Space Very Long Baseline Interferometry (SVLBI) Mission Operations

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The first space very long baseline interferometry (SVLBI) mission—the VLBI Space Observatory Program (VSOP)—using an 8-m telescope in orbit, has been successfully operated since 1997, and several follow-on missions are in development or under discussion. The SVLBI missions are among the most complex space science missions to date in terms of operations and coordination of the disparate worldwide mission-operations elements. In addition to spacecraft operations, nominal to any space mission, overall mission operations include a large ground operations component specific to SVLBI missions. This includes very wideband data acquisition and very high-precision frequency/time synchronization and orbit determination/navigation provided by a specialized network of five 10- to 14-m ground tracking stations around the world and the co-observing support of up to 40 ground radio telescopes around the world. The NASA Deep Space Network (DSN) and the U.S. Space Very Long Baseline Interferometry (VLBI) Project (U.S. SVLBI Project) at JPL are responsible for mission operations support with three of the five ground tracking stations and for co-observing support with the DSN 70-m ground radio telescopes. This article will describe the overall SVLBI mission operations system with particular attention to the mission elements provided by the DSN. The requirements for support of future missions and necessary improvements to increase the efficiency of mission operations and to decrease mission operations costs also will be described.

I. Introduction

Space very long baseline interferometry (SVLBI) missions employ at least one space-based radio telescope (SRT) operating in conjunction with a network of ground-based radio telescopes (GRTs) to conduct radio interferometric measurements of celestial radio sources. The observations conducted with such an interferometer provide images of radio sources with unprecedented angular resolution exceeding by orders of magnitude that achieved through other astronomical measurements (e.g., exceeding ~200 times the Hubble Space Telescope angular resolution).

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The first space very long baseline interferometry (SVLBI) mission—the VLBI Space Observatory Program (VSOP)—led by Japan's Institute of Space and Aeronautical Sciences (ISAS) [1] has been successfully operated for more than 3 years. (The VSOP spacecraft—the Highly Advanced Laboratory for Communications and Astronomy, or HALCA—was launched on February 12, 1997.) A significant part of the operational support for VSOP is carried out by NASA's Deep Space Network (DSN), managed by the Jet Propulsion Laboratory (JPL). Several follow-on missions are in development or under discussion. It is expected that the DSN will play a crucial role in operations support of future SVLBI missions.

Aspects of VSOP mission operations support have been described in numerous articles and technical documentation prior to the launch of VSOP (see, for example, [2–7]). In this article, we will describe the principles of SVLBI mission operations and their realization in the VSOP mission, with particular emphasis on the mission operations support provided by JPL and the DSN.

II. Mission Operations Requirements for SVLBI

Relative to other types of space astronomy missions, SVLBI missions have a set of unique operational requirements. These requirements arise from the nature of the VLBI technique and technology needed to realize the missions. The contemporary SVLBI missions are characterized by the following requirements.

(1) Ground radio telescopes to co-observe simultaneously with the space radio telescope. The current SVLBI project, VSOP, and its successors in the foreseeable future have only one radio telescope in space and rely heavily on co-observing with ground radio telescopes because an interferometer must consist of at least two telescopes to generate the interferometric output. At least four telescopes, and preferably many more, are required to obtain good quality radio source images. Moreover, since the size of the space radio telescope is relatively small and limited by existing launch capabilities to 8 to 20 m, the support of the large 70-m class ground-based antennas is crucial to obtaining sufficient sensitivity to be able to observe a valuable sample of radio sources.

(2) Very high science data rate (e.g., for VSOP, 128 Mb/s) exceeding data rates of most other types of space astronomy missions by two to three orders of magnitude. The detection threshold of an SVLBI interferometer is proportional to the inverse square root of the observational frequency bandwidth. Thus, a wider bandwidth provides better sensitivity for the interferometer. Bandwidths up to 2 to 4 GHz are envisioned for future space VLBI missions. If the radio telescope signal is digitized at the Nyquist rate with two levels of voltage (amplitude) quantization, such bandwidths correspond to digital data rates of 4 to 8 Gb/s.

(3) Transmission of data in real time to Earth. The data rate is so high that there is no currently envisioned technology to collect these data onboard during a typical experiment (e.g., the duration of a typical VSOP experiment is 5 to 10 hours or 1 to 2 orbits). The data must be transmitted to Earth in real time and recorded at the science data acquisition tracking stations. Moreover, the space telescope is only one element in a network of radio telescopes that simultaneously carry out the VLBI observations. Routinely, the number of co-observing ground-based telescopes may be around 10 or more. They record data at the same rate as the tracking stations that receive data from the space radio telescope. Then the data from all the telescopes (including the space telescope) are collected at a special data processing center (Correlator) and reduced through correlation and post-processing from $\sim 10^3$ Gb of raw data to the ~ 10 Mb of an average image. Any gaps in data transmission during the observation (due to a gap in tracking coverage for instance) represents data loss. The duration of a gap in data transmission is determined by the geometry of the interferometer (spacecraft orbit, orientation of the baseline, and location of the ground-based telescopes) and by the availability and location of the data acquisition stations. It is anticipated that such losses of data in the contemporary space VLBI missions should not be more than 10 to 20 percent.

(4) Precision frequency/clock synchronization of space-based telescope with the ground telescopes supporting the experiment.

    (a) To obtain successful correlation between the space radio telescope's and ground-based telescopes' data, the frequency stability of the receiver systems (local oscillators) at each telescope must be on the order of $\Delta f/f = 5 \times 10^{-14}$ in a time span of about 100 to 300 s—the usual integration time for VLBI experiments. This implies that hydrogen maser standards at all telescopes are needed as the sources of the reference frequencies. At present, it is not technically feasible to have an onboard hydrogen maser frequency standard. A two-way radio link with a stable oscillator on the Earth is needed to maintain the phase coherence between the space and ground telescopes.

    (b) To enable the Earth-to space interferometer to routinely produce the correlation output, the clock difference between the space telescope and ground telescopes must be maintained with an accuracy better than ±1 μs. Due to the uncertainties in the orbit and changing position of the spacecraft relative to the ground telescopes, the clock on the spacecraft cannot be accurately set, and the clock rate will be changing. The required accuracy of the onboard clock is achieved through the continuous measurement of the round-trip time with the same two-way radio link through which the phase coherency is maintained.

    (c) This frequency/clock synchronization needs to be provided continuously in the course of the observing session. As with the data transmission, breaks in synchronization will result in the degradation of the scientific output of an interferometer.

(5) Precision two-way Doppler measurements with a random error of 0.1 mm/s for a 1-minute integration time are crucial to provide the precision orbit determination needed to enable the data processing facilities (Correlators) to process/correlate the space telescope data in combination with the ground-based part of the interferometer.

Thus, in addition to spacecraft operations (including the spacecraft command control, housekeeping telemetry (TM) monitoring, and navigation) and space telescope operations (including control of mode of observations and monitoring of the space telescope systems), nominal to any space astronomy mission, the space VLBI mission operations system is required to support the following functions:

(1) Real-time high data-rate transmission from spacecraft to the ground.

(2) Continuous frequency/clock synchronization of the space radio telescope and continuous precision two-way Doppler measurements by maintaining a radio link between the ground-based frequency standard and the spacecraft.

(3) Ground-based telescopes co-observing with the space radio telescope.

(4) Distribution, processing, and archiving of the interferometric data.

(5) Coordination of operation of the multiple mission elements.

III. Space VLBI Mission Operations Elements and Their Functions

The space VLBI missions are among the most complex space science missions to date in terms of mission operations. Among space astronomy missions, such missions are leaders in regard to the number of elements involved in support of Earth-to-space interferometer operations. Additionally, these missions present numerous challenges associated with the missions' international character since many of the elements supporting the mission operations are distributed worldwide.

A. Ground Support System

Operational support for the space VLBI missions is executed by the ground support system, which involves five main components: (1) the science data acquisition network (or “science” network), (2) the spacecraft command and control tracking stations (spacecraft tracking network), (3) the co-observing ground radio telescopes (GRTs), (4) the data processing centers (DPCs), and (5) the orbit determination system (ODS).

The ground support system and its functions vary significantly depending on the type of space astronomy mission. Typically, the ground support system consists of a spacecraft tracking network (including tracking stations, spacecraft control center, and communication channels) through which the spacecraft and space telescope housekeeping telemetry is received, commands are transmitted, and navigation measurements are executed. The space astronomy missions with relatively low data rates (not more than 10 Mb/s) usually use the same tracking network for science data acquisition by integrating the science data streams with the spacecraft telemetry. But missions with high raw data output, like space VLBI missions, with expected data rates that may be as high as 8 Gb/s, are forced to use a special “science” network. This network in the space VLBI missions also functions to provide the transmission of the reference frequency/clock signal from the ground-based standards. This reference signal is used also for navigational (Doppler) measurements needed for precise orbit determination and for time-correction measurements needed for data-acquisition time setting.

The ground-based co-observing radio telescopes are very specific to the contemporary Earth-to-space VLBI missions. Telescopes located around the world are needed to enable the mission and to make it scientifically efficient. These telescopes have to observe at the same frequency bands as the space radio telescope. The data-recording formats at all co-observing telescopes, including space-based, must be compatible to enable the data processing (correlation). The ground-based telescopes must observe simultaneously with the space-based ones, which imposes a significant coordination problem since most radio telescopes are affiliated with different institutions and must support other radio astronomy programs.

Space VLBI missions have the highest raw (observational) data output among space astronomy missions. The initial processing of these data requires a specialized data processor or “correlator.” If the VLBI data are not combined in the correlator, these data will not have any value. The correlator processes the raw VLBI data (which sometimes may come from up to 20 telescopes as well as from science data acquisition stations that record the space radio telescope data) and reduces the amount of bytes of data by about three to four orders of magnitude. The output of the correlators then is used by the investigator to obtain an image or other astronomical information about the observed radio source.

Data processing centers (also called Correlators) process (correlate) data from the space radio telescope and the co-observing ground telescopes. Along with the initial data reduction, the SVLBI data processing centers perform data quality analysis and data archiving and dissemination. Historically, the VLBI Correlators maintained the VLBI tape databases and tracked tape movement between the VLBI telescopes and the Correlator. For the space VLBI projects, the Correlators additionally track tape movement between the science network and the correlator. There may be more than one Correlator needed to support the mission, since currently several VLBI data-recording formats are in use. Also, the existing VLBI Correlators, like ground-based telescopes, have to share the operational resources between many projects besides processing the SVLBI data.

The orbit determination system provides the information needed by the spacecraft and science tracking stations for communication with the spacecraft and the orbital information needed for data processing. These data are calculated based on the navigation measurements from both the spacecraft tracking stations (Doppler and range) and science data acquisition network (Doppler).

B. Mission Operations System

The mission operations system (MOS) is a conglomerate of operations facilities, computer hardware and software, and personnel. The MOS performs planning, resource allocation, mission-element performance monitoring and analysis, commanding, and archiving of the mission operations data. The major responsibility of the MOS is to provide safe and reliable spacecraft operations (including the spacecraft service bus and science payload/telescope). In order to do this, the mission operations system coordinates, plans, and allocates the mission resources, including spacecraft power, fuel for orbit and attitude corrections, and the time needed by the ground-based tracking network to track the spacecraft.

The space astronomy missions that, like VSOP, operate as "open" observatories (i.e., any qualified scientist can use it for observations if his proposal is accepted) usually establish a specific science operations system. This system oversees science planning, allocates the mission/telescope observing resources, monitors the quality of the science output, and archives the science data. One of the tasks of the science operations system is, in the event of a space telescope malfunction, to evaluate the observing capabilities and performance of the space telescope and to inform the proposers of changes to the telescope's configuration. Even during normal, routine operations of a space VLBI mission, significant simulations are needed to evaluate the optimal configuration of the space- and ground-based telescopes, the appropriate observing date for a given source, etc. This is also the task of the science operations system. This and other science operations functions are conducted by the mission's science operations and support groups. (The science operations system may be considered as the subsystem of mission operations. It is distinguished here from mission operations since it uses separate facilities and groups of people to perform the specific tasks.)

The mission operations structure and the functions of its elements may vary depending on the available resources and the rules of the agencies that participate in the mission. The form of the mission operations in the VSOP mission is shown in Table 1. It is worth noticing the diversity and number of the VLBI recording data formats (four) and the number of Correlators (three) involved. It is evidently not an optimal configuration because the use of multiple formats and facilities significantly complicates the mission operations. The mission inherited this diversity, along with the need to involve as many ground-based radio telescopes as possible to support the mission operations. Historically, the radio telescopes in different parts of the world used different VLBI systems. This compatibility problem was resolved by using subnets of telescopes operating in the same format and by using the special processor at the VSOP correlator, which converts the data between different VLBI formats. Also, the use of the DSN 26-m subnet, which was not in the original mission design, proved to be very useful for navigational measurements and telemetry reception outside of the Japanese Kagoshima station's view in case of a spacecraft emergency.

IV. Space VLBI Mission Operations (Data Flow)

The mission elements interact with each other through information and/or data product exchanges. There are basically two types of information exchanged—control (including plans, schedules, and commands) and data (data files containing the spacecraft and telescope health information, science data, etc.).

Figure 1 presents a generic diagram of the vital data and control information flow in an Earth-to-space VLBI mission. (In order to simplify the diagram, we assumed that all ground elements are operating nominally and are available for mission support. If one of the mission elements has operational problems, it will report the anomaly to the Mission or Science Operations Team and repair the problem with its own resources. In the rest of this section, the mission element data products are in *italics*).

The *science data* (science telemetry) from the space radio telescope are transmitted from the spacecraft and recorded on tapes at the tracking stations and sent directly to the data processing center (DPC).

Table 1. The VSOP SVLBI mission operations support structure.[a]

SVLBI mission operations element	VSOP element	Function/realization	Affiliation/location
Ground support system			
Science tracking network	Tracking network with 5 GTSs.	(1) Provide science data acquisition, onboard frequency/clock synchronization, orbit (Doppler) measurements; (2) Ku-band (∼15-GHz) channel used for data and reference signal transmission; SRT data recorded in VLBA, S-2, and VSOP-T formats.	(1) 3 NASA DSN 11-m antennas, one each in Goldstone (U.S.A.), Canberra (Australia), Madrid (Spain); (2)14-m NRAO antenna in Green Bank (U.S.A.); (3) 10-m ISAS antenna in Usuda (Japan).
Ground radio telescopes (GRTs)	About 40 GRTs.	(1) Provide co-observation with space radio telescope; (2) Telescopes co-observe in two bands: L-band (1.6–1.7 GHz) and C-band (∼5 GHz); data recorded in 4 VLBI data formats: MKIV, VLBA, S-2, VSOP-T.	These telescopes are affiliated with radio astronomy institutions from ∼17 countries, and the VLBI networks, including the VLBA, EVN, and NASA's DSN (70-m subnet), have committed up to 20% of their time to support SVLBI observations.
Data processing centers (Correlator)	Three Correlators.	(1) Provide SVLBI data correlation, data tape logistics, data archiving; (2) VLBA, S-2, VSOP Correlators process the data in MKIV/VLBA, S-2, and VSOP-T formats, respectively.	(1) VLBA Correlator (NRAO, U.S.A.),(2) VSOP Correlator (NAO, Japan), (3) S-2 correlator (HIA/CSA, Canada).
Spacecraft command and control tracking station(s)	Spacecraft operations center in ISAS and station in Kagoshima. 26-m DSN subnet.	(1) Spacecraft/telescope control, monitoring, orbit measurements; (2) S-band (2.2–2.3-GHz) channel used for communication.	(1) Spacecraft operations conducted from Kagoshima Space Center (Japan); (2) NASA DSN 26-m subnet provides navigation and TM support outside of the Kagoshima station's view in case of a spacecraft emergency.
Orbit determination system	Two orbit determination centers.	Provide orbit parameters to support the spacecraft operations (NASDA) and mission data processing (MMNAV).	(1) ISAS (Japan) provides spacecraft navigation support; (2) JPL MMNAV (U.S.A.) provides orbits for data processing.
Mission operations system	VSOG.	Coordinate overall mission operations, including spacecraft and ground support systems.	Located in ISAS (Japan); group membership is international.
	DOTS.	Coordinate and monitor operations of the DSN science tracking stations.	Located at JPL (U.S.A.); managed by the U.S. Space VLBI Project.
	GBES operations.	Support the GBES tracking station operations.	Located in Green Bank, U.S.A.; managed by the NRAO's Space VLBI Project.

[a] Acronyms: Canadian Space Agency (CSA); European VLBI Network (EVN); ground tracking stations (GTSs); Herzberg Institute for Astrophysics (HIA); Nobeyama Astronomical Observatory (NAO).

Table 1 (contd).[a]

SVLBI mission operations element	VSOP element	Function/realization	Affiliation/location
	GRT operations.	Ground radio telescopes and networks operations.	Operations conducted by teams of operators located at the telescopes sites or network operations centers.
	Correlator operations.	Support Correlator operations.	Operations conducted by Correlator Operations Teams.
Science operations system	Science Review Committee.	Conduct scientific peer review and ranking of proposals.	International membership.
	Science support groups.	Analyze the interferometer data output and propose ways to optimize it.	(1) Data analysts at the correlators; (2) JPL SVLBI Project Science Team; (3) VSOP Data Reduction Group.
	Principal Investigator.	Propose the experiments and observing programs.	Open to any qualified scientist from around the world.

[a] Acronyms: Canadian Space Agency (CSA); European VLBI Network (EVN); ground tracking stations (GTSs); Herzberg Institute for Astrophysics (HIA); Nobeyama Astronomical Observatory (NAO).

The *space radio telescope auxiliary data* containing the data time-tag information (time correction file), space radio telescope log (the records of events at the telescope and science tracking station during the observations), and other information are transferred through the Internet from the network stations to the network operations center, where they are stored on an Internet server for retrieval by other mission elements, including the DPCs. *Navigational measurements* in the form of Doppler measurements in the reference-frequency link channel also are transmitted through the Internet from the tracking stations to the network operations center, where they can be retrieved by the orbit determination system (ODS). In order to function, the science data acquisition tracking network must receive the *schedule* from the mission operations system and spacecraft *tracking predicts* (spacecraft orbit information and Doppler predicts needed for the communication channel).

Scheduling of the ground telescopes for co-observations is done by the SVLBI mission science operations system in a manner compatible with routine VLBI network operations. Long-term observing *plans* are agreed to well in advance but may be corrected in accordance with the current status of the spacecraft and other mission elements. The actual *schedule* files (electronic files that define the observing sequence and procedures) are distributed to the co-observing telescopes 2 weeks in advance of the observation. The *science data* tapes and *auxiliary data* from telescopes are delivered to the data processing centers for correlation.

All data required for correlation must be received at the respective correlator no more than 2 weeks after the observations are made. The *science data* tapes from the telescopes and science tracking stations are received by mail, while all the telescope supporting *auxiliary data* are sent electronically to the Internet servers maintained at the data processing centers. The space radio telescope *auxiliary data* (including the telescope log and time-correction file) are retrieved by the correlator from the Internet server maintained at the science tracking network operations center. This strict requirement on the data delivery timeline is very important. Because the number of data tapes available for VLBI operations is limited and the data correlation takes approximately the same amount of time as the experiment, data processing delays at the correlators may lead to the absence of tapes for future data recording at the telescopes or tracking stations and, accordingly, to the loss of data. In order to correlate the data that come on the tapes, the data

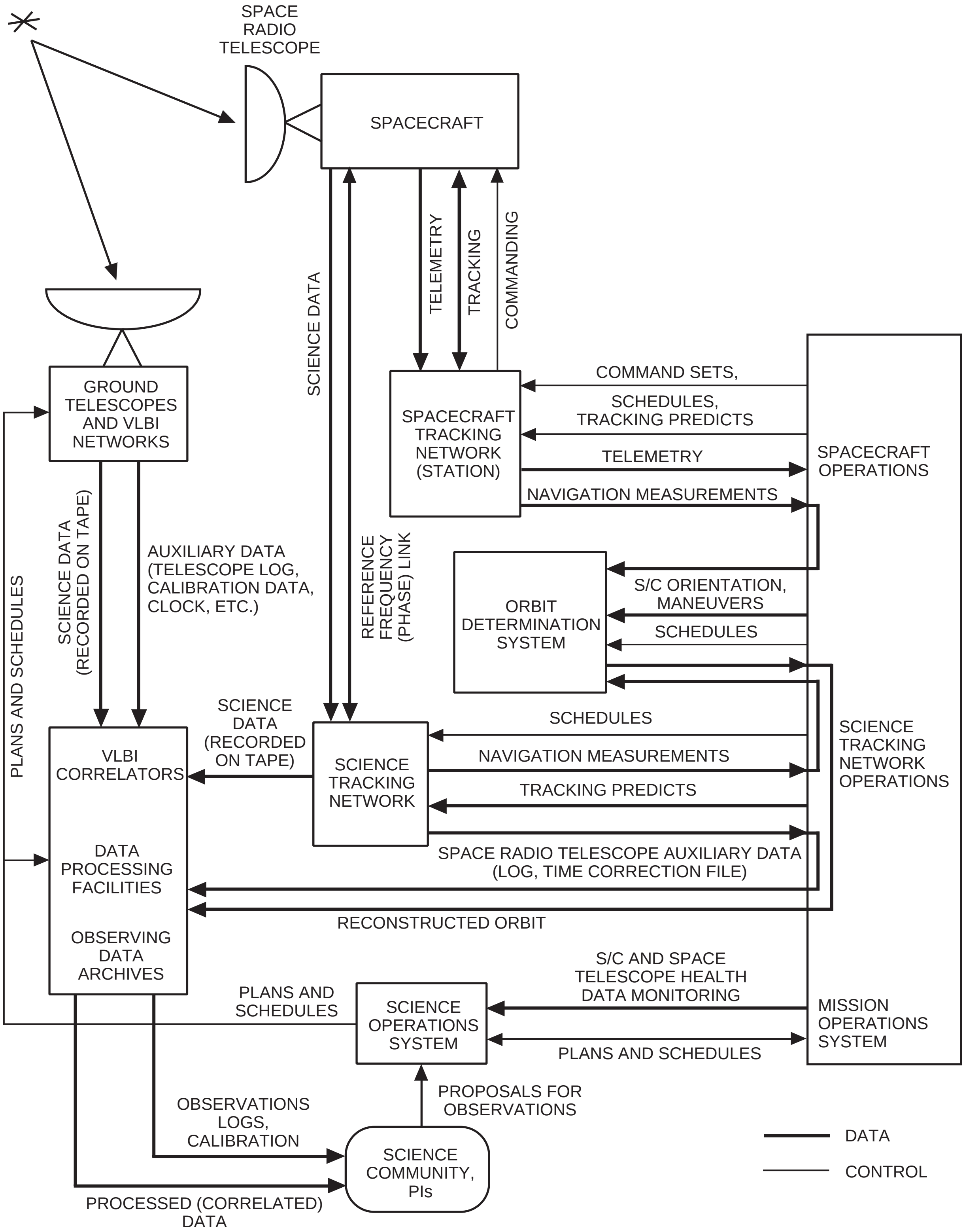

Fig. 1. Earth-to-space VLBI mission operations data flows.

processing centers must know the spacecraft's orbit with high accuracy at the moment the observations were made. This *reconstructed orbit*, the set of orbit parameters generated after the observing session using the navigational measurements that were made before and during the observations, is provided electronically to the DPCs by the orbit determination system according to the same timeline as the data tape delivery.

The control and monitoring of the spacecraft and space radio telescope are executed through the spacecraft tracking station or network of stations. The spacecraft tracking network (1) executes *commanding*, (2) provides *navigational measurements* by measuring the spacecraft distance and velocity (Doppler) through transmitting and receiving a radio signal, and (3) receives the spacecraft and space radio telescope *telemetry* and transfers these data to the orbit determination system and to spacecraft operations. To perform this function, the spacecraft tracking network must receive the *schedules*, *command sets*, and *tracking predicts* from the mission operations group. Since observations with the onboard telescope in the VSOP project are executed mostly in a spacecraft autonomous-operations mode, the spacecraft tracking station communicates with the spacecraft only during a small part of each orbit.

The VSOP spacecraft is using a communication channel for spacecraft operations that is different from the science data and reference-frequency transfer communication channels (see Table 1). The separation of these two channels (different frequencies, different onboard antennas, different radio complexes, etc.) provides the redundancy that can help to restore spacecraft functioning in the case of an emergency situation onboard the spacecraft. To provide even more safety for the mission, the spacecraft and the space radio telescope monitoring data are included in the *science data* flow that is received by the science network and then delivered to mission operations.

The orbit determination system receives the *navigation measurements* from both the spacecraft tracking stations and science network. It generates the *tracking predicts* information needed by the spacecraft and science tracking stations to point to the spacecraft and adjust the communication frequencies due to the Doppler effect from spacecraft motion, and the *reconstructed orbit* for data processing. In order to generate a highly accurate *reconstructed orbit*, additional information on the spacecraft's attitude and maneuvers is required. The significant mechanical forces (drag) generated due to the interaction of the large parabolic antenna of the space radio telescope with the atmosphere near the orbit perigee and with the solar wind have to be accounted for in the orbit reconstruction by way of mathematical modeling.

The request for an observation comes in the form of a *proposal* from a Principle Investigator (PI), which, before the observation can be carried out, is reviewed and evaluated by the mission Science Program Committee. The mission's science operations system evaluates the technical viability of the *proposal* in accordance with the current status of the mission systems. In order to do this, the Science Operations Group needs to know the status of both the space radio telescope and spacecraft systems. The *spacecraft and space radio telescope health data* are supplied by the mission operations system. Based on this information, the science operations and mission operations systems negotiate the long-term (duration about 1 year), mid-term (duration 3 to 4 months), and short-term observing *schedules/plans* for the spacecraft and space telescope operations. The science operation system also generates the *plans* and *schedules* for the ground telescopes and the VLBI correlators.

Finally, when the observations are completed and processed at the VLBI correlator, the *correlated data* as well as the *observation logs and data calibration* files are delivered to the Principle Investigator of the experiment from the data processing centers. The Principle Investigator is responsible for the observation's final product—the analysis and publication of results. The usual practice is that, during the first 6 months to 1 year after the experiment, the Principle Investigator has sole access to the data for analysis and publication. After this period, the data become available for analysis by the astronomical community at large.

The space VLBI mission/science operations rely heavily on the Internet. Most of the mission operations information products, except the VLBI data themselves, are distributed through the Internet. The need to reduce the cost of a mission has led to the use of distributed data archives, especially for the intermediate mission operations products. For example, in the VSOP SVLBI mission, the mission operations products (*schedules, auxiliary data files, spacecraft and space telescope records of events*, etc.) are stored on Internet servers maintained by the respective mission elements. If some mission element (e.g., data processing center) needs spacecraft orbit data or the space telescope *records of events*, the needed information can be downloaded from the relevant server via the Internet. Most of this information is needed only for mission support and is not needed for the Principle Investigators of the experiments, who are interested only in their experiment results. Thus, the access to these servers where the mission operations products are stored is generally restricted to the mission operation elements. Nevertheless, in the case of a problem with data processing or interpretation, these auxiliary data may be revisited and obtained directly from the archives.

V. JPL–DSN Segment of the VSOP Mission Operations

The overall management of the VSOP mission operations support in the DSN is carried out by the U.S. SVLBI Project under the direction of NASA's Office of Space Science. The JPL–DSN resources dedicated for the VSOP mission operations support include (1) an 11-m DSN subnet—three of five tracking stations supporting the VSOP science data acquisition and frequency/clock reference link; (2) a data oversight and transfer system (DOTS)—computers/software and a team of mission operators responsible for delivery of tracking and telemetry data from the DSN tracking stations to the other mission operations elements, as well as generation and delivery of schedule files for those stations, end-to-end validation of the scientific telemetry, and planning and implementation of the day-to-day mission operations; and (3) the U.S. SVLBI Project Science Team, which ensures, through evaluation of the scientific data and optimization of the planning of scientific observations with the VSOP, that the final scientific products of the mission (e.g., the radio quasar images) are of the highest quality.

Other JPL–DSN resources involved in the VSOP operations support are (a) the DSN's multimission navigation (MMNAV) system, which provides navigation support for the mission based on the trajectory measurements made with the 11-m subnet and 26-m DSN subnet (the former only in case of a spacecraft emergency), and (b) the DSN 70-m antennas, which conduct the co-observing observations with the space radio telescope on a noninterference basis with the support of the other DSN flight missions. The 11-m and 70-m DSN subnet operations, as well as the VSOP navigation support by the MMNAV, are carried out by JPL's Telecommunications and Mission Operations Directorate for the U.S. SVLBI Project.

The external and internal interfaces and data flow in the U.S. VLBI Project's VSOP mission operations segment are described in Table 2.

A. U.S. Space VLBI Project Mission Operations

The coordination of VSOP mission operations is executed through scheduling. Based on information on the status of the space radio telescope (SRT) and status and availability of the mission operations elements, the VSOP Science Operations Group (VSOG) generates SRT and GRT schedule files that contain the information needed to conduct the communication sessions between the 11-m tracking stations and the spacecraft and to conduct co-observing at the ground telescopes, respectively. The DOTS automatically retrieves the SRT file from the VSOG Internet server, which is located in Japan, every 15 minutes. Similarly, the ground radio telescopes retrieve the schedule files from a few designated VLBI servers located in radio astronomy organizations around the world (regional servers), at which the VSOG places the file. The DSN 70-m subnet retrieves its schedule file from the very long baseline array (VLBA)/National Radio Astronomy Observatory (NRAO) server in Soccoro, New Mexico.

The DOTS at JPL serves as the centralized interface point between the VSOP mission Science Operations Group (VSOG) and the DSN 11-m tracking network. Input products to the DOTS are from the network, and its specifications are governed by the interface agreements between the U.S. SVLBI

Table 2. U.S. SVLBI Project's VSOP mission operations segment.

Mission operations element	Input	Output/product	User
DOTS	(1) SRT schedule file *(2) Monitor data* *(3) Tracking data* (4) Station logs (5) DSN frequency and time system report (6) Predicted orbit (7) Reconstructed orbit	Uplink products	
		DSN schedule file	11-m DSN
		Predicted orbit file	11-m DSN, GBES
		Downlink products	
		Time correction file	Correlators
		Reconstructed orbit	Correlators
		Station status report	VSOG
		Station logs (S-2, VLBA)	VSOG
		Telemetry header file	VSOG
		Station monitor data file	VSOG
11-m DSN subnet	(1) DSN schedule file (2) Predicted orbit file (3) Data link signal (4) Frequency/clock synchronization link signal	Space radio telescope science data on VLBI tapes, VLBA, or S-2 formats	DOTS, MMNAV
		Tracking data (time difference File, phase residual file)	DOTS
		Station monitor data file	DOTS
		Telemetry header file	DOTS
		Station logs (events, S-2, VLBA)	DOTS
MMNAV	11-m tracking data	Predicted orbit	DOTS
		Reconstructed orbit	DOTS
70-m DSN subnet	(1) GRT schedule file	Science data on VLBI tapes	Correlators
	(2) Radio source signal	Telescope calibration and log files	Correlators
Project Science Team	(1)Predicted orbit	Optimized long-term observation schedule	VSOG
	(2) Correlated SVLBI data (test experiments)	Monitoring SVLBI interferometer performance	VSOG

Project and the DSN. The output products of the DOTS are governed by interface agreements with other VSOP mission elements. The logical flow of data may be divided into uplink and downlink stages, where uplink refers to the scheduling of the DSN tracking stations, resulting in space VLBI satellite tracking, signal acquisition, and VLBI recording, and where downlink refers to the results of a particular VSOP satellite tracking pass. The DOTS computers are running a few programs that process the input data and generate the output files [time correction file (TCF) and telemetry header file (THF)] needed by the Correlators and VSOG. (The TCF is used by the Correlators to correct the time stamps of digitized space radio telescope data recorded at the tracking stations to enable the SVLBI data correlation; the THF contains the spacecraft telemetry and is used by the VSOG for spacecraft health monitoring.) The downlink products are stored at the DOTS Internet server, from which they are retrieved by the Correlators and VSOG.

DSN 11-m tracking stations receive the DSN schedule and station configuration files generated at the DOTS through the DSN network scheduling subsystem (NSS) once a week. They conduct the communication sessions with spacecraft according to the schedule, producing tapes with science data recorded in two VLBI formats depending on the configuration of the space VLBI experiment (the co-observing telescopes must record their data in the same format), a set of tracking measurements, and log files, which then are delivered to the DOTS through the Internet in near-real time (in Table 2, given in italic) or post-pass. The tracking measurements are also delivered to JPL's multimission navigation system to generate the predicted and reconstructed orbit files.

The DSN's multimission navigation system supplies the predicted orbit for the DSN 11-m tracking network and the Green Bank OVLBI Earth Station (GBES)/NRAO tracking station once a week. These predicts are used for antenna pointing and frequency Doppler-shift predictions. The highly accurate reconstructed orbit for a period of 7 days is derived from the results of tracking measurements and made available for Correlators once a week.

The data flow from the stations to DOTS as well as the metrics of the 11-m subnet performance are monitored through the U.S. SVLBI Project mission operations system Web site on the Internet. The history of the DSN 11-m subnet operations is shown in Fig. 2. On average, the DSN support accounts for more than 70 percent of the operational time of the VSOP mission. The intervals with low numbers of science passes indicate the periods when the spacecraft was recovering from a nonoperational state or in a period of frequent eclipses.

The performance of the 11-m DSN subnet is crucial for the success of the mission. A set of metrics was developed to monitor its performance. Figure 3 depicts the history of the subnet performance in terms of a percent data valid (PDV) metric. Although at the beginning of the mission the performance of the stations was not very good, by the end of the mission's in-orbit checkout period (the third quarter

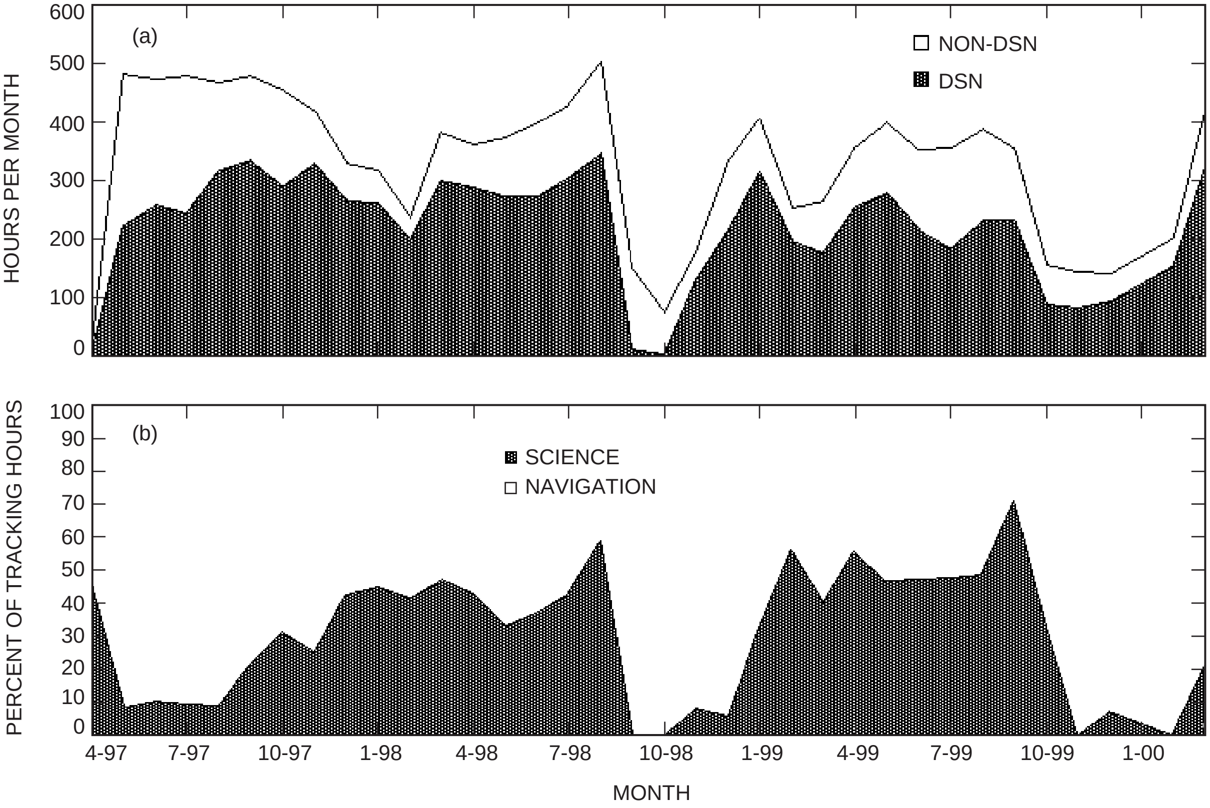

Fig. 2. History of VSOP operations support by the DSN 11-m antennas: (a) hours of support by DSN versus non-DSN stations and (b) percent of DSN stations' tracking time used for data reception (science, gray scale) and for navigation measurements (white).

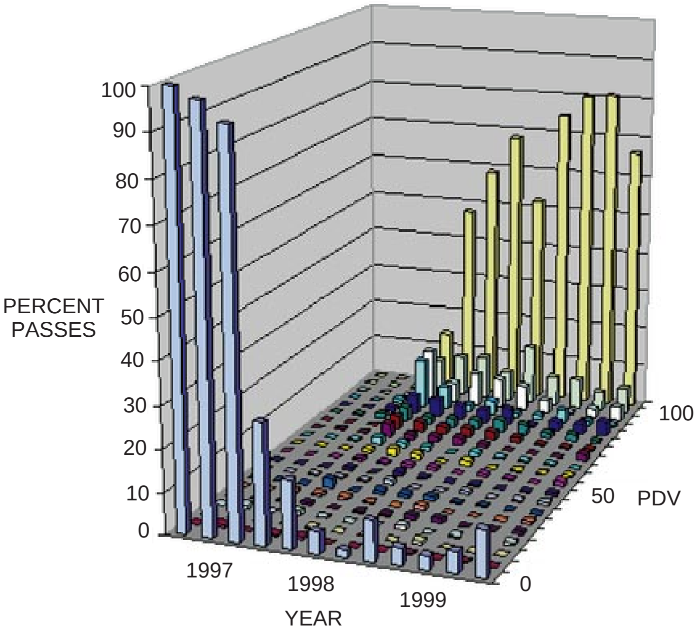

Fig. 3. History of the DSN 11-m network performance.

of 1997), it was significantly improved with ~50 percent of the passes having a PDV of >95 percent. (The project requirements for mission support is a PDV of >95 percent). Due to the significant efforts of the project and the DSN personnel, the performance of the network has gradually improved, reaching about 70 to 80 percent of tracks, which meets or exceeds the requirements (a PDV of >95 percent).

The high-quality navigation support provided by the JPL MMNAV system has been crucial to the success of the mission. The accuracy of the predicted and reconstructed orbit solutions provided by the MMNAV exceeded the requirements, which significantly simplifies spacecraft and Correlator operations.

B. DSN 70-m Co-Observing and Mission Science Operations

The DSN 70-m antennas are participating in the SVLBI co-observing along with other ground-based telescopes around the world. The DSN supported observations at one (L-band) of two of the VSOP operational bands—1.6 to 1.72 GHz (L-band) and 4.9 to 5.0 GHz (C-band). By the end of 1999, the L-band experiments accounted for about 20 percent of the VSOP program. The DSN time was allocated for co-observing on a noninterference basis with other flight projects supported by the DSN. Despite this, DSN L-band co-observing support was provided for more than 60 percent of the VSOP L-band observations (see Fig. 4). This fact shows the importance of the large 70-m antennas to the SVLBI mission (a majority of the ground-based telescopes that participated in co-observing with VSOP were in the 25-m-size class).

The performance history of the DSN 70-m antennas in terms of the percent data delivery (PDD) metric (the ratio of the duration of a recorded radio source signal to the time requested by the VSOP project) is given in Fig. 5.

The U.S. SVLBI Project Science Team provided significant input in two areas of VSOP mission operations: (1) two packages of simulation and scheduling software [6,7], which were used extensively during the mission for long-term planning and scheduling of the experiments, were developed and (2) assistance was provided in evaluation of the scientific output depending on the Earth-to-space interferometer configuration. An example of the output product of the simulation software is given in Fig. 6. Such plots—representing a graphical evaluation of the quality of the image of radio sources, depending on

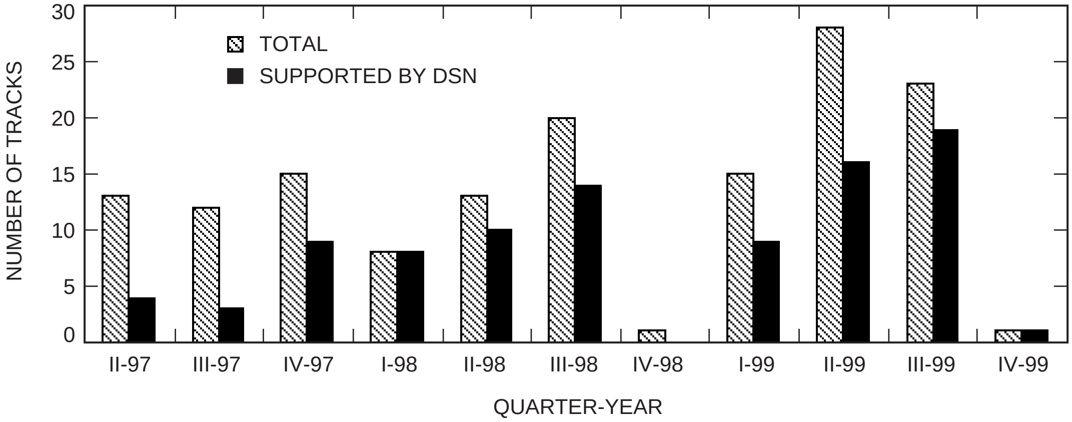

Fig. 4. History of the VSOP L-band co-observing support.

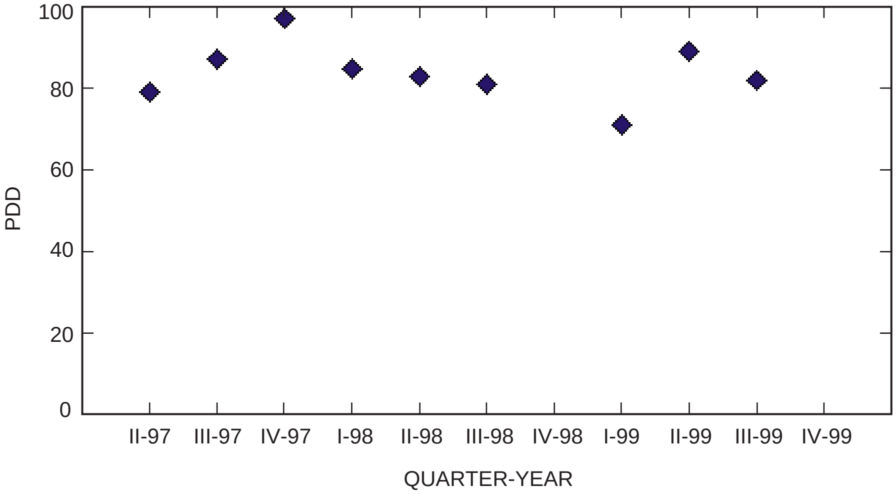

Fig. 5. DSN 70-m SVLBI co-observing performance.

the their positions in the sky, spacecraft orbit, and the configuration of the ground telescope network supporting the experiment—have been routinely used for mission operations planning. The all-sky plot (see Fig. 6) shows the zone of avoidance (~70 deg around the Sun) within which experiment planners (PIs) must not choose the target for observation in September 2001 and the UV coverage (the track of the projection of the interferometer baseline on the sky while the orbiting telescope is moving in its orbit), which characterizes the quality of the image that can be obtained, depending on the position of the source in the sky (the more dense the picture, the better the quality).

C. Project Special Operations

Aside from routine operations in support of the VSOP mission, a number of mission-critical events have been supported by the U.S. SVLBI Project.

Although the technique of frequency/clock synchronization through a radio link with the spacecraft was tested in the first Earth-to-space VLBI experiments with the Tracking and Data Relay Satellite System (TDRSS) [8] (performed in the mid-1980s), implementation of the technique at the DSN tracking stations needed to be verified. A set of extensive tests with a special satellite built by the U.S. SVLBI Project, the Summer Undergraduate Research Fellowship Satellite (SURFSAT-1), which carries onboard a transponder

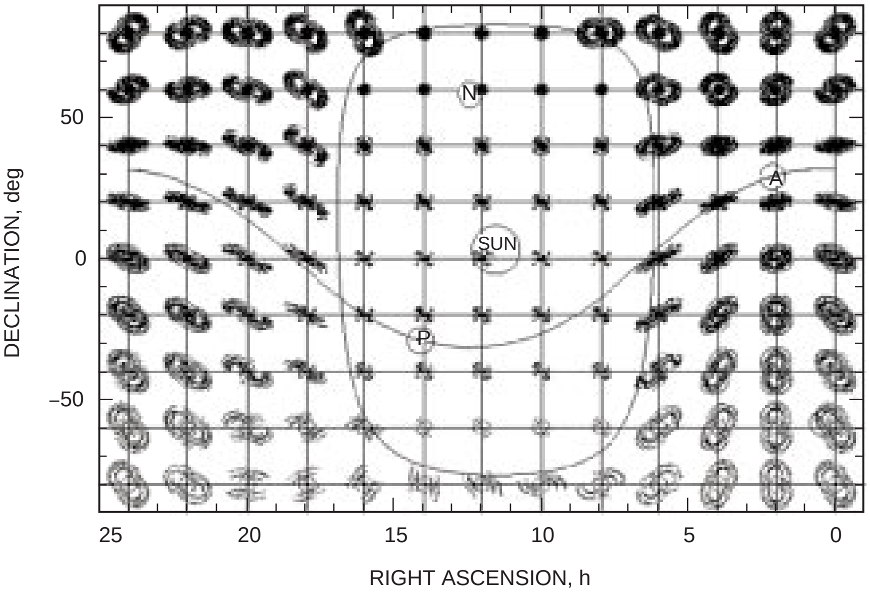

Fig. 6. Sky plot for the chosen Earth-to-space interferometer configuration in September 2001 (where "P" denotes the galactic pole, "A" the galactic antipole, and "N" the North Pole).

imitating the VSOP satellite, was performed prior to the launch of VSOP [9]. The test successfully demonstrated the readiness of the frequency/clock synchronization system at the DSN tracking stations and the VLBA (U.S.A.) and S-2 (Canada) correlators.

The VSOP mission in-orbit checkout continued for 6 months after launch. Checkout of the end-to-end performance of the Earth-to-space interferometer with the involvement of the SVLBI tracking network and ground-based telescopes began about 1.5 months after launch, after the space antenna was deployed and the spacecraft checkout was completed. The 11-m DSN subnet and DOTS supported the mission operations from the very beginning. Despite intensive pre-launch testing, the final tuning of the system (adjusting the science telemetry and frequency/clock synchronization systems) took a significant amount of time (∼4 months, see Fig. 3).

During its 3 years of operations, the HALCA spacecraft had a few emergency events that caused an interruption in observations lasting for a few months. During these periods, the DSN provided additional support with the DSN 26-m subnet operating in ∼2.3 GHz (S-band)—the VSOP spacecraft's communication channel. The 26-m DSN subnet support, including navigation measurements and spacecraft telemetry in S-band, proved to be crucial for successful recovery of the spacecraft. The DSN subnet tracked the spacecraft during the periods when it was not visible from the main spacecraft tracking station in Kagoshima. The results of the tracking were immediately made available by the DOTS to VSOP mission operations. The extended tracking coverage helped to determine the spacecraft status and maintain navigation, which ultimately shortened the nonoperational periods, and thus, increased mission efficiency.

VI. DSN Operational Support for Future SVLBI Missions

The JPL–DSN space VLBI mission operations segment (including the 11-m subnet and DOTS) was designed and built to support two missions: VSOP (Japan) and RadioAstron (Russia). Although the RadioAstron mission launch has been delayed, the development of the spacecraft and space radio telescope for the mission has significantly advanced in the last few years, and there is hope that the mission will be launched in the next 2 to 3 years. Aspects of RadioAstron mission operations are described in [10,11].

The prime differences between VSOP and RadioAstron that determine the differences in the mission operations are (1) a different orbit, (2) different communication channels for science data acquisition and frequency/clock synchronization, and (3) a different set of observing wavelengths and possible space radio telescope observing modes. All elements of the JPL–DSN space VLBI mission operations segment are capable of supporting the RadioAstron mission.

A few next-generation space VLBI missions are under consideration within different space agencies [12,13]. These missions plan to have significantly larger data rates (up to 8 Gb/s is envisioned) and to observe at higher frequencies (up to 86 GHz) to realize higher sensitivity and higher angular resolutions. The higher data rates will require a significant upgrade of the data-link electronics, including changes to support this link at higher frequency bands—37 to 38 GHz (Ka-band) and/or 74 to 84 GHz (W-band)—allocated to the Space Research Service to accommodate a few Gb/s data streams [14]. The ground-based telescopes with large (∼25- to 30-m class) high-precision apertures capable of operating at millimeter wavelengths will be needed to provide sufficient sensitivity of the Earth-to-space interferometer. It is essential for decreasing of mission operations cost that tracking and co-observing support operations for future space VLBI will be automated (unattended by operations personnel) as much as possible.

JPL and the DSN are uniquely suited to support the next-generation space VLBI missions. NASA's deep-space communication currently is evolving to exploit the Ka-band, which will provide the technology needed to develop the required wideband communication channels. The DSN 34-m-class antennas are capable of effectively operating at up to 100 GHz, thus providing the opportunity to support co-observing with future SVLBI missions. In the course of getting ready for and operating the VSOP mission, DOTS and the DSN 11-m subnet operations have been significantly automated, providing experience for upgrading to support future missions. The operations tools and knowledge that were developed will help to effectively operate the future SVLBI systems.

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