IPN Progress Report 42-149 May 15, 2002

Space Very Long Baseline Interferometry Ground-Station Segmented Architecture

J. C. Springett[1]

The ground tracking stations (GTSs) that supported the VLBI Space Observatory Program (VSOP) space very long baseline interferometry (SVLBI) mission were all implemented as a unified architecture, a configuration that makes use of a single antenna for all communications. VSOP provided extensive engineering insight and verification of the necessary functionality for SVLBI GTSs. Lessons learned from these experiences, along with technique refinements and changing prerequisites, compel future GTSs to be constructed in the form of a segmented architecture, where functionally separate antennas are used for data reception and for phase transfer and telemetry. It is believed there are significant economic and operational advantages to the segmented approach. However, some concern has been expressed that the segmented architecture might introduce unusual data and phase transfer timing problems, making it more difficult for the VLBI correlator to obtain fringes. To assuage these anxieties, a segmented experiment was successfully conducted at the Goldstone tracking facilities during the summer of 2001.

I. Introduction

This article introduces a methodology, along with basic requirements, for the architectural design and performance of next-generation space very long baseline interferometry (SVLBI) ground tracking stations (GTSs).

Future SVLBI missions will transfer very long baseline interferometry (VLBI) data to the ground at rates of 1.024 Gb/s and higher;[2] as a comparison, the just concluded VLBI Space Observatory Program (VSOP) mission had a data rate of 128 Mb/s. In addition to the communication of data, spacecraft telemetry critical to the science aspect of the mission also must be delivered to the ground. For VSOP, this was accomplished by encoding the telemetry within the frame synchronization headers of the VLBI data frames. Another function performed is the transmission of a phase-stable frequency reference from

---

[1] NeoComm Systems, Inc., La Crescenta, California.

[2] For details on advanced mission data rates, see [1].

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

the ground tracking station to the spacecraft. Known as phase transfer,[3] the integrity of this process requires that the uplink frequency be transponded and sent back at a different frequency to the ground tracking station.

VSOP provided extensive engineering insight and verification of the necessary functionality for SVLBI GTSs. Lessons learned from these experiences, along with technique refinements, compel the advanced GTS concepts and prerequisites discussed herein.

II. Station Essentials and Types

For VSOP, a single downlink carrier frequency was used for all functions. The GTSs that supported the VSOP mission were all implemented as a unified architecture. This configuration makes use of a single antenna (in the DSN 11-m diameter, Green Bank 13.7 m, and Usuda 10 m) for all communications. But the fact that VLBI data, spacecraft telemetry, and phase transfer were totally combined into a composite signal resulted in some undue complications that future ground tracking stations should avoid.

During ongoing studies of future SVLBI missions, it also has been recognized that the prerequisites for the phase transfer and telemetry data services are, for all practical purposes, independent of VLBI data transmission requirements. For one thing, the phase transfer and telemetry data functions need far less downlink effective isotropic radiated power (EIRP). Also, phase transfer and telemetry are inherently narrowband, while VLBI data are very wideband. For these reasons, a functionally separate ground station from that employed to receive data is favored for phase transfer and telemetry. Referred to as the segmented architecture, it is envisioned that an existing medium-to-large antenna will be utilized for data reception, while a new, relatively small antenna will furnish the phase transfer and telemetry needs. With this scheme, separate data and phase transfer/telemetry carriers are required (see Section IV and [1, Section III] for details).

It is also believed there are significant economic advantages to the segmented approach. First, adapting an existing antenna (such as a DSN 34-m beam-waveguide antenna or one of many decommissioned 13.7-m and larger radio astronomy telescope antennas) for high-data-rate reception (no uplink transmission required) can be accomplished at a substantially lower cost than a new antenna. Second, a small (≈3-m) phase transfer antenna (PTA) may be installed at the same general location (but perhaps kilometers apart) as long as they are both within the satellite antenna's Earth footprint. Although there will almost certainly be a variety of data antenna types worldwide, each ground station site should accept a common PTA implementation, thereby minimizing design and production costs.

It has been recognized that the segmented architecture, especially where there may be a wide separation between the data antenna and PTA, might possibly introduce unusual data and phase transfer timing problems, making it more difficult for the VLBI correlator to obtain fringes. Because of this concern, a segmented experiment was conducted at the Goldstone tracking facilities during the summer of 2001. The details are reported in the Appendix, and the results show that no critical uncertainties exist.

III. Signal Characteristics

It is difficult to fully appreciate ground station design and performance without some knowledge of the signal forms being received. The following signal characteristics are those proposed for use by the VLBI

[3] A prime requirement for an SVLBI radio telescope is that the composite space/ground frequency/phase stability be essentially as good as that for any ground radio telescope. This goal is achieved by referencing a GTS to a hydrogen maser frequency standard (the basis for all frequencies and timing within the GTS) and imparting its stability to the spacecraft through a microwave uplink. Phase degradations introduced by the GTS and spacecraft hardware, plus the propagation medium, are measured using a two-way phase transfer loop (uplink plus downlink). From this measurement, accurate time correction information is derived and utilized by the VLBI signal correlator to remove most of the degradations that otherwise would result in significant coherence losses of the observables.

Space Observatory Program 2 (VSOP2) [1, Section III]. (Note that these will be used for illustrative purposes throughout the remainder of this article.)

Partitioning the data reception and phase transfer services requires individual downlink carriers, which may be expressed mathematically in the forms

$$s_{\mathrm{LCP}}(t) = \sqrt{2P_{\mathrm{data}}}\left[d_{IL}(t)\cos\left(\omega_{dL}t\right) + d_{QL}(t)\sin\left(\omega_{dL}t\right)\right] + \sqrt{2P_{\mathrm{pilot}}}d_{tlm}(t)\sin\left(\omega_{pL}t\right) \tag{1}$$

$$s_{\mathrm{RCP}}(t) = \sqrt{2P_{\mathrm{data}}}\left[d_{IR}(t)\cos\left(\omega_{dR}t\right) + d_{QR}(t)\sin\left(\omega_{dR}t\right)\right] + \sqrt{2P_{\mathrm{pilot}}}d_{tlm}(t)\sin\left(\omega_{pR}t\right) \tag{2}$$

where subscripts containing L and R respectively designate left circularly polarized (LCP) and right circularly polarized (RCP) components. The VLBI data modulations d_{IL}, d_{QL}, d_{IR}, and d_{QR} represent essentially independent, ± 1 amplitude symbol streams (256 Msymbols/s). The signal parameters, using VSOP2 link budget values, a phase transfer tracking signal-to-noise ratio (SNR) of 30 dB in 1 kHz, and a telemetry bit rate of 8 kb/s, are

$$\begin{aligned} P_{\mathrm{data}} &= 3.5 \text{ W} \\ P_{\mathrm{pilot}} &= 80 \text{ mW} \\ f_{pL} &= 37.116 \text{ GHz} \\ f_{dL} &= 37.372 \text{ GHz} \\ f_{dR} &= 37.628 \text{ GHz} \\ f_{pR} &= 37.884 \text{ GHz} \end{aligned}$$

Figure 1 shows the RF spectra for both equations. The signal equations and associated spectra are ideal. Data modulation employs rectangular quadrature phase-shift keying (QPSK), and telemetry modulation is rectangular binary phase-shift keying (BPSK). Carrier static (offset) phase relationships between the various components are arbitrary (not systematized by design or implementations). Offsetting the carrier frequencies by the symbol clock of 256 MHz (one-half the 512-Mb/s bit clock) minimizes cross-polarization interference. The carriers placed at the data spectra nulls are referred to as "pilots." Each pilot carrier is BPSK modulated by the spacecraft housekeeping telemetry data (8 kb/s). The telemetry data structure conforms to Consultative Committee for Space Data Systems (CCSDS) criteria.

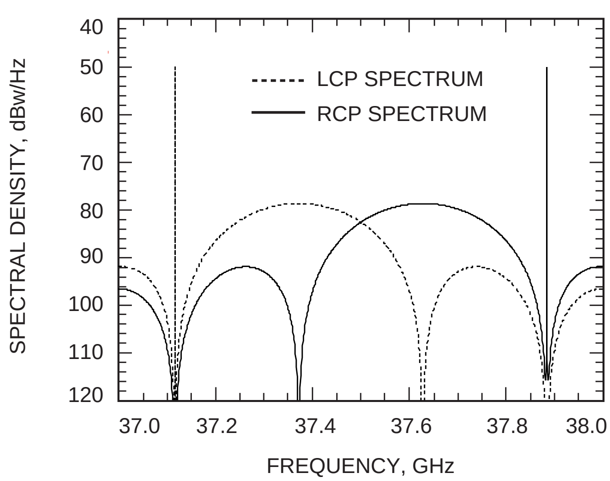

Fig. 1. VSOP2 LCP and RCP RF spectra.

In the United States, the National Telecommunications and Information Administration (NTIA) establishes regulations regarding the emission spectrum and, in particular, the determination of necessary bandwidth. To meet such regulations, some form of spacecraft transmission filtering must be employed to minimize Ka-band out-of-band (<37- and >38-GHz) spectral levels. Filtering invariably introduces some corrupting consequences in the forms of data waveform distortion and cross-channel interference, but these effects should be small, if not inconsequential. However, the design and implementation of the data receiving system data matched filter should consider the effects of spacecraft bandpass filtering.

IV. Segmented Architecture Overview

Figure 2 presents a block diagram of the segmented architecture, designating the principal signal paths and functions. Not indicated are the reflector's pointing systems or any specific control (computer), monitor, or interface items (which are generally antenna specific and, therefore, beyond the scope of this article).

A. VLBI Data Antenna

As previously mentioned, it is contemplated that the data reception antenna will make use of some existing antenna system by means of refurbishment or augmentation. Most antenna sites consist of the antenna position plus a local control room. Typically, these may be physically removed by 100 m (more or less), but, collectively, they will be referred to as the antenna location. Additionally, a remote site (perhaps kilometers away) may be more accessible and favorable for general operations.[4] Figure 1 assumes an antenna/remote site arrangement, with appropriate interconnection links.

Because the RF signal involves orthogonal polarizations (see the spectra depiction in Fig. 1), simultaneous RCP and LCP reception is required. After separation of the RF signals from each polarization, two virtually identical channels follow from the low-noise amplifier (LNA) input through to the VLBI data recorder. Each channel accommodates a 512-Mb/s QPSK data stream.[5]

Downconversion (D/C) from RF is expected to result in IF1 (typically from 3 to 10 GHz). Since the two RF carriers are at different frequencies, distinct downconversion references are required to produce the same IF1 frequency for both carriers. Because there are no strict frequency/phase stability requirements for data reception, the references to the downconverters may even be implemented using independent oscillators (as contrasted with a high-performance frequency standard). The IF1 signals are then transferred from the antenna to the remote site utilizing fiber-optic (F/O) or coaxial cables. All these functions might be contained solely within the antenna proper or divided between the antenna and control room.

At the remote site, D/Cs translate the QPSK data signals from IF1 to IF2 (256 MHz).[6] Again, there is no precise requirement on the stability of the downconverter's reference. The gigabit receiver functions to carrier regenerate, track, and demodulate the QPSK IF signals, followed by detection and differential decoding of the symbol streams. Outputs from the gigabit receiver are two pairs of 256-Msymbols/s data streams (plus symbol clock). Following recovery, the VLBI data symbols are processed by mission-unique data decoders, followed by recording. Only the decoding and recording operations require a precision frequency and time standard.

[4] The only regularly attended operations should be those associated with recording.

[5] This is the basic modulation type and minimum data rate envisioned for VSOP2. However, VSOP2 and other new SVLBI missions might transmit rates up to 4 Gb/s using bandwidth compressive modulation types [1, Section IV]. For this reason, each channel should provide a bandwidth of 1 GHz.

[6] The data demodulator/detector (gigabit receiver) envisioned requires an IF input equal to the QPSK symbol rate. See Subsection V.D and [1, Subsection V.B].

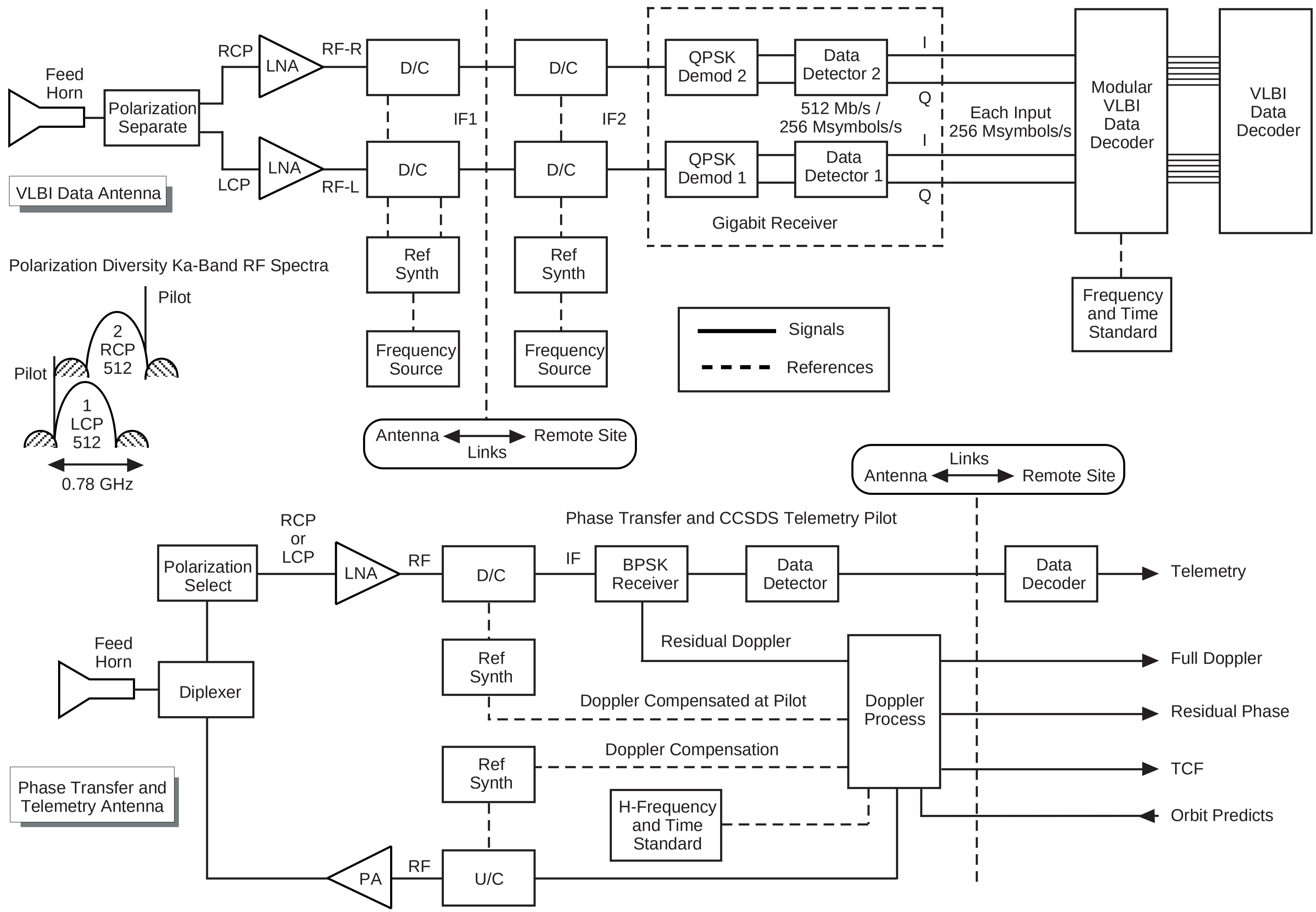

Fig. 2. Segmented station architecture.

The data antenna configuration depicted in Fig. 1 is generic, but convenient. An alternative might locate all the remote site operations within the antenna control room. Another variation is to place only the decoding and recording equipment remotely.

B. Phase Transfer Antenna

A distinct phase transfer antenna design should be utilized for all ground stations, along with a single manufacturer for its production. This approach will result in the lowest costs (installation and operation) and highest reliability (spares and repairs) for all sites.

It is envisioned that the PTA will be placed somewhat away from the data antenna[7] and operated in an autonomous manner. It is also envisioned that, because of its small size (≈3 m), the PTA can be constructed as a fully integrated unit placed inside a radome structure (see Subsection VI.B). The PTA is shown in Fig. 2 with simple interfaces (schedule and orbit predicts, and receiving products) from/to some remote (or external) site (via local area networks (LANs) or the Internet). All external communications should take place through the antenna's station control computer (SCC).

As shown in Fig. 2, an uplink frequency (between 40.0 and 40.5 GHz) is transmitted to the spacecraft and turned around in a transponder, and the receive frequency is one (or the other) of the two pilot carriers. This comprises the phase transfer link. The demanding requirement for phase transfer is to keep the station's phase instabilities within prescribed limits (see Subsection VI.E). A hydrogen-maser frequency standard is required. The other distinctive feature is Doppler compensation, a technique well understood and proven on the VSOP mission. (See Subsection VI.F for Doppler and phase processing requirements.)

Spacecraft telemetry is recovered using a BPSK receiver, data detector, and data decoder. The telemetry structure will conform to CCSDS standards and may be readily implemented using commercial hardware.

The remote site indicated in Fig. 2 may be the same as that employed for the data antenna or a far-off mission operation center connected via the Internet.

V. Data Antenna Requirements

The following subsections provide general guidelines for the implementation and performance requirements of the data antenna.

A. Minimum Receive Signal Level and Receive *G/T*

Low-end data antenna size is predicated on the use of existing 13.7-m radio telescope antennas, assumed to have a nominal efficiency of 50 percent at 38 GHz. The following receive conditions are based on VSOP2 anticipated performance:

$$\text{minimum signal level at antenna} = -187 \text{ dBW at 10-deg elevation}$$
$$\text{minimum receive } G/T \text{ at 38 GHz} = 48 \text{ dB/K (no atmosphere)}$$

B. Antenna Pointing Requirements

Antenna pointing is expected to make use of programmed pointing based on commanded angle predictions derived from the spacecraft's orbit state vector. (The use of some form of autotrack, if available,

[7] If the data antenna is located at a radio astronomy complex, the PTA, because it radiates at a frequency between 40.0 and 40.5 GHz, should be located so as to minimize radio frequency interference (RFI) to any radio telescope.

is acceptable but not essential.) Because initial pointing to the spacecraft could be sufficiently in error due to imprecise orbit data, provisions should be made for a spatial search, as well as for the ability to invoke pointing offsets in both angle and time.

For a 13.7-m antenna, the recommended pointing loss due to 50-km/h wind gusts should not exceed 1.5 dB 99 percent of the time. Since the link will be designed for a 13.7-m antenna, larger antennas should be allowed proportionately larger pointing loss according to

$$\text{allowable wind pointing loss (dB)} = 1.5 + 10 \log \left(\frac{D}{13.7} \right) \tag{3}$$

where D is the diameter of the antenna in meters.

C. RF/IF Structures

Refurbishment or augmentation of an existing antenna will involve problems unique to that antenna, so no specific guidelines are provided regarding the feed horn structure and RF beam optics.

Simultaneous orthogonal LCP and RCP signals will be received, so good polarization separation is required. As a goal, the cross-polarization isolation should be better than 22 dB (25 dB or more preferred).

Both received data carrier frequencies should be downconverted to a common IF (IF1) somewhere in the frequency range of 3 to 10 GHz. These IF signals most likely will be transferred to some distant location. Whatever medium is employed (fiber optic or coaxial), adequate equalization must be provided. In fact, from the LNA through all downconversions, and up to the input of the gigabit receiver, the composite transfer characteristic should have an amplitude slope of less than 2 dB over a 700-MHz wide (IF $\pm$ 350 MHz) band. Additionally, group delay slope (linear fit to actual group delay) over this same band should not exceed 1.5 ns. The second downconversion from IF1 of 256 MHz is essential for meeting the input requirements of the gigabit receiver (see Subsection V.D).

As stated in Subsection IV.A, there are no stringent frequency and phase stability requirements on the downconversion chain. This being the case, transfer of a highly stable frequency standard from the control room to the downconversion subsystem located within the antenna is unnecessary (although such a link may already exist). The use of a quality ($\pm$0.1 ppm) crystal oscillator followed by local oscillator (LO) frequency synthesis (multiplication) should be adequate.

The center frequency acquisition and tracking capabilities of the gigabit receiver have not been established. Ka-band Doppler will be as high as 2 MHz. For these reasons, it may become necessary to predictively tune the LO for the second downconverter so that its nominal output of 256 MHz falls within the frequency tracking range of the gigabit receiver.

An RF/IF minimum linear dynamic range of 60 dB should be provided. However, this may prove difficult if fiber-optic inter-site cables are employed. Therefore, consideration should be given to providing some type of automatic gain control (AGC) in conjunction with the first downconverter.

D. Gigabit Receiver

Implementation of the gigabit receiver is expected to be common to all data antennas. Its design is predicated on the use of a Goddard Space Flight Center-/JPL-developed application-specific integrated circuit (ASIC) capable of acquiring, tracking, demodulating, and detecting a BPSK symbol stream of up to 300 Msymbols/s. Two such ASICs, operating from a common signal sample stream, can thereby handle 512-Mb/s QPSK (256-Msymbols/s in-phase (I-data) in one ASIC, and 256-Msymbols/s quadrature-phase (Q-data) in the other ASIC). The ASICs are preceded by a very high speed analog-to-digital converter

(ADC) and serial-to-parallel converter. Critical to good performance is the anti-aliasing 256-MHz band-pass filter in front of the ADC. This filter has a bandwidth of around 460 MHz and must have excellent amplitude symmetry and phase linearity with respect to 256 MHz over this range.

It is believed that at least one commercial manufacturer will incorporate this advanced technology into a complete gigabit receiver that has all of the necessary functional and operational provisions (including AGC, differential decoding, standard interfaces, software, and control).

E. Advanced VLBI Data Decoding

The data decoders should also be identical at all data antennas. The National Radio Astronomy Observatory (NRAO) is expected to provide the design for the decoder. It will be modular in that each sub-unit will accommodate 512 Mb/s (2×256 Msymbols/s). VSOP2 therefore requires two modules. The decoder will acquire and track the frame headers[8] and reformat the VLBI data into a fixed number of channelizations (yet to be determined). A special feature of the new decoder will be a capability to capture blocks of precisely time-tagged data for on-site or remote diagnostic processing. Real-time data capture and transfer will be accomplished using a VxWorks/PCI bus system.

F. Advanced VLBI Data Recording

Recording data rates of 1.024 Gb/s and higher is a technological challenge. Presently, there is a migration away from tape-based to hard-disk-based recording, although new cassette tape systems are still being pursued. The Mark 5 recorder comes from the Haystack Observatory [2, abstracted from pp. 1–2]:

> The Mark 5 system is being developed as the first high-data-rate VLBI data system based on magnetic-disc technology. In January 2001, a study of price data for tape and disc clearly showed an accelerating price decline for discs vs. tape, in concert with disc-industry projections for dramatic continued disc improvement in terms of cost per unit storage. With sustained data rates of 1024 Mbps, and capacity limited only by the ever-increasing capacity of magnetic discs, the Mark 5 represents a radical departure from the traditional VLBI dependence on magnetic tape. A Mark 5 goal is a minimum of 24-hour unattended operation at 1 Gbps.

Concurrently, Canada's Space Geodynamics Laboratory is developing a new cassette tape recorder [3, p. 1]:

> The Space Geodynamics Laboratory S3 recorder is a new-generation gigabit VLBI record/playback system which builds on the success of the S2 recorder. The S3 can record and play back wideband digital data at rates up to 1 Gbps/s (1024 Mbps), or 2 Gbps for the S3-E. The system electronics is designed to be scalable up to 4 Gbps for use with future generations of video or data storage drives. Currently the system uses JVC Digital-S professional grade tape transports, but different types of transports or data storage drives may be connected by replacing the Storage Module Interface PCI cards. Unattended recording time is 60 hours at 1 Gbps with a robotic tape changer, or 30 hours at 2 Gbps.

Sony and Toshiba are also moving forward with Gbps recorders. Clearly, a revolution in Gbps data recording is under way, and the next few years promise significant advances over the current state of the art.

---

[8] Headers will principally consist of a frame synchronization code, plus some additional frame identifiers (frame count, etc.). Unlike VSOP, VSOP2 headers will not contain encoded telemetry (this will be transmitted on the pilots).

VI. Phase Transfer Antenna (PTA)

The requirements and performance of the PTA are predicated on a common design and implementation for all ground stations.

A. Size, Gain, Receive *G/T*, and Transmit Power

The PTA antenna should be a 3-m (nominal) commercial standard unit, with a minimum aperture efficiency of 50 percent. The following receiving conditions should be met:

$$\text{minimum signal level at antenna} = -204 \text{ dBW at 10 deg elevation}$$
$$\text{minimum receive } G/T \text{ at 38 GHz} = 31 \text{ dB/K (no atmosphere)}$$

The PTA uplink should meet the following transmitting conditions:

$$\text{transmit gain at 40 GHz} = 59.0 \text{ dBi}$$
$$\text{transmitter power} = 2 \text{ W minimum}$$
$$\text{transmitter to feed loss} = 1.0 \text{ dB maximum}$$

Additionally, provision should be made to phase-continuously attenuate the transmitter power to the feed from maximum to 20 dB below maximum. Transmitter (power amplifier) output power should be regularly monitored (measured).

B. Radome

Placing the PTA inside a fully enclosed radome structure provides distinct advantages. For one thing, the antenna and all subsystems become protected from the natural environment, thereby increasing reliability and performance. Additionally, because the PTA might be located almost anywhere, enclosure in this manner enhances safety to both equipment and persons.

Consequently, it is recommended the entire PTA be placed within a radome-topped substructure, preferably with the radome constructed of self-supporting, sandwich wall, interlocking panels. The entire structure should be water and wind tight, and it should be environmentally controlled using air conditioning. Nominal control limits are

$$\text{temperature} = 23 \text{ C} \pm 2 \text{ C}$$
$$\text{relative humidity} = 40\text{–}60 \text{ percent}$$

The substructure may contain all electronic equipment not installed within the antenna's feed/hub/pedestal. Radome one-way transmission losses for dry and clean surface conditions are

$$\text{loss } 37.0-38.0 \text{ GHz} = 0.7 \text{ dB maximum}$$
$$\text{loss } 40.0-40.5 \text{ GHz} = 1.5 \text{ dB maximum}$$

C. Antenna Pointing Requirements

Pointing gain loss relative to true boresight (not including predictive pointing errors) should not exceed 0.3 dB. With a radome, no extraordinary means to counter wind mispointing are required. Provision for autotracking is not necessary.

D. RF/IF Structures

Provision should be made to programmatically select either LCP or RCP. The downconverter and upconverter must meet the following conditions:

$$\begin{aligned}
\text{receive frequencies} &= \text{ 37.116 (LCP) or 37.884 (RCP) GHz} \\
\text{transmit frequency} &= \text{ TBD on the range 40.0–40.5 GHz} \\
\text{reference frequency resolution} &= \text{ 1 mHz (with Doppler compensation)}
\end{aligned}$$

Either received pilot frequency should be downconverted to an IF commensurate with the (fixed) input frequency of the BPSK receiver. Although Fig. 2 shows single upconversion (U/C) and D/C blocks, this will likely have to be done in two steps to facilitate Doppler compensation. Independent phase-continuous Doppler compensation, at a rate of 1000 steps/s over a delta-frequency range of ± 2.5 MHz, is provided to the U/C and D/C.

All frequency references and Doppler compensation timing must be derived from a hydrogen maser standard frequency.

It is essential that the composite RF, IF, cable wrap(s), and reference frequency hardware meet the phase transfer requirements given in Subsection VI.E. Cable wrap(s) should be given special consideration to ensure that temporal quadratic phase generated due to cable motion and temperature changes meets the residual quadratic phase specification.

An RF/IF minimum linear dynamic range of 60 dB should be provided. Although some type of AGC might be employed, care must be exercised to ensure that it does not introduce significant residual quadratic phase.

A very desirable configuration is to locate all critical phase-sensitive hardware behind the reflector, above the cable wraps. Then, apart from the challenge of getting the hydrogen-maser frequency to that area, all other cable wraps transfer essentially baseband analog and digital signals.

E. Phase Transfer and Timing Performance

The integrity of phase transfer and timing is affected by both ground station design philosophy and hardware limitations. The various microwave and electronic circuits involved with performing the phase transfer block functions incorporate components such as amplifiers, filters, mixers, frequency multipliers, phase-locked oscillators (PLOs), etc. Generally speaking, linear devices (amplifiers, filters) tend to introduce rapidly varying random components in the form of white phase noise, while nonlinear elements (mixers, frequency multipliers, PLOs) contribute a combination of white and flicker phase noise. Of equal or even greater importance are slowly varying (systematic) phase undulations, due principally to the effects of temporal temperature gradients on circuits and cables, plus phase variations from the motion of antenna azimuth and elevation cable[9] wraps. The quadratic phase terms are critical.

The introduction of random and systematic phase components into the ground station uplink and downlink paths may be highly or moderately reciprocal or completely non-reciprocal. What matters are the residual components that remain after reciprocity has been taken into account. These residuals are responsible for unrecoverable coherence loss of the radio telescope observables [4]. Subject to further assessment, the preliminary maximum allowable residuals for the PTA stations are (referred to 38 GHz)

$$\begin{aligned}
\text{random phase noise} &= \text{ 2.5 deg rms in a 5-Hz bandwidth} \\
\text{quadratic phase} &= 3 \times 10^{-4} \text{deg/s/s sustained over 300 s}
\end{aligned}$$

[9] The word "cable" generally connotes coaxial cable, fiber-optic cable, or waveguide.

F. Phase Transfer and Doppler Processing Functions

The functional block Doppler process shown on Fig. 2 involves a multiplicity of operations, including

(1) Generation of uplink and downlink Doppler compensation frequency (or phase) versus time profiles from the spacecraft's orbit state vector

(2) Formatting and output of Doppler compensation data to numerically controlled oscillators (NCOs)

(3) Demodulation of the BPSK receiver's tracking voltage-controlled oscillator (VCO) output to I and Q baseband forms

(4) Simultaneous quantization of I and Q baseband signals

(5) Conversion of sampled I and Q signals to unambiguous phase

(6) Processing of unambiguous phase to produce reconstructed two-way Doppler

(7) Processing of unambiguous phase to produce residual phase

(8) Processing of residual phase to generate a time correction file (TCF)[10]

This generic process is discussed in [4]. A dedicated real-time Doppler computer should be used to perform the computational aspects of the above-listed operations. A crucial prerequisite is to meet the real-time requirement without introducing time-dependent errors and processing "glitches" into the output products. Critical Doppler and phase processing issues have been addressed by Border.[11,12] The following general requirements should be met:

$$\begin{aligned} \text{Doppler compensation rate} &= 1000 \text{ steps/s} \\ \text{Doppler compensation range} &= \pm 2.5 \text{ MHz} \\ \text{Doppler compensation step accuracy} &= 1 \text{ mHz} \\ \text{baseband I and Q sampling rate} &= 10 \text{ kHz} \\ \text{sampling ADC size} &= 12 \text{ bits (minimum)} \\ \text{TCF output rate} &= 10 \text{ samples/s} \end{aligned}$$

For the VCO output to baseband I and Q conversions, care must be taken to minimize phase computation errors due to I–Q demodulator circuit amplitude and quadrature imbalance and voltage offsets.

G. Telemetry Data Reception and Decoding Functions

The pilot-modulated housekeeping telemetry is expected to include the entire spacecraft telemetry mix (engineering and science). Frame structure (packets) is expected to conform to CCSDS international standards. The telemetry BPSK receiver, data detector, and data decoder should be based on commer-

[10] Doppler predicts should be generated in coordinate time, which is the reading on a perfect clock just outside the satellite and is stationary in an inertial frame. The difference between proper and coordinate time is calculated from the equations of special and general relativity. Further, since the PTA will be universally designed to operate at all installations, as well as to provide time corrections to several different correlators, the Doppler processor must generate the Doppler compensations and produce the complete time correction file, with the relativistic corrections. This technique was successfully used at NRAO's Green Bank tracking station for VSOP.

[11] J. S. Border, "Formulation for Compensated Doppler," JPL Interoffice Memorandum 335.1-96-007 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 22, 1996.

[12] J. S. Border, "Effects of Ground Station Delays on Compensated Doppler," JPL Interoffice Memorandum 335.1-96-011-Corrected (internal document), Jet Propulsion Laboratory, Pasadena, California, June 20, 1996.

cially available equipment compatible with the following requirements. (The low telemetry data rate should permit use of a software decoder.)

$$\begin{aligned}\text{telemetry rate} &= 8\ \text{kb/s}\\ \text{BPSK receiver tracking bandwidths} &= 1000,\ 500,\ 250,\ 100\ \text{Hz}\\ \text{data } E_b/N_0 &= >10\ \text{dB}\\ \text{BPSK data differential decoding} &= \text{required}\\ \text{telemetry decoding packet forms} &= \text{TBD}\end{aligned}$$

Links from the telemetry data detector to the data decoder at a remote site are assumed to make use of existing LANs within the station complex. Alternatively, local decoding of the telemetry could be processed and reassembled into packets that are sent to other locations using the Internet.

H. PTA Oversight and Control Interfaces

The following general interface data and monitor guidelines should be considered.

Information inputs to the PTA are basically the schedule and the state vector (orbit) for the spacecraft. Pointing-angle data and radiometric predicts must be generated by the PTA's SCC and Doppler computer. External interaction with the PTA during a tracking pass should be limited to observing monitor data and reporting anomalies. Local non-track diagnostic and verification access should be through a general control computer port connected to a laptop computer.

The PTA should deliver monitor data, plus spacecraft telemetry data, in real time over a local LAN to some appropriate remote facility, where they are processed for display and forwarding to user agencies by means of appropriate protocols and links. Doppler data, the time correction file, and station performance log files may be distributed post-track.

VII. Conclusions

This article has presented the rationale and design concepts for a space VLBI GTS segmented architecture. Sufficient details have been provided to establish high-level implementation and performance criteria. The most demanding technological challenges concern the development of Gb/s data receivers, decoders, and recorders. Additionally, a verification experiment has conclusively demonstrated that the segmented architecture performs as presumed, and no significant problems with time correction or correlation of VLBI data were found.

References

[1] J. C. Springett, "Achieving Future Space Very Long Baseline Interferometry Gigabits-per-Second Data Rates," *The Interplanetary Network Progress Report 42-149, January–March 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–26, May 15, 2002.
http://ipnpr.jpl.nasa.gov/progress_report/42-149/149G.pdf

[2] A. R. Whitney, *Preliminary Design Specifications for Mark 5 VLBI Data System*, Mark 5 Memorandum 005.2, Rev. 1.2, Massachusetts Institute of Technology Haystack Observatory, Westford, Massachusetts, November 15, 2001. ftp://web.haystack.edu/pub/mark5/005.2.pdf

[3] W. Cannon, *S3 Gigabit VLBI Recording System*, CRESTech Space Geodynamics Laboratory, North York, Ontario, Canada, October 9, 2001. http://www.sgl.crestech.ca

[4] J. C. Springett, *Phase Stable Frequency Transfer for Orbiting VLBI Radio Telescopes*, NeoComm Systems, Inc., La Crescenta, California, October 15, 1992.

Appendix

PTA Concept Verification Experiment

Proposing use of a segmented station architecture invariably raises various questions, among them being concerns about time correction (the "Delta T file" or TCF) as well as correlator fringe production. After all, it took considerable time and effort to perfect this process for the unified architecture used to support VSOP, so suspicions that something significant might be compromised by the segmented approach are to be expected. A brief study concluded that the quickest way to get answers is to directly test the concept. Accordingly, an experiment was devised to gather phase transfer and navigation data at one antenna and the VLBI data from another antenna during a portion of a scheduled VSOP science observation. This experiment was set up at the Goldstone, California, tracking facilities using DSS 23 (the 11-m SVLBI tracking station) to accomplish phase transfer and DSS 13 (a 34-m beam-waveguide research and development station) to receive the data.

The experiment arrangement is shown in Fig. A-1. For regular or normal tracks, DSS 23 carries out all functions: phase transfer, metric recovery (two-way Doppler), and VLBI data reception (including recording). In this circumstance, the switch shown is in the "normal" position. During the experiment, the 11-m station continues to accomplish phase transfer and metric recovery. However, the input to the VLBI data subsystem is now obtained from the 34-m antenna, with the switch in the "test" position. For the experiment, approximately 30 minutes of data were taken with the configuration in the normal mode, and the remaining hour was devoted to the test mode.

The baseline between DSS 13 and DSS 23 (including vertical displacements) is 12.489 km. But the F/O electrical length between the two sites is much longer, due to the circuitous path it takes at the Goldstone complex. Critical to the experiment is a precise knowledge of the differential data waveform delay between the two QPSK demodulators (demods). This was quite accurately measured by observing the displacement between the two received data waveforms during a track.

Figure A-2 shows the DSS-23 vital performance data. TCF-RELCORRCal is the time correction information, including relativistic corrections; Dop.Res is the residual two-way Doppler remaining after predictive removal on both uplink and downlink carriers; TCF is the clock setting event (CSE) epoch difference between the station 1pps and the satellite-data-derived 1pps; PRFRes is the residual random phase measured on the two-way phase transfer link. All these indicators are typical and satisfactory. Of

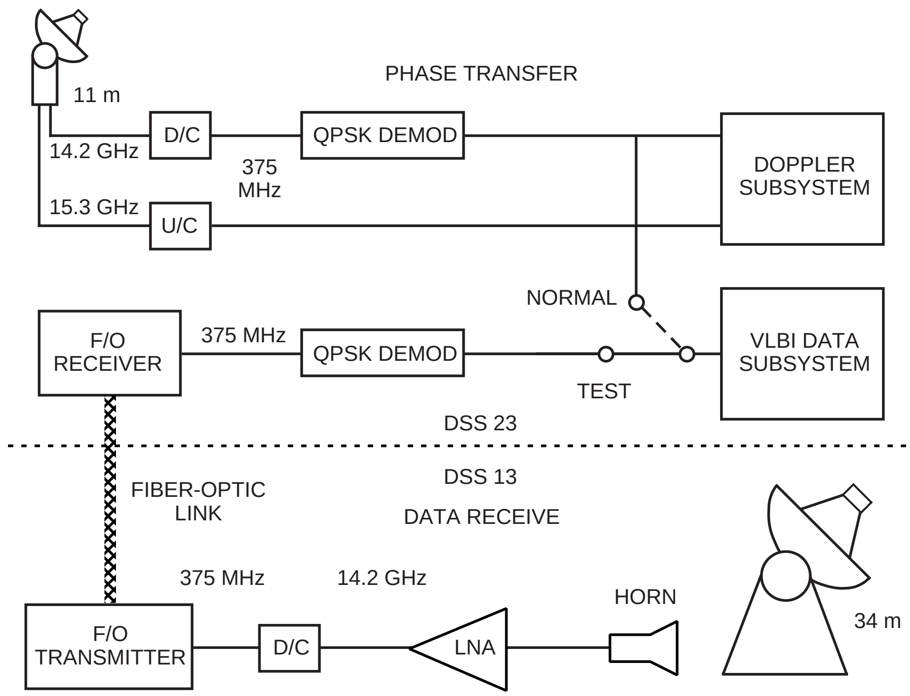

Fig. A-1. Configuration for the segmented architecture experiment.

particular note are the two steps that prominently occur in the TCF. These are known as clock setting events. The first at about 16:44 happened (and was expected) when the switch shown in Fig. A-1 was moved from normal to test. The second step occurred around 17:00 when the DSS-13 antenna wandered off point, accompanied by a significant drop of received signal level which, in turn, caused the QPSK demodulator and data subsystem to lose lock and reset.

All VLBI data were stored on Canadian S2 recorders and subsequently processed by the Canadian S2 SVLBI Correlation Centre at the Dominion Radio Astrophysical Observatory (DRAO), Penticton, British Columbia. The following is a brief excerpt from the informal test correlation report:[13]

> Test correlations have been carried out at DRAO on experiment W059a2 where two different tracking station set-ups were used at Goldstone (GZ). The tracking pass was initially observed using the 11m setup with which we have much experience and confidence (certainly at the correlator!). This part of the pass was from 16:18 to 16:44 UT. At that time, the setup was changed to the 34m (DSS-13) receiving astronomy data and the 11m receiving the phase-link data. This setup was used from 16:44 UT until the end of the pass at 17:43 UT.
>
> The correlator models were defined using the standard TCF for the pass, plus a +210 microsecond clock offset for 16:44 to 17:43 UT, and including the geocentric coordinates of the 34m in the array geometry model. The correlation delay window was set to search for fringes within a ± 16 microsecond window, and the correlator was dumped every 0.5 seconds, covering fringe rates as high as 100 ps/s.
>
> Most importantly, space-ground fringes were found throughout the whole of the GZ pass, from 16:18 to 17:44, so the experiment with the station set-up and the subsequent set-up at the correlator was a success.

[13] DRAO, Canada, informal report to JPL, October 9, 2001.

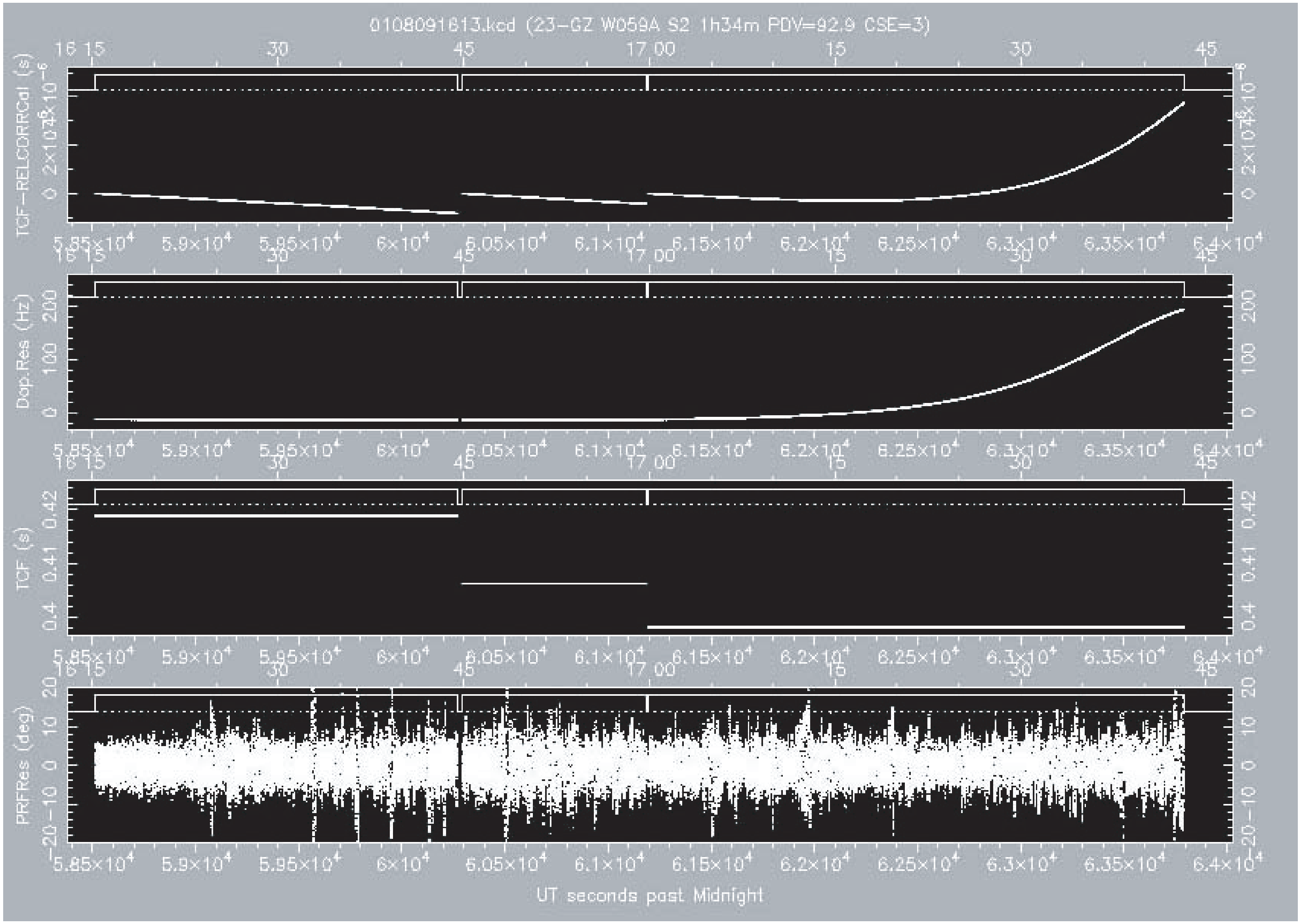

Fig. A-2. DSS-23 performance data.

Figure A-3 shows correlation results for two different baselines: between the Australian Telescope (AT) Compact Array and VSOP, and between VSOP and Mopra, Australia. Figures A-3(a) through A-3(c) and A-3(f) through A-3(h) show, respectively, the complex fringe amplitude, SNR, and phase, while Figs. A-3(d) and A-3(i) indicate single-band delay (SBD), and Figs. A-3(e) and A-3(j) show the delay rate (DRATE). As should be expected, the SBD steps correspond with the TCF steps of Fig. A-2. Each data point on the plots is the product of a 300-s integration (except the last point in time, which was a 200-s integration).

The experiment conclusively demonstrated that a segmented architecture performs as presumed and that no significant problems with time correction or correlation were evident. This judgement is based on the regularity and smoothness of the plots of Fig. A-3. It seems—unless one was informed that two antennas were involved—that these plots would lead one to assume the single 11-m antenna was used for the entire test pass (with the CSEs simply representing anomalies that are well known to happen from time to time).

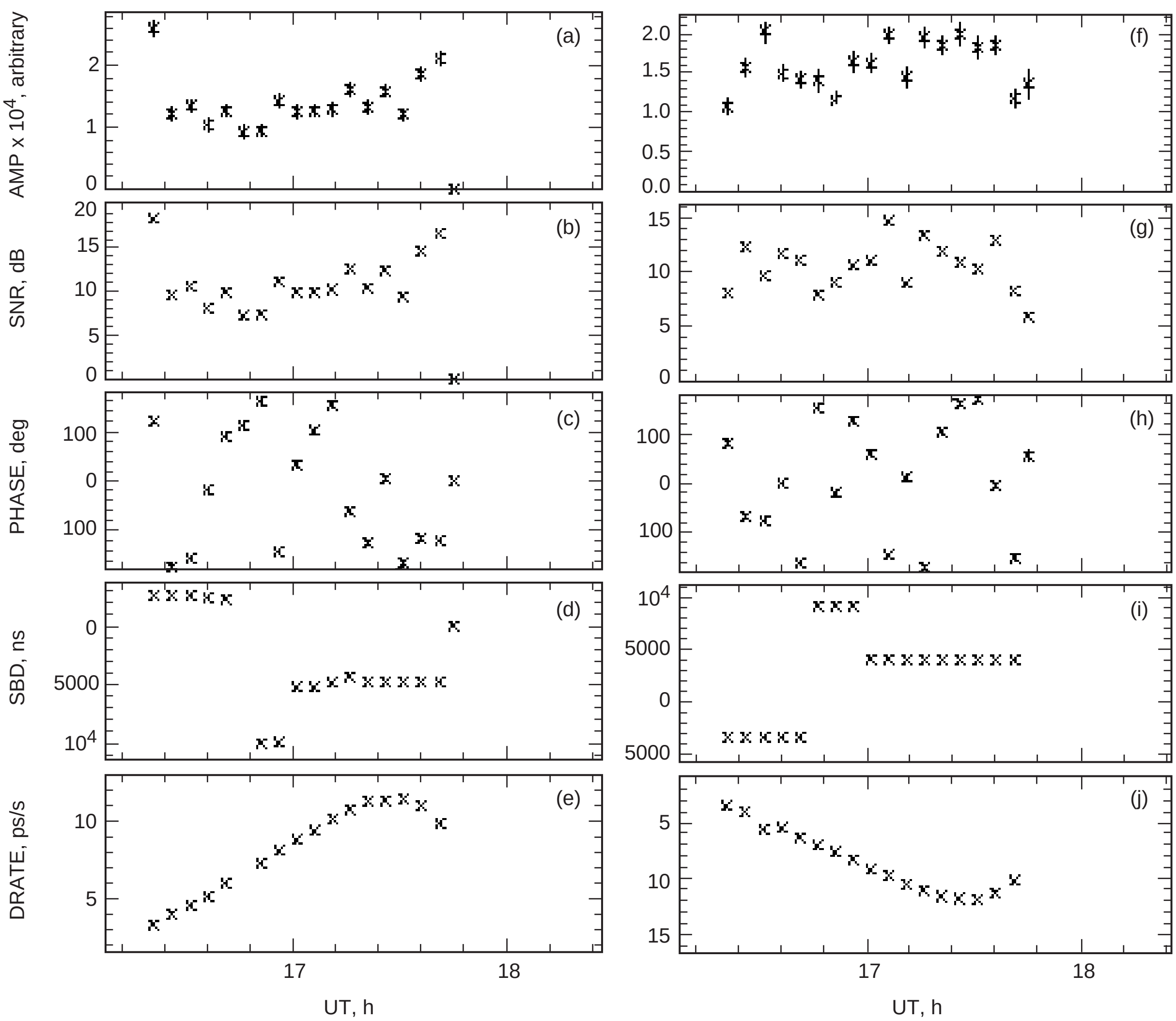

Fig. A-3. Correlator results for the Australian AT VSOP baseline: (a) complex fringe amplitude, (b) SNR, (c) phase, (d) SBD, and (e) delay rate, and for the VSOP Mopra, Australia, baseline: (f) complex fringe amplitude, (g) SNR, (h) phase, (i) SBD, and (j) delay rate.

This experiment was unable to check every nuance between the existing unified and proposed segmented architectures. For example, a single downlink carrier had to be used for the experiment, whereas separate data and phase transfer carriers, separated in frequency by the symbol rate, are specified for the segmented system. But the effects of this, and other small differences, are considered secondary to the now demonstrated proof of the quintessential segmented concept.