseline Interferometry (VLBI) astrometric measurement technique and identifies the capabilities and performance of Deep Space Network (DSN) equipment used to support wideband VLBI measurements.

### ***1.2 Scope***

The content of this module is limited to a discussion of the data gathering and data processing equipment used by the DSN to support VLBI. Experiment design and the quality of the results are influenced by many other factors that are discussed elsewhere in this handbook. Among these factors are antenna performance parameters discussed in modules 101, 103 and 104, and frequency reference performance discussed in module 304. VLBI experimenters may also be interested in station locations discussed in module 301 and extra-galactic radio source positions provided by module 107. It should be noted that the equipment discussed in this module is the major contributor to the information content of modules 301 and 107.

## ***2 General Information***

The DSN uses its VLBI capability to measure the earth orientation parameters that establish the relationship of the Terrestrial Reference Frame containing its stations to the Celestial Reference Frame used for spacecraft navigation. VLBI is also used to determine the relative locations of its stations and the locations of extra-galactic radio sources (EGRSs). The EGRSs are used as reference points for delta-differential one-way ranging ( $\Delta$ DOR) spacecraft navigation (see module 210). Because the DSN uses equipment that is compatible with that used by the international VLBI community, other agencies can coordinate their observation schedules with DSN scheduled activities and the resultant data can be shared between the DSN and external experimenters.

### ***2.1 Description of Very-Long Baseline Interferometry***

Very-Long Baseline Interferometry is a technique for measuring the precise time difference between the arrival of a waveform originating from an EGRS at two (or more) stations. Figure 1 provides an illustration of the technique. The stations simultaneously observe an EGRS. As they are widely separated, their baseline,  $B$ , passes through the Earth. At each station, the instantaneous phase of the received signal (a random Gaussian process) is recorded in each of several channels; this is known as VLBI data acquisition. The measured difference in arrival time can be converted to an approximate path length difference by multiplying by  $c$ , the speed of electromagnetic waves in a vacuum. In actuality, the conversion is much more complex as the wave front must pass through several layers of the Earth's atmosphere – each of which has a different propagation speed.

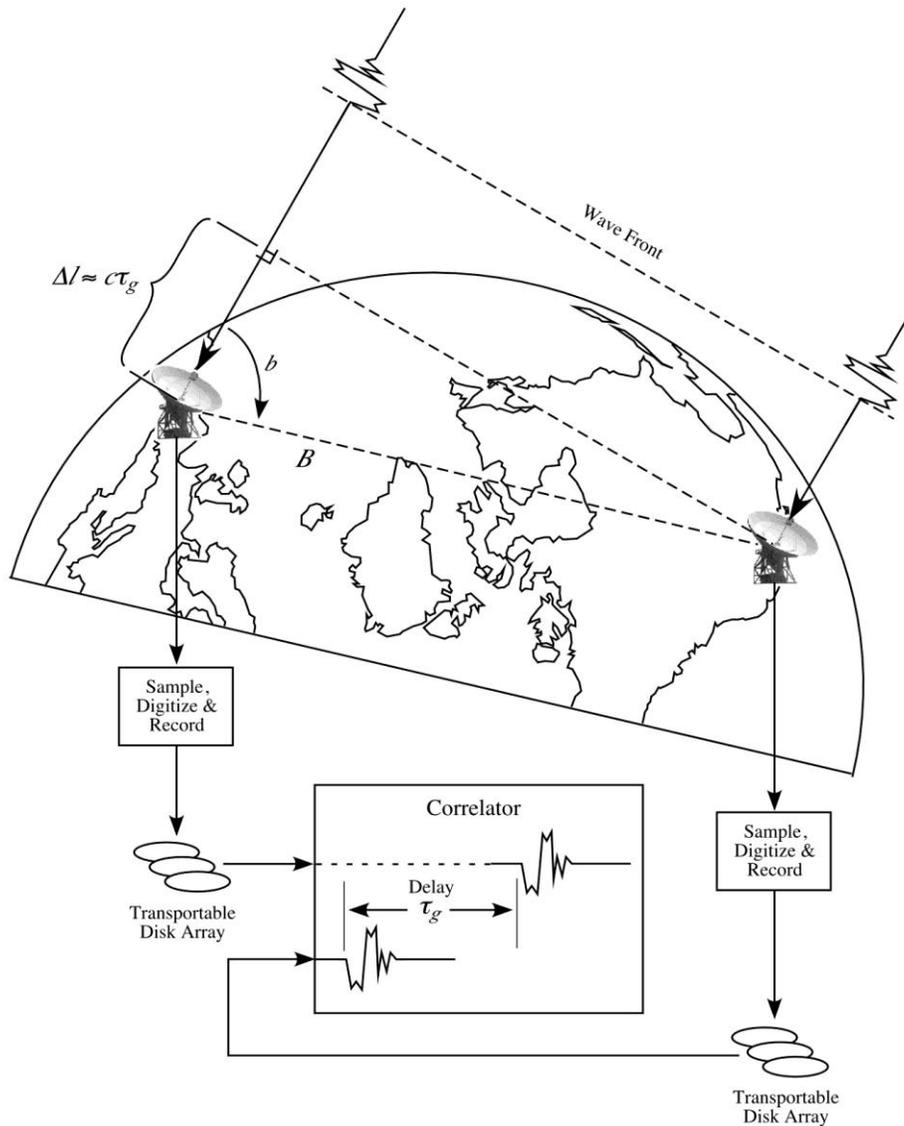


Figure 1. Very-Long Baseline Interferometry

The recorded data from the participating antennas are brought together at a correlator. The data from matching channels at the different radio telescopes are cross-correlated to determine the geometric time delay,  $\tau_g$ ; this is known as VLBI data correlation. After converting the time delay to a path length by a process that takes into account atmospheric delay and other effects, the angular relationship between the baseline of the two stations and the radio source can be determined by the relationship  $b = \cos^{-1}(\Delta l/B)$ . It is important to note that this is not a complete solution for the angular position in the sky of the radio source. This calculation only provides information about the location of the radio source in the plane defined by the interferometer baseline and the direction of arrival. The correlation of data from the observation of additional radio sources is necessary to completely define the baseline. By making sufficient observations and assuming some reference, it is possible to calculate a singular solution that

estimates each station's coordinates, the angular positions of all observed sources, the offset and rate differences between the two station frequency references, and several parameters relating to propagation. Additional observations above the minimum enable statistical uncertainties in the estimation to be reduced. A complete discussion of the process is contained in Reference 2.

The precision of a VLBI measurement improves with the length of the baseline. The location of the DSN stations provides baselines of 66% (Goldstone to Madrid) and 83% (Goldstone to Canberra) of the Earth's diameter. The third baseline, Canberra to Madrid, is 98% of the Earth's diameter but provides very limited mutual visibility (see module 301). To mitigate mutual visibility effects, additional antennas are often involved in VLBI measurements allowing a station between DSN locations to serve as a "relay" to tie-together observations made in different portions of the sky during an observation session.

## 2.2 *Bandwidth Synthesis*

The signal-to-noise ratio obtained by correlating the signals from two observing stations depends on the characteristics of the stations, the bandwidth of the channel being correlated and the observation time. It can be calculated from the following expression (Reference 3).

$$SNR_{CH} = 2.05 \times 10^{-4} (\gamma_v S) D_1 D_2 \sqrt{\frac{\eta_1 \eta_2 B_{CH} T}{T_{Sys1} T_{Sys2}}} \quad (1)$$

where

$(\gamma_v S)$	= correlated flux density where $S$ is the total flux density (jansky)
$D_1, D_2$	= antenna diameters (m)
$\eta_1, \eta_2$	= antenna efficiencies
$B_{CH}$	= channel bandwidth (Hz)
$T$	= observation time (s)
$T_{Sys1}, T_{Sys2}$	= antenna system noise temperatures (K)

The factor  $2.05 \times 10^{-4}$  includes all normalization constants and allowances for degradation due to one-bit quantization and the fact that only one polarization is received.

When multiple channels are being correlated simultaneously and they have approximately the same  $SNR_{CH}$ , the post-correlation SNR for use in equation (3) can be calculated by

$$SNR = \sqrt{n} \cdot SNR_{CH} \quad (2)$$

where  $n$  is the number of channels in the correlation.

The error in delay measurement resulting from the correlation of data from two VLBI stations is expressed by

$$\sigma = \frac{c}{2\pi \cdot SNR \cdot BW} \quad (3)$$

where

- $c$  = the speed of electromagnetic propagation
- $SNR$  = the post-correlation signal-to-noise ratio
- $BW$  = the observation bandwidth

It can be seen from equation (3) that an extremely large data volume for transport to the common correlation site would be needed if the entire bandwidth were recorded. For example, if a post-correlation SNR of 40 (16 dB) is available, a bandwidth of 125 MHz would be required to achieve a delay error of 1 cm.

The data volume is significantly reduced by the technique of *bandwidth synthesis* (Reference 4). This technique uses several narrow channels spread across the observation bandwidth to achieve an *RMS bandwidth* of

$$BW_{RMS} = \sqrt{\frac{\sum_{CH=1}^n (f_{CH} - f_{AVG})^2}{n}} \quad (4)$$

where

- $f_{CH}$  = center frequency of each channel used in the bandwidth synthesis
- $f_{AVG}$  = the average of all channel center frequencies used in the bandwidth synthesis
- $n$  = the number of channels

As an example of the efficiency gained by bandwidth synthesis, a typical X-band VLBI measurement will use the eight 2-MHz channel pairs shown in Table 2 corresponding to an RMS bandwidth of 140 MHz. By employing hard limiting, one-bit quantization, and a sampling rate equal to twice the bandwidth of each channel, the total recorded bandwidth is reduced to 64 MHz.

### 2.3 *DSN VLBI Support Equipment*

A diagram showing the major items of DSN equipment used to support wideband VLBI is provided by Figure 2. All DSN 34-m HEF antennas and 70-m antennas are available for VLBI data acquisition. In addition, some 34-m BWG antennas have been used for VLBI.

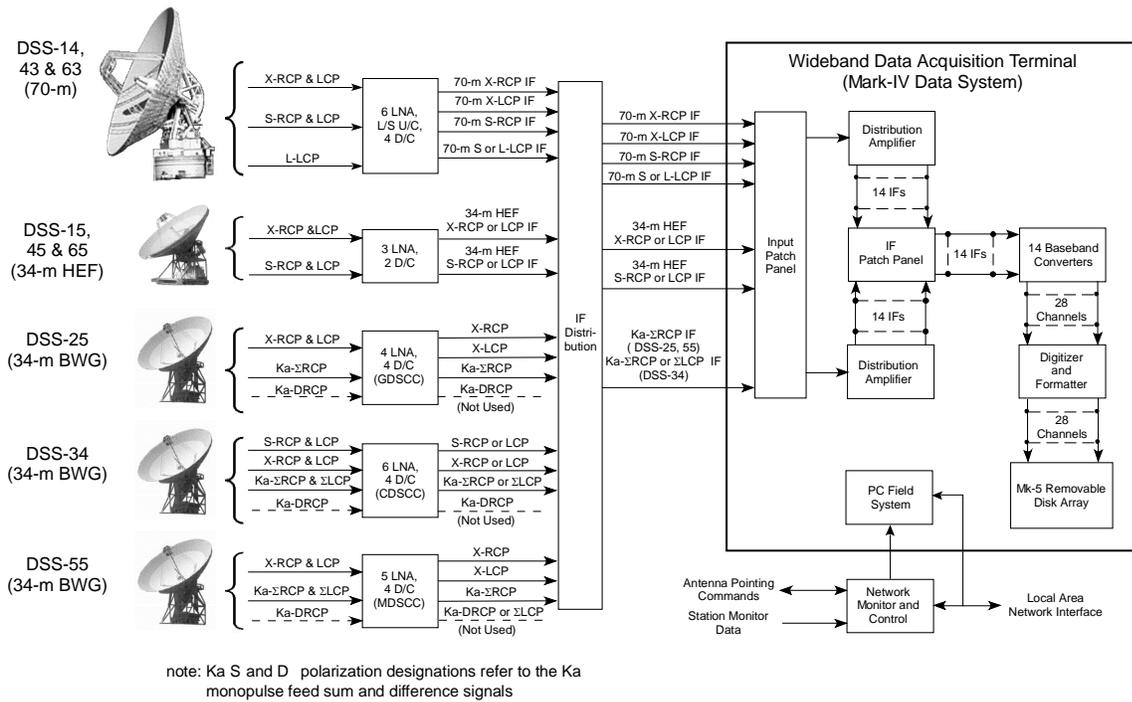


Figure 2. DSN Equipment for Wideband VLBI Support

Received signals are processed by a standard Mark-IV Data Acquisition Terminal (DAT). Beginning in 2013 the DAT will be replaced by a new system that is compatible with the new systems being deployed in the astronomical community. The VLBI data is recorded on a Mark 5 disk array. Recording on Mark-IV tape is no longer supported. The new system will interface directly with the DSN Network Monitor and Control Subsystem.

### 2.3.1 Signal Reception

Signals that are collected by the antenna are amplified by a cryogenically-cooled low-noise amplifier (LNA). For every observation band, except L, the LNA is followed by a downconverter that translates the radio-frequency signal to an intermediate frequency (IF) to be forwarded to the Signal Processing Center (SPC). The downconverters are located on the antenna and are derived from the station frequency standard. Their frequencies are 2.0 GHz for S band, 8.1 GHz for X band, and 31.7 GHz for Ka band. The L-band signal at a 70-m antenna is upconverted to S-band using a 620-MHz local oscillator and then switched into one of the S-band downconverters. From that point forward, it follows the path normally taken by a signal originating in the S band.

DSS-25 at the Goldstone DSCC, DSS-34 at the Canberra DSCC, and DSS-55 at the Madrid DSCC are available for Ka-band VLBI support. However, the Ka-band configuration of each of these antennas is somewhat different. The Ka-band feed of DSS 25 supports RCP but does not support LCP. DSS-34 supports both RCP and LCP and is capable of routing either polarization to the VLBI data acquisition equipment. DSS-55 supports both polarizations but only the RCP signal is available for VLBI. The frequency and polarization capabilities of the DSN for VLBI are summarized in Table 1.

Table 1. Frequency and Polarization Support Capabilities for VLBI

Subnet or Station	L-band	S-band	X-band	Ka-band
70-m subnet (DSS-14, 43, & 63)	LCP(1) (1628–1708 MHz)	RCP and LCP (2200–2300 MHz)	RCP and LCP (8200–8600 MHz)	–
34-m HEF subnet (DSS-14, 43, & 63)	–	RCP or LCP (2200–2300 MHz)	RCP or LCP (8200–8600 MHz)	–
34-m BWG, DSS-25	–	–	(2)	RCP (31.8–32.3 GHz)
34-m BWG, DSS-34	–	(2)	(2)	RCP or LCP (31.8–32.3 GHz)
34-m BWG, DSS-55	–	(2)	(2)	RCP (31.8–32.3 GHz)

- (1) L-band cannot be used simultaneously with any other band.  
(2) Received but not routed to VLBI data acquisition terminal.

### 2.3.2 *Subreflector Position*

Gravity deformation of the primary reflector and the structure that supports the subreflector as the antenna moves in elevation causes a change in the antenna focal position. To compensate for this, the subreflector undergoes a programmed motion relative to the feed to achieve the maximum antenna gain at every elevation angle. However, this motion introduces a time-varying phase delay to the received signal that is undesirable for wideband VLBI.

During wideband VLBI data acquisition at the 34-m HEF and 70-m antennas, the subreflector motion is usually disabled and the subreflector placed in a position that gives the best gain for a 45° elevation angle. This eliminates the time-varying phase delay associated with subreflector motion. However, it also causes some loss of antenna gain when the antenna is not at 45°.

Subreflector motion should not be disabled when a BWG antenna is used for wideband VLBI observations in the Ka band. This is because gravity deformation also affects antenna pointing by an amount that is significant at Ka-band although not so at S- or X-bands and subreflector motion must be enabled in order to have the antenna point as commanded. The resultant phase delay changes can be modeled and removed in post processing

### 2.3.3 *Data Acquisition*

The current hardware configuration consists of Mark-IV signal processing (down-conversion and filtering) and the data is recorded on Mark-V disk arrays rather than tape. The antenna IFs are supplied to a patch panel where any two of them can be selected as the DAT's input.

Either of these two IFs can be routed to each of 14 baseband converters. The baseband converters mix the IF with a local oscillator derived from the station frequency standard using the single-sideband mixing technique to avoid spectrum fold-over (Reference 5).

The result is two filtered baseband channels corresponding to the upper and lower sidebands centered about the local oscillator frequency.

The outputs of the baseband converters are routed to a formatter where they are digitized using one-bit digitization, placed into recording frames along with timing and parity data, and sent to one or two disk arrays. The disk array (Reference 6) was designed to be a direct replacement for the Mark IV tape unit but is limited to saving the data from a maximum of 16 tracks. All 28 tracks can be recorded when two disk arrays are used. The entire DAT and recorder system is controlled by the PC Field System

The replacement hardware also has an IF switch for selecting the input sources but all the frequency selection and filtering is done digitally. There will be 16 frequency channels available, each with upper and lower sidebands. The new hardware will provide center frequencies and bandwidths that match the Mark-IV equipment it is replacing.

#### **2.3.4      *Phase Calibration Tones***

The 34-m HEF and 70-m antennas include phase calibration generators (PCGs) for all of their supported frequency bands (Reference 7). The PCGs inject a set of tones, uniformly spaced in frequency, into the receive signal path ahead of the LNA. The purpose of these tones is to permit calibration of irregularities in phase delay occurring along the signal path to the DAT and phase differences within the DAT resulting from each video converter having a separate local oscillator. The tones are spaced 1.0 MHz apart and are derived from the station frequency reference. The power in the phase calibration tones is less than 1% of the signal power in any given bandwidth. With such a small power, the phase calibration tones do not interfere with the VLBI measurements. The 1.0 MHz spacing guarantees that at least one tone will be present in each 2-MHz or greater bandwidth normally used for VLBI. Selection of channel center frequencies will assure that one tone will be present in one sideband of each channel for narrower bandwidths. DSS 25 has a prototype Ka-band PCG with tone spacing that may be selected as either 5.0 MHz or 1.0 MHz. The tones are derived from the station frequency reference as is the case with the standard phase calibrators.

In the VLBI correlator, a measurement is made of the relative phase delay of the calibration tone in each channel. This is accomplished by correlating the recorded channel with a local (baseband) model of the individual calibration tone. These phase delay measurements enable the phase slope of the entire instrumentation system to be estimated and any phase offsets introduced into the individual channels within the DAT to be removed. The result is a group delay calibration with a precision of 0.0015 ns for a 100-s integration time.

In addition to the precise measurement of phase delay in post processing at the VLBI correlator, the phase calibration tones are also monitored in real-time by a digital tone extractor (DTE) to detect instrument and configuration problems.

#### **2.3.5      *Correlation***

The JPL VLBI correlator accepts VLBI data in Mark V format. The recorded data from as many as four antennas may be cross-correlated. When the recorded data from one antenna is cross-correlated with that of another antenna, an interferometer is formed and the

differential delay for that interferometer is determined. As many as six interferometers can be formed with recorded data from four antennas.

## **2.4            *Experiment Design***

The configuration and sequence of events for any wideband VLBI experiment are defined in a VLBI experiment (VEX) file. The VEX file is a format invented by members of the VLBI community to prescribe a complete description of a VLBI experiment, including scheduling, data-taking and correlation. Parameters from this file are read by the Personal Computer Field System (PCFS) and are translated to the necessary antenna pointing and other commands needed to operate DSN equipment by the Network Monitor and Control (NMC). The NMC also subscribes to DSN monitor data to deliver ancillary data to the PCFS for inclusion in the experiment log file.

The one or two observation bands (L, S, X or Ka) for the experiment are chosen subject to the band availability on the antenna being used. A set of channels is defined for each observation band. In order to achieve high precision, the span of channel frequencies (within the band) should be wide. The two outermost channels determine this precision. The other channels are needed to resolve the phase ambiguity. Simultaneous measurements at S- and X-band enable the differential delay in the ray path to the two observing stations caused by the Earth's ionosphere to be calibrated (Reference 2).

The channels are defined in pairs. A channel pair is created within each video converter, whose local oscillator determines the center frequency of the pair. At each complex, up to 14 video converters may be used simultaneously resulting in a maximum of 28 channels. Each of the 14 channel pairs is assigned to one or the other observation band. A typical set of channel-pair frequencies is shown in Table 2 for simultaneous observation in the S and X bands. Also shown in Table 2 is the local oscillator frequency for the video converter that produces the corresponding channel-pair frequency. It may be noticed that the channel-pair frequency equals the local oscillator frequency of the video converter plus that of the first downconverter (2.0 GHz for S band and 8.1 GHz for X band).

Each channel is digitized with a selected depth of 2 bits per sample resolution. The sampling rate is at the nominal Nyquist rate (2 samples per period) for filters which will nominally be 2, 4, 8, or 16 MHz wide. For example, a 16 MHz filter will have a sample rate of 32 Msamples/sec and so with 2 bits/sample it would produce 64 Mbits/sec. The resultant parallel digital streams are formatted, time-tagged and recorded in the Mark 5 (disk array) format.”

Table 2. Typical Channels (S and X Bands) for Wideband VLBI

<b>Channel Pair</b>	<b>Video Converter Local Oscillator</b>
2217.99 MHz LSB & USB	217.99 MHz
2222.99 MHz LSB & USB	222.99 MHz
2237.99 MHz LSB & USB	237.99 MHz
2267.99 MHz LSB & USB	267.99 MHz
2292.99 MHz LSB & USB	292.99 MHz
2302.99 MHz LSB & USB	302.99 MHz
8210.99 MHz LSB & USB	110.99 MHz
8220.99 MHz LSB & USB	120.99 MHz
8250.99 MHz LSB & USB	150.99 MHz
8310.99 MHz LSB & USB	210.99 MHz
8420.99 MHz LSB & USB	320.99 MHz
8500.99 MHz LSB & USB	400.99 MHz
8550.99 MHz LSB & USB	450.99 MHz
8570.99 MHz LSB & USB	470.99 MHz

### 3            *References*

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