VSOP Operational Activities

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Chapter 1

BACKGROUND OF DOCUMENT

1.1 Purpose

The purpose of this document is to summarize mission-unique data formats and operational plans and to make this information available to the organizational elements supporting the space VLBI missions: VLBI Space Observatory Programme (VSOP) and RadioAstron. To a degree, the document is intended to provide only a general overview of the international aspects of the mission as there are many internal procedures that remain invisible to outside mission elements. As a result, we have attempted to concentrate on the interfaces among mission elements; providing, for example, details of the data products, format, and delivery requirements. It is the responsibility of involved agencies to maintain and document any procedures used to produce a product that will flow through an interface. This document concentrates on the operations related to the MUSES-B spacecraft, the VSOP mission, and the organizations that are involved. It is intended as a handbook for individuals who are involved in the space VLBI mission.

Throughout the document, some added emphasis may have been placed on space VLBI operations with respect to the U. S. Space VLBI Project at the Jet Propulsion Laboratory (JPL). This is a natural result since the two lead authors have significant more insight into space VLBI details at JPL than those that affect operations at the ground radio telescopes or at ISAS. Therefore, we are willing to expand or add to this document those areas that we may have neglected. In addition, if we have made incorrect assumptions in operations that we have little regular contact with, we would like to remedy the situation in future editions of the document. Suggested changes may be submitted according to the contact point listed in §1.3.3.

1.2 Document History

The document is based on discussions held during 1994–1996 by the authors and space VLBI individuals primary though e-mail, space VLBI work weeks, and working groups. It is intended that the document reflect the operational plans that are being revised, updated, or polished (especially as launch approaches), and so future revisions will be released when deemed necessary. Because the space VLBI mission involves international agencies, all of which are allocating varied resources, individuals who feel that significant changes to this handbook are needed should bring this to the attention to one of the authors.

The editions of this document are reflected in Table 1-1. The following changes have been made to Version 2.0:

- The overall presentation of the document is in a book manuscript format;

- The figures have been moved into the body of the text;
- The descriptions of the uplink and downlink processes have been greatly expanded:
- A number of data interfaces have been updated;
- Technical literature chapters have been added as appendices;

Table 1-1: Release Dates

Version	**Release Date**
2.0	11 March 1996
1.5	17 August 1995
1.4	22 March 1995
1.3	03 January 1995
1.2	nonexistent
1.1	19 October 1994
1.0	05 October 1994

1.3 Using This Manual

The structure of the document is relatively straightforward. A number of chapters, namely §2–§6, are devoted to an overview of the space VLBI mission elements. These chapters are intended to provide a short introduction to the mission elements and can be skipped by a more experienced reader. We have deliberately kept the overall description brief, choosing instead to direct the reader to a number of references for further inquiries.

Prelaunch and early mission activities are covered in §7–§8. These chapters include, for example, a description of launch activities (e.g. planned ΔV maneuvers) and a timeline of in-orbit-checkout. A description of the data flow for mission operations is given in §9. This chapter groups the products into uplink and downlink processes associated with each mission element and briefly outlines activities that will need to occur for a successful completion, from scheduling to correlation, of a space VLBI experiment. We have included this chapter as a lead-in to the more detailed description of the space VLBI data transfer processes described in §10. This chapter includes the format for all data products that are exchanged among mission elements and also presents the on-line and archive storage requirements for the mission. In future revisions of the document, this particular chapter will most likely be expanded upon, as it will contain computer sites, IP addresses, and directory trees from which to transmit and retrieve files.

The remainder of the document (§11–§15) concentrates on the data most closely associated with the mission elements. The products are grouped according to the agency responsible for its generation (although it is not always a clear separation). For each product, a description of the product, the generating mission elements, and delivery requirements are listed.

The document contains many acronyms, abbreviations, and references. Where possible, we have defined the acronyms and abbreviations at the first textual usage in the main body. However, especially in the case of figures, we have sometimes used abbreviations that have not already been defined in the text. As a result, the reader may wish to refer to Appendix A. References to existing documents from which this manual has obtained much of its information are given in Appendix B. The reader may also wish to consult these documents. And finally, we have also included in Appendix C, a listing a subset of the scientific literature that has been written on space VLBI, emphasizing the early demonstrations of the TDRSS experiments and the upcoming VLBI Space Observatory Programme.

1.3.1 Writing Conventions

We have attempted to highlight the first reference to an operational document or data interface by italics and underlines, (e.g. *"Detailed Document"*). These documents are also listed in Appendix B. Any additional references to these documents are then given by author and date, (e.g. Author Date). In a number of cases, interfaces are given in a table but are only shown as a sequence of letters and numbers. An example is MON-5-17 and TRACK in Table 10-2. Again, these are fully identified in Appendix B. Journal articles are referenced only by author and date (e.g. Author Date). To aid the reader in understanding what a data product is, they are put in bold face type, (e.g. **data product**), for the first textual usage in §9.

1.3.2 Electronic Access to Materials

Copies of this document as well as some (but not all) of those listed in Appendix B are available on-line at:

http://sgra.jpl.nasa.gov/mosaic_v0.0/JPL_Project_dir/memo_ps.html

or

http://sgra.jpl.nasa.gov/mosaic_v0.0/Operations_dir/IMOG_dir/IMOG_Documents.html

or

http://sgra.jpl.nasa.gov/mosaic_v0.0/Operations_dir/VSOG_dir/VSOG_Documents.html

The latest version of this document and its accompanying figures are also available as a *tar*-file and can by obtained by anonymous-ftp by typing:

```
% ftp sgra.jpl.nasa.gov
ftp> cd /pub/users/abw/ops
ftp> binary
ftp> get ops.tar
ftp> bye
```

Many figures have been included in this version, some of which describe various data flows or data contents. These figures may not appear if the reader obtains the LaTeX version of the document and has not also retrieved the figures and/or referenced them correctly inside of the LaTeX files. The PostScript version already contains all the figures.

1.3.3 Suggesting Changes

We ask that individuals using this document be aware that we have presented preliminary information that is based on what is currently known or available for the mission. As an example, some of the timelines and delivery requirements are only a prediction, and real-life operations might be similar or drastically different. We hope to continue updating the document as more details become known. We also acknowledge that there remain some details which have been neglected and need to be written, but at this time, still remain blank. To suggest changes or additions, please e-mail one of the authors at:

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Chapter 2

MISSION DESCRIPTION

2.1 Background of Space VLBI

The concept of performing Very Long Baseline Interferometry (VLBI) experiments involving a space-borne telescope has been considered seriously since the mid-1970s. Several missions, namely QUASAT (Schilizzi 1988) and IVS (European Space Agency 1991) have been proposed but have not been successful in getting approved by their respective space agencies. However, demonstrations of the viability of the concept and the potential science return were done using the TDRSS satellite in 1986–1988 (Levy *et al.* 1989; Linfield *et al.* 1989). Since then, two spacecraft dedicated to VLBI observations have been approved: VLBI Space Observatory Programme (Hirabayashi, Inoue, and Kobayashi 1991), led by the Institute of Space and Astronautical Science (ISAS) in Japan, and RadioAstron (Kardashev and Slysh 1988), led by the Astro Space Center (ASC), in Russia.

Space VLBI Timeline

- Late 1980s: QUASAT and IVS considered as possible space mission;
- Late 1980s: TDRSS satellite demonstrations;
- Late 1980s: VSOP and RadioAstron mission approved for launch;
- August 1995: VSOP Announcement of Opportunity issued;
- November 1995: VSOP proposals due;
- Late 1996: Tracking network on-line;
- September 1996: MUSES-B (VSOP) launch from Kagoshima on new M-V-1 rocket;
- January 1997: First guest observer data.

2.2 Technical Operations Support

The VSOP mission is a collaborative effort among many international organizations involved in radio interferometry. ISAS will launch an 8-m radio telescope into high Earth orbit in September 1996. The VSOP spacecraft, often referred to as MUSES-B, is shown in Figure 2-1. The spacecraft will be carried into orbit via the first flight of the M-V-1 rocket

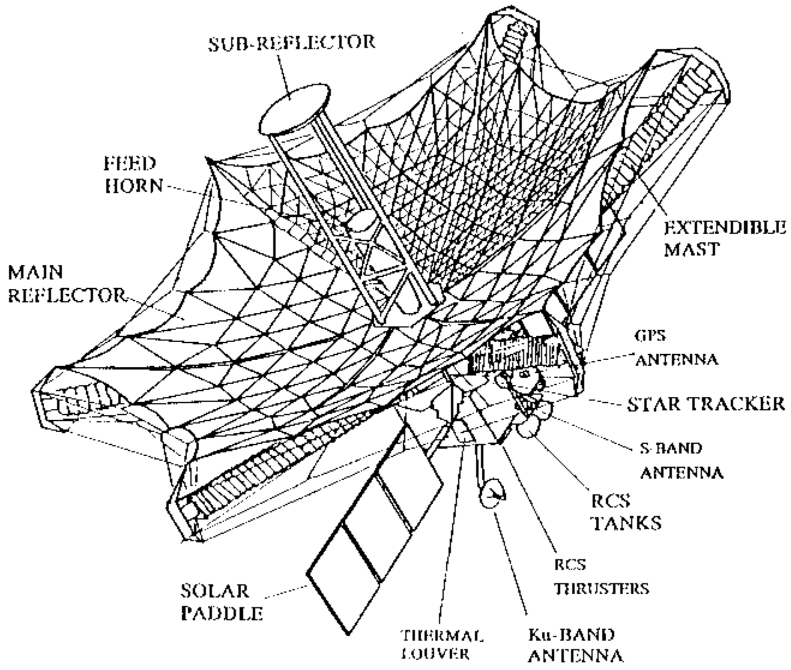


Figure 2-1: Schematic of the MUSES-B Spacecraft

(see Figure 2-2). The launch and subsequent commanding of the spacecraft will be from Kagoshima Space Centre (Japan).

A network of ground tracking stations in Australia, Japan, Spain, and the United States will track the spacecraft and record its wideband VLBI data. In addition to these tracking stations, tracking and navigation support during the initial orbit acquisition and in contingency cases (not including VLBI data recording) will involve the Deep Space Network (DSN) 26-m tracking stations. Tracking data from the Green Bank tracking station, operated by National Radio Astronomical Observatory (NRAO), and the 11-m DSN tracking stations, operated by the DSN, will be made available to the mission operations center at ISAS. The tracking data will contain information about the health and safety of the spacecraft and space VLBI experiment data.

Pre-pass and post-pass navigation data will be exchanged between the two navigation groups at ISAS and JPL. Time commitments from networks of ground radio telescopes (GRTs) and VLBI arrays will enable meaningful co-observations with the spacecraft of radio sources. Processing, or correlation, of the data products initially will take place primarily at NRAO's VLBA correlator and at the VSOP correlator. The S2 correlator funded by the Canadian Space Agency (CSA) will also be used; after its completion in 1998. The correlator of the Joint Institute for VLBI in Europe (JIVE) will participate as

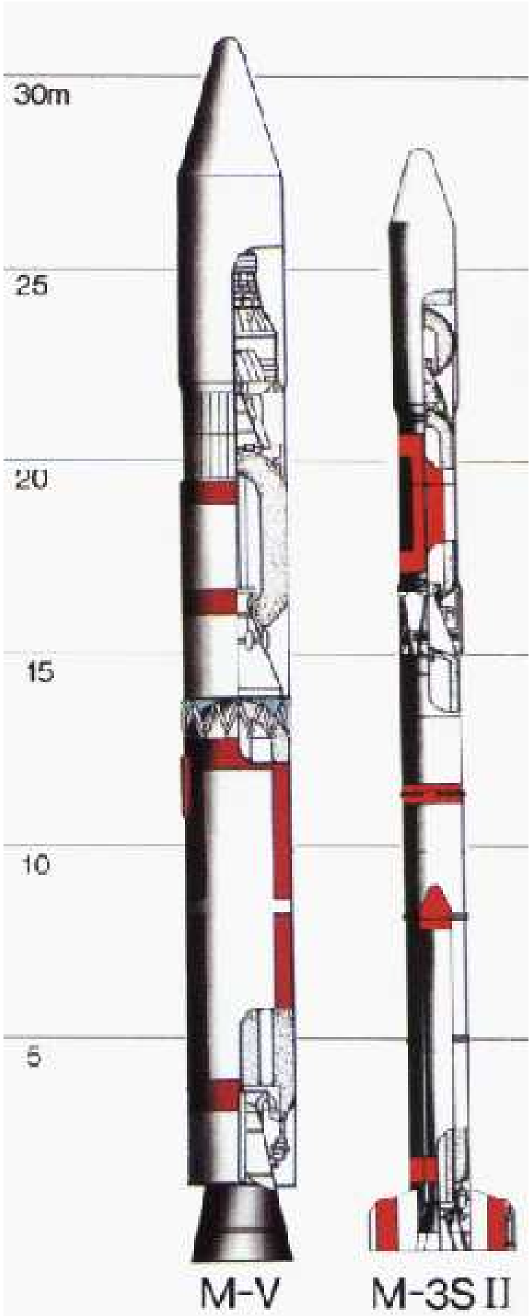


Figure 2-2: Schematic of the M-V-1 and M-3S II Rockets

well. Table 2-1 shows the characteristics of the VSOP mission.

Table 2-1: MUSES-B Mission Characteristics

Item	**Characteristics**
Communications	
Command, Telemetry, Range, & Doppler Data	Kagoshima Space Centre
Early Orbit & Contingency	DSN 26-m Subnet
Science Acquisition, Phase Link, & Doppler Data	DSN 11-m Subnet
	10-m Usuda (ISAS)
	14-m Green Bank (NRAO)
Frequency	
Command, Early Orbit, & Contingency	Uplink 2.1 GHz
	Downlink 2.3 GHz
Science Acquisition, Phase Link, & Doppler Data	Uplink 15.3 GHz
	Downlink 14.2 GHz
Launch System	
Cargo	MUSES-B
Date	September 1996
Rocket	ISAS M-V-1
Nominal Orbital Elements	
Apogee Altitude	19,500 km
Inclination	31°
Lifetime	3 yrs
Perigee Altitude	1,000 km
Period	5.93 hr
Spacecraft Mass	831 kg
Telemetry	Real-time 128 Mbps

2.3 Mission Phases

The VSOP mission is divided into four phases during which different kinds of mission operations will be conducted. The first phase is the Launch Phase which begins several weeks before launch and ends with the injection of the spacecraft into orbit. The second phase is the Spacecraft Checkout Phase, which will be a detailed on-board checkout and verification of the spacecraft's systems. The third phase is the Space-Ground Checkout Phase during which the spacecraft's receivers are tested in conjunction with several ground radio telescopes. This testing period will involve continuum and spectral line observations of astrophysical sources and may last 6 or more months. Following the satisfactory conclusion of the space and ground systems checks, the Observational Phase will commence, during which continuous routine observations by the astronomical community will take place. This will comprise remaining lifetime of the VSOP mission with periodic engineering and calibration monitoring of performance of the spacecraft.

2.4 Mission Objectives

The VSOP spacecraft was first chosen as an engineering test-bed mission; and later, along with extensive cooperation by other international agencies, evolved to become an astrophysics spacecraft. The primary *engineering objectives* are:

- Deploy and measure accuracy of large mesh antenna;
- Obtain high stability phase link;
- Downlink, record, and process wideband data transmission;
- Obtain high accuracy attitude control for flexible structure;
- Obtain high accuracy orbit determination for VLBI observations.

The spacecraft will be designated an astrophysics mission, following the completion of the engineering goals listed above, and as a result, will become the first dedicated space VLBI spacecraft. The space radio telescope will co-observe with many of the world's ground radio telescopes utilizing the principles of VLBI to probe the inner engines of active galactic nuclei (AGN) and to conduct spectral observations of maser sources. The primary *scientific objectives* of the VSOP mission are:

- High-resolution imaging of AGN;
- Monitoring of structural changes in superluminal sources;
- High brightness temperatures surveys of AGN;
- Measurement of proper motion as a function of redshift in AGN;
- Distribution of spot sizes in H_2O and (possibly) OH masers;
- Measurement of distances to external galaxies using H_2O maser motions.

2.5 Mission Duration

The VSOP spacecraft does not have the capability to be retrieved from orbit in the event of a major malfunction. Its power production relies entirely on solar-powered paddles and batteries. The degradation of the solar cells will constrain scientific observations later in the mission lifetime. Hence, the primary mission is expected to last $\sim$3 years, with reduced operations for up to $\sim$5 years.

Chapter 3

SPACE VLBI MANAGEMENT RESPONSIBILITIES

The success of the VSOP mission depends on many international agencies, each of which has its own governing body. Many of the detailed responsibilities are further discussed in *"Operational Responsibilities for VSOP"* (Ulvestad and Hirabayashi 1994). The following sections summarize the general management structure as shown in Figure 3-1.

3.1 Institute of Space and Astronautical Science

ISAS is responsible for the following:

- Overall coordination and direction of the VSOP mission;
- Provision of a M-V-1 launch vehicle to inject the spacecraft into orbit;
- Management and operation of the Usuda 10-m tracking station and Usuda 64-m radio telescope;
- Launch operations and subsequent commanding and monitoring of the spacecraft;
- Provision of orbits for planning, tracking, and for the VLBI correlators.

3.2 Jet Propulsion Laboratory

JPL is responsible for the following:

- Management and operation of the DSN 11-m tracking stations;
- Management and operation of the DSN 70-m antennas;
- Provision of DSN 26-m support during the early phases of the mission;
- Provision of orbits for tracking and for the VLBI correlators;
- Project and system management associated with the U. S. involvement in space VLBI.

3.3 National Radio Astronomy Observatory

NRAO is responsible for the following:

- Management and operation of the Green Bank 14-m tracking station;
- Management and operation of the NRAO telescopes;
- Correlation of space VLBI experiments at the VLBA correlator;
- Provision of space VLBI data analysis support to U. S. scientists.

3.4 National Astronomical Observatory

The National Astronomical Observatory (NAO) is responsible for the following:

- Management and operation of radio telescopes in Japan;
- Correlation of space VLBI experiments at the VSOP correlator;
- Provision of space VLBI data analysis support to scientists;
- Provision of tape translation facilities.

3.5 Joint Institute for VLBI in Europe

JIVE is responsible for the following:

- Management and operation of European VLBI Network (EVN) telescopes;
- Correlation of space VLBI experiments at the JIVE correlator.

3.6 Canadian Space Agency

CSA is responsible for the following:

- Provision and maintenance of S2 recorders to GRTs and tracking stations;
- Correlation of space VLBI experiments at the Canadian S2 correlator.

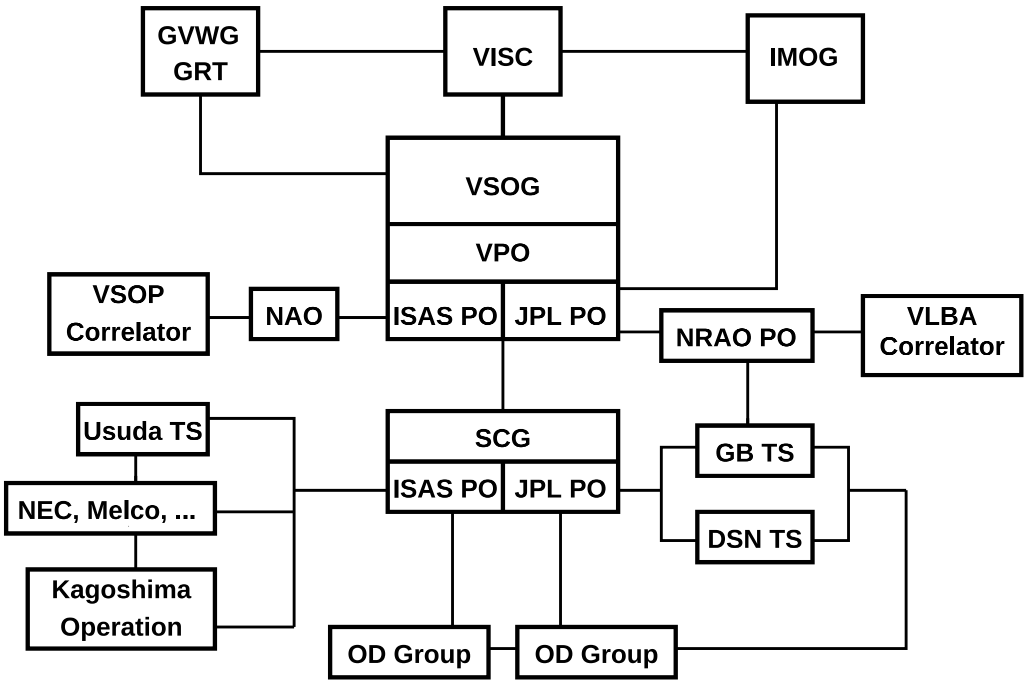


Figure 3-1: Space VLBI Project Structure

Chapter 4

MISSION OPERATIONS GROUND SUPPORT

The overall mission operations support configuration has been shown in Figure 3-1. These groups and their responsibilities are described in the following sections.

4.1 Global VLBI Working Group

The Global VLBI Working Group (GVWG) represents many of the world's ground radio telescopes in negotiations with the VSOP mission related to space VLBI issues. These negotiations have resulted in time commitments from the ground radio telescopes to space VLBI experiments (see §6.3 and Table 6-2).

4.2 International Mission Operations Group

The International Mission Operations Group (IMOG) is responsible for the planning and development of interface agreements that are necessary for mission elements to carry out the day-to-day operations (see *"IMOG Charter"* (IMOG 1994)). This group contains members from many of the major operational elements associated with the space VLBI mission. Correlator interfaces (e.g. merged correlator input log files and time corrections files) and provision of telemetry headers have been primarily negotiated within this group.

4.3 Navigation Groups

Two navigation groups will provide most of the support for VSOP. Both will be responsible for providing predicted orbits and reconstructed orbits. The DSN Multi-mission Navigation Team at JPL is responsible for providing a predicted orbits to the DSN and NRAO tracking stations and a reconstructed orbit to the VLBA correlator. The second group, at ISAS, is responsible for providing the same data to the tracking stations in Japan and the Mitaka correlator. Other correlators may choose to use either the JPL or ISAS reconstructed orbit. In addition, National Space Development Agency (NASDA) will provide ISAS with a planning orbit using data acquired from the Kagoshima command station. Both groups will exchange navigation-related data to produce an optimal data product. The reconstructed orbits delivered to the correlators may differ in accuracy as they are derived using different solar pressure models.

4.4 Satellite Control Group

The Satellite Control Group (SCG) at ISAS is responsible for operating the spacecraft and ground system consoles to initiate spacecraft command uplink and to monitor the status of the spacecraft engineering systems. The uplink of the command file will occur about once per day (or every 4 orbits) from the Kagoshima Space Centre. Monitoring of the spacecraft will occur in near-real-time as the telemetry headers are captured at each tracking station and then made available to the SCG. The SCG is also responsible for the evaluation of the spacecraft performance, trend analysis, and investigation of spacecraft anomalies.

4.5 VSOP Science Operations Group

The VSOP Science Operations Group (VSOG) at ISAS is responsible for the global space VLBI operations. The group's responsibilities include scheduling of mission resources such as ground radio telescopes and tracking stations, analyzing telemetry and space VLBI data for performance and calibration of the space radio telescope, and packaging space VLBI auxiliary data needed by the correlators. The group is also responsible for monitoring and analyzing the performance of the on-board science bus and payload.

Chapter 5

SPACECRAFT DESCRIPTION

5.1 MUSES-B

Table 5-1 lists the characteristics of the MUSES-B spacecraft. In the launch configuration, the spacecraft will be stowed in an area approximately 2.7 meters in length and 2.2 meters in diameter. The deployment of the mesh antenna and measurement of its surface accuracy will be one of the first engineering goals of the mission. The extendible mesh design of the antenna will be deployed in a hexagonal shape about 10 meters in diameter (an equivalent aperture diameter of 8 meters). More information on the deployment sequence can be found in Natori *et al.* (1994). The mass of the antenna is approximately 30% of the 831-kg spacecraft mass budget. The spacecraft will be powered by silicon solar cells on two deployable 7-m^2 solar paddles. These paddles will provide about 700 W of electrical power, degrading by about 5% per year. During the first year of the mission, the power budget will permit observing at times when the spacecraft is not in eclipse. After the first year or two, the power budget will place progressively more severe restrictions on observations. Reaction wheels will be used to slew the spacecraft; their accumulated angular momentum will be dumped by use of magnetic torquers near perigee. The expected nominal lifetime of the spacecraft is 3 years.

5.2 Instrument Module Overview

The 8-m radio telescope operates with three receivers at the Cassegrain focus. All receivers detect left-circular polarization only. Nominal bandpasses are 1.60–1.72 GHz, 4.7–5.0 GHz, and 22.0–22.3 GHz. Local oscillators are tunable to enable observations within the entire frequency range of each band, with allowed oscillator settings at intervals of 1.0 MHz. All frequencies on the spacecraft are locked to a hydrogen maser at the operative tracking station by means of a tone sent up from the ground. Two-way frequency measurements of that tone are used to correct time and frequency errors at the correlator and to extract Doppler information. The antenna aperture efficiencies at 1.6, 4.8, and 22.2 GHz are expected to be 38%, 54%, and 47%, respectively. Respective system temperatures are predicted to be 100, 120, and 200 K. There are three possible observing modes, two with 32-MHz channelization and one with 16-MHz channelization. Only the last mode is compatible with the majority of the world's radio observatories. It consists of two 16-MHz channels, which may be contiguous or well-separated within a band (or at different bands), each of which is sampled at the Nyquist rate and digitized with two bits per sample. The 128 Mbps of data are divided into 640-kbit blocks and downlinked at 14.2 GHz. Each block has 12 bytes of VLBI data replaced by header data containing synchronization codes as well as spacecraft telemetry that is used for monitoring and calibration purposes.

Table 5-1: MUSES-B Characteristics

Item	**Description**
Attitude Control	3-N Thrust Engines (8) Orbit transfer and emergency use only Reaction Wheel (4) Magnetic Torquers (3)
Attitude Sensor	Acceleration Sensor (2) Geomagnetic Aspect Sensor (2) Gyroscopes Mechanical (4) Optical Fiber (1) Star Trackers (2) Sun Sensors (6)
Attitude Specification Pointing Accuracy Pointing Constraints	 $36''$ $288° <$ Sun angle $< 72°$
Data Storage Housekeeping Data Science Data	 25m36s @ 8 kbps mode 3h24m28s @ 1 kbps mode 13h39m12s @ 256 bps mode Real-time @ 128 Mbps
Deployed Antenna Maximum Diameter Physical Area Shape	 10 m 50 m^2 Hexagonal
Global Positioning System	
Low Gain Antenna Diameter Downlink FWHM Uplink	 45-cm Parabolic dish on deployable boom 14.2 GHz 4° (−5 dB @ 14.2 GHz) 15.3 GHz
On-Board Computers	Attitude Control System Data Handling Unit Global Positioning System Ku-Antenna Control System Star Trackers
Power	Solar Array (2) 700 W, 5% degradation per yr
Space Radio Telescope Observing Bands System Temperatures Polarization 7-σ Flux to VLBA Antenna	 1.6, 4.8, and 22 GHz 100, 120, and 200 K Left Circular Polarization 90, 110, and 450 mJy
Stowed Configuration Diameter Length	 2.2 m 2.7 m
Mass	831 kg

MISSION ELEMENTS

Ground-based radio interferometric observations require an array of ground radio telescopes to observe the scientific target and a correlator to processes the VLBI data. By placing a radio telescope in space, additional support from a network of tracking stations is needed to provide a stable reference clock to the spacecraft and to record the data received by the orbiting element. Table 6-1 and Table 6-2 list the participating space VLBI mission elements.

6.1 Ground Tracking Stations

A network of five tracking stations will be used to provide the two-way phase link necessary to receive precise timing, navigation, and tracking-related data. In addition, these tracking stations will receive and record the wideband VLBI data from the VSOP spacecraft on VLBI tapes that are shipped to the correlators. The nearly 6-hr orbit of the spacecraft translates into tracking sessions ranging from a few minutes to 4–5 hours at each tracking site. A typical tracking pass will last approximately 3 hours. The selection criteria of tracking passes (since there may be some overlap between tracking stations) will be to maximize the tracking coverage for a particular station. However, tracking passes as short as a few minutes are critical for reconstructed orbit analysis and must be included when designing the optimal tracking schedule. Operational constraints such as staffing limitations and availability of correlators and auto-correlators will also impact the tracking schedule. The orbital precession and period will cause the tracking load to vary from day to day and throughout the year at each site, both in terms of total hours of tracking and time of day when tracking is necessary. An analysis of the tracking station selection process is given by Ulvestad *et al.* (1995a) in *"Rules for Scheduling of Tracking Stations for VSOP"*.

6.1.1 Deep Space Network 11-m Tracking Stations

NASA is building three new 11-m antennas, one at each DSN complex in Australia, Spain, and the United States to support the space VLBI missions. Collectively, these tracking stations are referred to as the Orbiting VLBI Tracking Subsystem or OTS. The 11-m stations are fully automated and will be scheduled through the Network Support Subsystem (NSS) located at JPL. It is intended that these 11-m tracking stations will be initially dedicated to supporting VSOP and RadioAstron but may also provide support for additional spacecraft some time in the future. The capabilities of these stations are discussed in *"Design Requirements, DSN Orbiting VLBI Subnet,"* (JPL 1993). Data from the OTS is transmitted to the Ground Communications Facility (GCF) at JPL. The tracking and navigation data is normally kept on-line for 4 days, and off-line for 30 days after which it is deleted.

Table 6-1: Ground Tracking Stations and Correlator Facilities

Mission Element			
Tracking Stations	Agency	Recorder	On-line
Goldstone, California, USA	NASA	VLBA, (S2?)	1995
Green Bank, West Virginia, USA	NRAO	VLBA	1995
Madrid, Spain	NASA	VLBA, (S2?)	1996
Tidbinbilla, Australia	NASA	VLBA, (S2?)	1996
Usuda, Japan	ISAS	VLBA, VSOPT	1996
Correlators	Capacity	Playback	On-line
EVN-JIVE, Dwingeloo, Netherlands	16	Mrk IV	1998
S2, Toronto, Canada	6	S2	1996
NRT Usuda, Usuda, Japan	2	VSOPT	1996
VLBA, New Mexico, USA	20	VLBA	1994
VSOP, Mitaka, Japan	10	VSOPT, copiers	1996

Retrieval of this data and further processing of it will by done by the U. S. Space VLBI Project to meet the IMOG specifications. Navigation data will be transmitted directly to the JPL Multi-mission navigation team for processing.

6.1.2 Green Bank 14-m Tracking Station

NASA has funded refurbishment of a 14-m antenna and construction of a fourth U. S. tracking station at the NRAO facility at Green Bank, West Virginia; this station was the first station to be proposed, funded, and built for space VLBI. Like the DSN 11-m tracking stations, it is fully automated and dedicated to space VLBI. The only staffing requirement is an operator to mount and dismount the VLBI tapes and to respond to emergencies. A comprehensive overview of this facility is available in *"Green Bank Earth Station Critical Design Review"* (D'Addario *et al.* 1992).

6.1.3 Usuda 10-m Tracking Station

ISAS has constructed a new 10-m antenna in Usuda, Japan to enable tracking of the VSOP spacecraft. The Usuda tracking station is not fully automated and hence its tracking activities will be constrained by limited staffing resources. This tracking station will be dedicated solely to support of the VSOP mission.

6.2 Correlation Facilities

Two VLBI correlators will process the bulk of the space VLBI data early-on in the mission. These are the VSOP correlator at NAO in Mitaka and the VLBA correlator at NRAO in Socorro. The EVN-JIVE correlator at the Netherlands Foundation for Research in Astronomy (NFRA) in Dwingeloo and the Canadian S2 correlator are expected to participate when they become operational. Each correlator uses playback drives from a single type of wideband recording system; the VSOP correlator will also have the capability to copy S2 and VLBA tapes to the VSOPT tape format. The correlator hardware and software are currently being configured to accept spacecraft trajectory data (reconstructed orbit) and time corrections files. The correlators also must be capable of accommodating the larger delays and delay rates associated with baselines to a space VLBI element.

6.2.1 EVN-JIVE Correlator

The EVN-JIVE correlator is based on the Mrk IV data acquisition system, and will be capable of cross-correlation of 16 stations simultaneously. Projected completion date is 1997–1998, (a year or more after launch of MUSES-B). It is planned that the EVN-JIVE correlator will accommodate data recorded on S2 recording systems, either via direct playback or by tape-copying to Mrk IV tapes. If so, this will be the only correlator capable of processing space VLBI experiments involving S2-equipped Australian telescopes and large numbers of telescopes in the Northern Hemisphere (e.g., VLBA or full EVN). Until the EVN-JIVE correlator is fully operational for space VLBI experiments, there will be no facility available to process VSOP experiments involving large numbers of Northern and Southern Hemisphere telescopes without extensive tape-copying.

6.2.2 S2 Correlator

The S2 correlator is being developed at the Dominion Radio Astronomical Observatory (DRAO), funded by the National Research Council of Canada. This correlator will have six playbacks, thus being capable of correlating experiments involving VSOP and five ground radio telescopes in a single pass. The correlator is based on the S2 record and playback system developed at the Institute for Space and Terrestrial Science (ISTS) in Toronto, Canada. The projected completion data is late 1996 or 1997.

The S2 VLBI recorder developed at ISTS is a high-speed digital data recorder which can record and play back wideband digital data at rates up to 128 Mbps. The S2 consists of two “transport array” modules which house eight industrial-grade video transports, each transport capable of 16 Mbps operation, and an “electronics” module which provides user interface and data handling electronics. The current unattended operating time (time between tape changes) is up to 8.5 hours at 128 Mbps. The S2 uses standard, commercially-available, low-cost S-VHS tapes. Plans are underway to place S2 recorders at one or more DSN 11-m tracking stations by VSOP launch. Two versions of the S2 recorder exist, the S2 Record Terminal (S2-RT) and the S2 Playback Terminal (S2-PT). These two versions are identical in all respects, except that the S2-RT is housed with only a single decoder and deformatter module used for data decoding and diagnostics during recording; the S2-PT contains the full complement of eight decoder modules for full data playback capability. All S2-PT’s have the ability to record as well, enabling their use for general recording purposes and at tape copy machines.

6.2.3 VLBA Correlator

The VLBA correlator, in Socorro, New Mexico, has a 20-station capacity and includes 24 playback drives for enhanced efficiency. There are no tape-copy facilities, so the VLBA correlator can only process data from space VLBI experiments if it is recorded using the VLBA or Mrk IV data recording systems. Because of its large capacity, the VLBA correlator will be capable of processing experiments involving as many as nineteen ground telescopes cross-correlated with the spacecraft in a single pass through the correlator. NRAO has committed the correlator for processing of all experiments involving NRAO telescopes, including the Very Large Array (VLA), or Very Long Baseline Array (VLBA), and both the 43-m and 100-m telescopes at Green Bank. In addition, NRAO has committed the correlator for processing up to 20 days of experiments involving EVN ground telescopes, with the assistance of EVN-JIVE personnel. Requests for additional correlator time will be considered on a case-by-case basis.

6.2.4 VSOP Correlator

The VSOP correlator is based on the VSOP recording and playback system; only VSOPT-format tapes can be accommodated with this correlator. It has a 10-station capacity. The correlator also will have two VLBA-to-VSOPT tape copy units and one S2-to-VSOPT tape copy unit, each incorporating a VLBA playback drive or an S2 playback unit. The same VSOPT recorders will be used both for correlation and for tape-copying, so it is unlikely that the two activities will occur simultaneously. The limited number of playback drives means that the VSOP correlator will be capable of processing only those experiments that utilize a small number (i.e. less than 10) of radio telescopes. For example, it will likely process experiments that involve co-observing by telescopes in Japan and Australia.

6.2.5 Usuda Near-Real-Time Correlator

Rapid searching for fringes may take place on calibration observations involving the radio telescopes in Japan and the Usuda tracking station by using the Usuda near-real-time correlator. This is vital for rapid assessment of the ability to detect fringes on a space-ground baseline, and can be used as a check for detecting fringes on routine space-ground observations or during contingencies. Use of this correlator requires simultaneous tracking by the Usuda tracking station and co-observing by the Nobeyama or Usuda ground radio telescopes.

6.3 Ground Radio Telescopes

Ground radio telescopes must observe simultaneously with the VSOP spacecraft in order to form the space-ground interferometers. Telescopes of the 25-m class or larger are needed in order to provide the required sensitivity on the baselines to the spacecraft; (the longest projected baseline will be 2.6 Earth diameters). The scientific goals of the experiment and capabilities of spacecraft and radio telescope will generally dictate the arrays of telescopes that will participate in an experiment.

In general, the observatories prefer to grant their time in fairly large blocks, almost always 12 hours in duration or longer. Many prefer blocks of several days or even weeks. The most efficient scheduling for the spacecraft would make use of small blocks of time, which may leave the GRTs with other small blocks that could not be allocated. The final method of time allocation and how the unscheduled blocks are "counted" for or against the space missions is still to be determined.

The preliminary commitments of the ground radio observatories have been detailed in the minutes of the meeting of the GVWG held at Onsala Observatory in 1993 (Booth and Preston 1993) and range from 3–30% depending on the observatory. Some observatories or networks have retained option of granting additional time if the overall proposal quality is very high. This will be known after the proposal deadline in November 1995 and will be reevaluated by the end of February 1996. Table 6-2, a subset of information contained in *"Proposer's Guide VLBI Space Observatory Programme"* (VSOP Science Operations Group 1995) (see Table 8 in particular) lists participating ground radio telescopes and number of their characteristics. The time commitments of each radio telescope may vary due to proposal pressure and these values listed in Table 6-2 should be considered preliminary. For example, the Green Bank time commitment has been recently increased to 14%, a doubling of allocated days to space VLBI.

6.4 Wideband Data Compatibility

The tracking stations, correlators, and ground radio telescopes rely on a number of different recording and playback equipment, based on the VLBA, Mrk IV, VSOPT, or S2 systems. Although all this equipment is capable of recording and processing (at minimum) the common international VSOP observing mode, the systems are not inter-operable. Except for the mutually compatible Mrk IV and VLBA systems, each correlator can play back only data recorded on a single type of system. This leads to a situation wherein it is not possible for all desired combinations of ground telescopes to co-observe with the spacecraft. The compatibility problem is being addressed to a certain extent by the use of tape-copy machines or multiple recording systems in some radio observatories and tracking stations. A complete analysis of the possible combinations of mission elements is beyond the scope if this document, but may be inferred by using the appropriate columns of Table 6-1 and Table 6-2.

Table 6-2: Ground Radio Telescopes and VLBI Networks
(from VSOP Science Operations Group 1995, p. 17.)

GRT	**Location**	**Dia.** (m)	**1.6 GHz** SEFD (Jy)	**5.0 GHz** SEFD (Jy)	**22 GHz** SEFD (Jy)	**Recorder**	**%**
Arecibo	Puerto Rico	305	2.5	3.5	—	S2	4
EVN:	...	...	...	...	...	...	...
Effelsberg	Germany	100	19	44	127	VLBA,Mrk IV	11
Jodrell	UK	76	44	—	—	Mrk IV	~5
Jodrell	UK	26	—	320	910	Mrk IV	10
Medicina	Italy	32	1176	284	1084	Mrk IV	20
Metsahovi	Finland	14	—	—	2600	VLBA	25
Noto	Italy	32	784	187	1225	VLBA	15
Onsala	Sweden	20	—	—	1597	Mrk IV	5
Onsala	Sweden	25	394	1000	—	Mrk IV	20
Shanghai	China	25	1176	467	2419	VLBA,S2	25
Simeiz	Ukraine	22	1848	3036	1000	Mrk IV?	15
Torun	Poland	32	240	240	—	Mrk IV	15
Urumqi	China	25	990	934	2419	Mrk IV?,S2?	25
WSRT	Netherlands	14x25	120	108	—	Mrk IV	15
Goldstone	USA	70	49	—	65	Mrk IV	11
Green Bank	USA	43	75	130	400	VLBA	<8
Hartebeesthoek	South Africa	26	420	970	—	Mrk IV,S2?	UN
Hobart	Australia	26	550	550	1500	S2	10
Kashima	Japan	34	231	365	1356	VSOPT,Mrk IV	UN
Madrid	Spain	70	49	—	65	Mrk IV	11
Mopra	Australia	22	350	450	1000	S2	25
Narrabri	Australia	6x22	60	80	170	S2	~5
Nobeyama	Japan	45	—	—	217	VSOPT,VLBA	~10
Parkes	Australia	64	50	90	600	S2	~5
Tidbinbilla	Australia	70	49	—	65	Mrk IV,S2	11
Usuda	Japan	64	69	69	?	VSOPT,VLBA	UN
VLA-27	USA	27x25	13	14	78	VLBA	<3
VLBA	USA	10x25	298	296	930	VLBA	30

PRELAUNCH READINESS AND LAUNCH OPERATIONS

7.1 Prelaunch Readiness

Acceptance testing of individual mission elements is currently in progress and will not be discussed in detail here. Several different types of activities have been identified by individual groups to test parts of the space VLBI process. These include the use of SURFSAT-1[1] as a tool to test the DSN and Green Bank tracking stations, reprocessing of the TDRSS space VLBI tapes by the VLBA correlator, and ground radio telescope experiments that test the tape-copying facilities at the Mitaka correlator. Ultimately, an end-to-end verification is necessary to ensure system readiness prior to launch and it has been documented in *"International Operations Test Plan for VSOP"* (Ulvestad and Murata 1995). With respect to the data flow process, a simulated 42-day period in the life of the VSOP mission has been completed (see *"Six-Week Time Line: Data Products"*, Wiercigroch 1996b).

7.2 Launch Operations

7.2.1 Launch Site

The VSOP spacecraft will be launched (currently scheduled for September 1996) and commanded from the Kagoshima Space Centre, which is located in the district of Uchinoura, Japan. The facility is located on the southern tip of Kyushu, the southernmost of the four main islands of Japan. During operations, a 20-m antenna will be used to provide an uplink to the spacecraft approximately once per day. This station also will receive telemetry describing the spacecraft performance, including the trajectory vectors derived by the on-board GPS receiver. The frequencies for the transmission of S-band range rate telemetry and commands are 2084.4 MHz (uplink) and 2263.6 MHz (downlink). The command sequence will be generated at ISAS by the SCG, and sent to the Kagoshima Space Centre for uplink to the spacecraft in real-time.

7.2.2 Launch Vehicle Description

The MUSES-B launch vehicle will be the M-V-1 rocket developed by ISAS. This will be the first of a number of launches using M-V-1 rocket. The rocket, as shown in Figure 2-2, has

[1] SURFSAT-1 is a student-built spacecraft that was launched on November 4, 1995. For more information, consult http://sgra.jpl.nasa.gov/html_surfsat/SURFSATHomePage.html.

three solid-fueled stages plus a solid-fueled apogee kick motor. The rocket is 31 meters in length and its payload faring is 2.5 meters in diameter. The mass of the rocket is 130,000 kg and the mass of the solid propellant is 70, 30, and 10 Mg for each stage respectively.

7.2.3 Launch Sequence of Events

The launch sequence of events is shown in Table 7-1 (Ichikawa 1995). The actual timeline will change as the launch date approaches. The injection of the spacecraft will be into an elliptical orbit with an apogee altitude near 19,500 km and a perigee altitude of 215 km. The perigee height will be raised in four maneuvers to a value of 1,000 km. The orbit inclination will be 31°. The initial argument of perigee will be approximately 105° (apogee in the South), but this element will precess with a period of approximately 1.2 years, (depending on the final orbit achieved), over which apogee will move from South to North and back again.

Table 7-1: MUSES-B/M-V-1 Sequence of Events
(from Ichikawa 1995.)

Day	Event
1	Lift-off
	Nose faring opened
	Satellite separation
	Satellite spin down
	ANC
	Spin sun acquisition
	Rate damping
	Solar paddle deployment
	Ku antenna deployment
	−Z-axis sun acquisition
	Initial attitude establishment
	X, Y, Z-axis attitude determination at KSC
	Tracking data acquisition
	Attitude control
	Y-axis normal to ecliptic plane
	Tracking data acquisition
2	Attitude control for ΔV
	ΔV1
	Reaction wheel runup
	Tentative attitude determination
	Reaction wheel control start
	Star tracker mapper data acquisition
	Tracking data acquisition

MUSES-B/M-V-1 Sequence of Events - cont'd

Day	**Event**
3	Star tracker mapper data acquisition Attitude determination Star identification
4	Initial three axis attitude establishment Tracking data acquisition On-board bus instruments check
5	ΔV2 Tracking data acquisition
6	On-board bus instruments check Tracking data acquisition
7	ΔV3 Tracking data acquisition
8	On-board bus instruments check Tracking data acquisition
9	ΔV4 Tracking data acquisition
10	On-board bus instruments check Tracking data acquisition
11	Large antenna prehead attitude Antenna subreflector extension Attitude control ($-$Z sun direction)
12	Antenna support extension Main reflector deployment
13–14	Observation instruments function checkout (functional check phase end)
15–TBD	(adjustment and performance check phase) Star Tracker adjustment Attitude & orientation control system adjustment Pointing adjustment Observation instruments performance check
TBD	VSOP total system check

Chapter 8

VERIFICATION OF SPACE RADIO TELESCOPE PERFORMANCE

The VSOP mission phases are detailed in Table 8-1. Verification of the spacecraft and will begin immediately after launch; the progression from one phase to the next may overlap as repeated tests (such as pointing) of the spacecraft will occur periodically. A detailed description of the current plan can be found in *"In-Orbit Checkout Plan for VSOP Radio Telescope"* (Ulvestad *et al.* 1995c). Table 8-2 illustrates the general in-orbit checkout procedure. The general philosophy is to proceed from the lowest observing frequency to the highest frequency, from the easiest observations to the most difficult, and from the most accessible (based on location or other factors) ground elements to the least accessible elements.

Table 8-1: VSOP Mission Phases

Phase	Duration	Objective
Launch	1 day	Inject spacecraft into orbit.
Spacecraft Assessment	25–30 days	Assess performance of bus.
		Acquire link from tracking stations.
		Conduct initial pointing tests.
Space-Ground Checkout	4–6 months	Assess space-ground interferometer.
		Verify integrity of science data.
Observational	3–5 years	Begin guest observations.
		Conduct periodic calibration tests.

8.1 Spacecraft Checkout Phase

The space radio telescope checkout begins with the spacecraft systems. Engineers from NEC Corporation, Mitsubishi Electric Corporation, Nihon-hikoki, and the SCG will be available during this period to ensure successful antenna deployment. Deployment of the 8-m space antenna is not planned until approximately 12 days after launch, by which time most of the basic spacecraft subsystems will have been verified. However, new attitude-control calibration will be required after deployment of the antenna. It will take several days for the attitude-control system to be capable of adequate pointing at 1.6 GHz. The required pointing accuracy is 0.1 of a beamwidth (about 5 arcminutes), which initially will be calibrated using OH masers. Following pointing tests for a given frequency, antenna gain measurements will be made. Command and control of the spacecraft will be returned to NEC engineers for further calibration of the attitude-control system while the data is being analyzed.

Table 8-2: In-Orbit Checkout Timeline
(from Ulvestad *et al.* 1995c, p. 10.)

Event	**Optimistic Dates** 1996–1997
Launch	15 September
Antenna Deployment	26 September
1.6-GHz Antenna Check	30 September – 03 October
Spacecraft Checks	
Usuda Ku link	04 October – 07 October
Attitude Control System, etc.	27 September – 03 October
Initial 1.6-GHz Pointing	05 October – 12 October
Ku Link Checks to all Tracking Stations	08 October – 12 October
1.6-GHz Fringe Check	14 October – 02 November
First 1.6-GHz Imaging Observation	04 November – 30 November
1.6-GHz Pointing Measurements	21 October – 28 October
5-GHz Pointing Measurements	30 October – 16 November
22-GHz Pointing Measurements	26 November – 02 January
5-GHz Test Imaging	03 December – 31 December
22-GHz Fringe Check	14 December – 06 January
Transition Phase	
22-GHz Pointing	03 January – 31 January
1.6-,5-GHz Science	04 January – 31 January
22-GHz Test Imaging	01 January – 28 February
Routine Guest Observations	01 February

Tests of the phase link to the tracking stations will be made during the same time period as the 1.6-GHz gain measurements. These tests will serve several purposes, including checks of the spacecraft local oscillator system and phase stability, verifying the tracking-station performance, and verifying the validity of the two-way Ku-band Doppler data. It will be appropriate to begin by checking the phase link using only a limited subset of tracking stations; perhaps selecting a nearby site where staff resources are readily available. The current plan is to begin by testing the phase link to the Usuda tracking station first, then to bring the other tracking stations on-line as soon as possible thereafter.

Following the 1.6-GHz gain measurements and further pointing improvements, 5-GHz and 22-GHz gain measurements will be performed. After the attitude-control system is fully calibrated, a 22-GHz single-dish observations of H_2O masers will be used to establish a pointing table as a function of Sun angle. This process is likely to take a fairly long time, and will be interleaved with the first space VLBI observations at lower frequencies.

8.2 Space-Ground Interferometer Checkout Phase

The first observations to test the end-to-end space-ground interferometer will be made as soon as possible after the 1.6-GHz gain is reasonably well established and the first phase link has been made. Although it will be desirable to establish phase links to all tracking stations, the first space VLBI observations may take place before all phase links are verified. A 1.6-

GHz space VLBI observation of a strong OH maser source, on a short projected baseline, will be attempted first. Data also will be taken on one or more strong continuum sources such as 3C 273. If possible, the data set will be taken with at least two different tracking stations; to allow redundancy. One scenario will be to use the Usuda tracking station and the Usuda and Kashima radio telescopes so that the space VLBI data will be processed with the nearby Mitaka correlator. Alternatively, the Goldstone or Green Bank tracking station may be used along with the 70-m radio telescope at Goldstone and the VLBA Pietown antenna. This data will be sent to the VLBA correlator in Socorro, New Mexico. Two teams will then be able to independently search for fringes at the different correlators. This process may take days or weeks.

Following the acquisition of the first fringes on both spectral-line and continuum sources and the establishment of phase links to all tracking stations, the next objective will be to produce radio images. These maps will require at least 48 hours of observing time to obtain enough VLBI data for several images. The objective will not be to produce a scientific quality image, rather to demonstrate the ability to image a source adequately with the VSOP elements. While the analysis of the 1.6-GHz imaging data is taking place, high-frequency pointing tests and the first 4.8-GHz space VLBI observation will continue. Finally, after the high-frequency pointing and gain calibration is complete, the first 22-GHz VLBI observations of strong H_2O masers and continuum sources will be scheduled. Again, the requirements of these observations will be to locate fringes on target sources for each frequency and to demonstrate mapping capability. After these tasks are successful, the scientific observations proposed by principal investigators will take priority. Scientific observations at lower frequencies may take place while the 22-GHz checkout is being completed.

8.3 Scientific Observations Phase

Following the validation of the space-ground interferometer, the majority of the remainder of the mission lifetime will be used to carry out scientific observations proposed by the astronomical community. These space VLBI experiments have been selected by an open review process from the proposals put forth by the astronomical community or have been approved based on contributions made to the space VLBI mission. The first space VLBI experiment is expected to start in the January–February 1997 time frame, during which concurrent testing of the space-ground interferometer may still be continuing. Periodic engineering checks will take place throughout the mission lifetime.

Chapter 9

END-TO-END SPACE VLBI SYSTEM

In this chapter, we describe the end-to-end space VLBI data transfer system and categorize the data products in terms of uplink and downlink processes. An uplink product, for example, is a data product that is generated before a source is observed, and hence mostly involves scheduling the ground radio telescopes, spacecraft, and tracking stations. A downlink product is generated during or after the experiment. Although this designation is rather arbitrary, it will allow us to describe the events associated with an experiment.

Figure 9-1 shows the timeline for a given observation. The majority of the uplink products are generated several weeks prior to a scheduled experiment. For example, the scheduling of tracking stations and ground radio telescopes takes place approximately 1–4 weeks in advance whereas the command file that is uplinked to the spacecraft is prepared one day prior to the observation. During or following the experiment, a large number and variety of data products are generated, processed, and delivered to different agencies. Some of these are files that contain information on the performance of the spacecraft or tracking stations and others are necessary for input into the correlator. The final delivery of the required downlink products at the correlator is within two weeks of the time the observation was completed. The correlation process itself may take 1–2 additional months, so the total time for an experiment from scheduling to correlation will be approximately 2–3 months. During in-orbit checkout, the process associated with data transfer will be expedited until the space radio telescope is well understood. Figure 9-2 shows the overall data transfer for space VLBI. Each of the processes shown is further discussed in §11–15. A near-real time delivery requirement implies that the data has to be received within 30 minutes and a post-pass requirement implies the data has to be received within 3–4 days.

9.1 VSOP Science Operations Group Operations

The space VLBI scheduling process will involve negotiations with ground radio telescopes, tracking stations, and other mission elements; all of which have allocated some percentage of their resources. Since these agencies also have obligations to other users, the efficiency of the space VLBI scheduling may not be optimized. The scheduling process is as follows (see Figure 9-3):

• A **long-term predicted orbit**, a **target list** (based on the results of the scientific and technical review process), are used to generate the **long-term experiment schedule** from the available **mission element resources**.

• A **short-term experiment schedule** covering approximately 3–4 months is generated.

• SVLBSCHED2 is used to produce a **pseudo-space radio telescope file.**

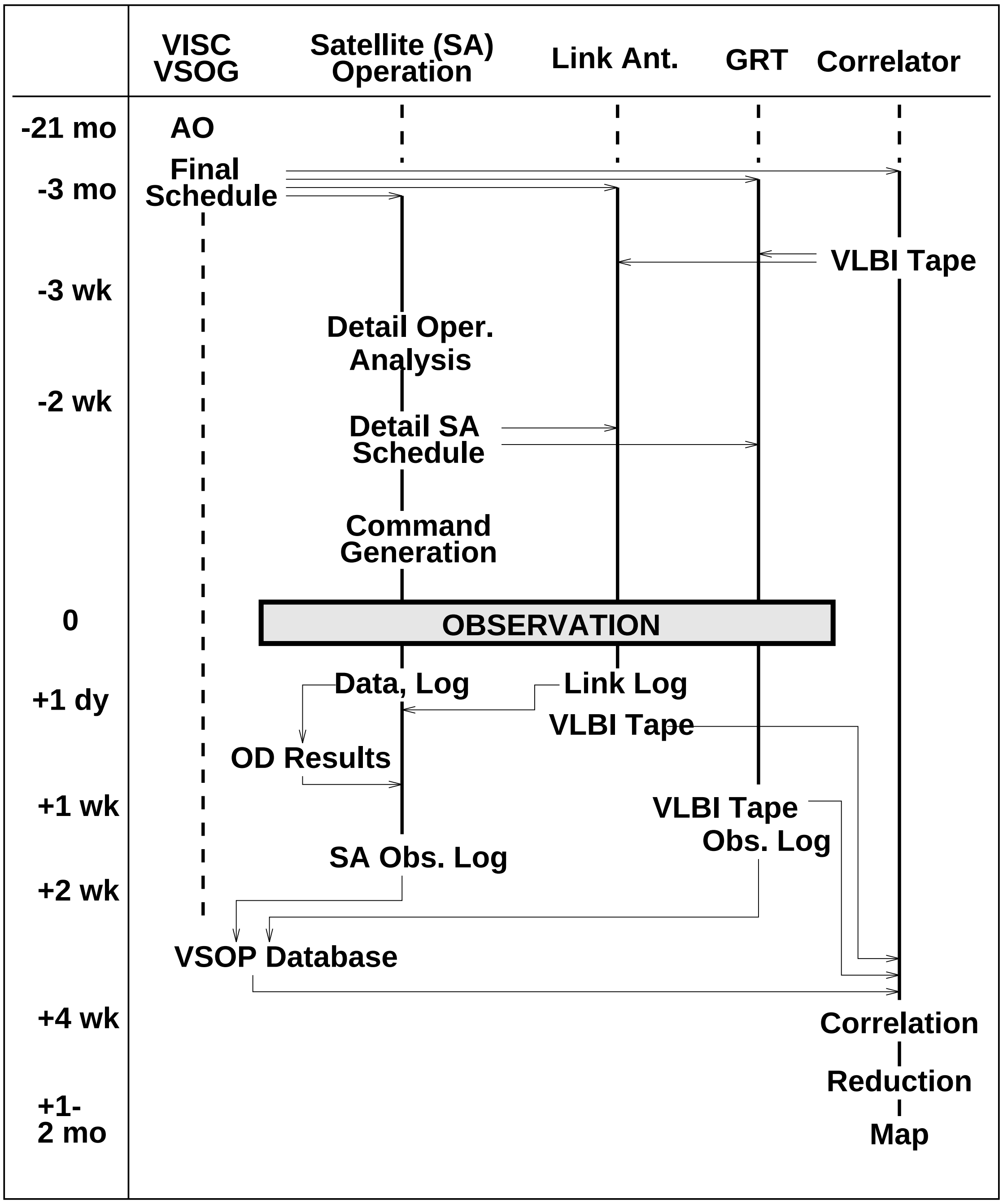


Figure 9-1: Space VLBI Experiment Timeline

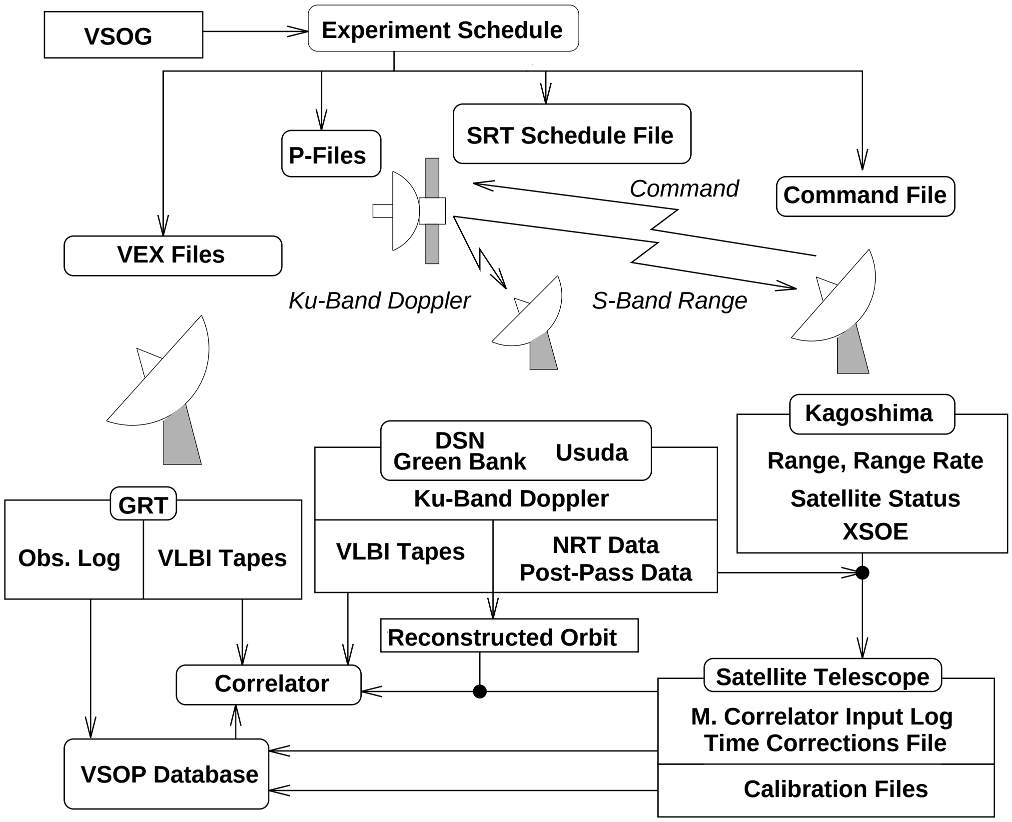


Figure 9-2: General Data Flow Overview

- The ground radio telescope constraints (e.g. cable wrapping, skyline, and elevation limits) are checked with a modified version of SCHED/PC-SKED.

- The spacecraft constraints (e.g. attitude change time, power, and thermal control) are checked with a modified version of MESON.

- All schedules for the mission elements are iterated to maximize the available resources and minimize the scheduling constraints.

- The **VEX files** for the ground radio telescopes are generated by the software WALKER SCHED.

- The **command file** for the spacecraft is generated.

- The final **space radio telescope schedule file** is generated to operate the Ku-band link stations.

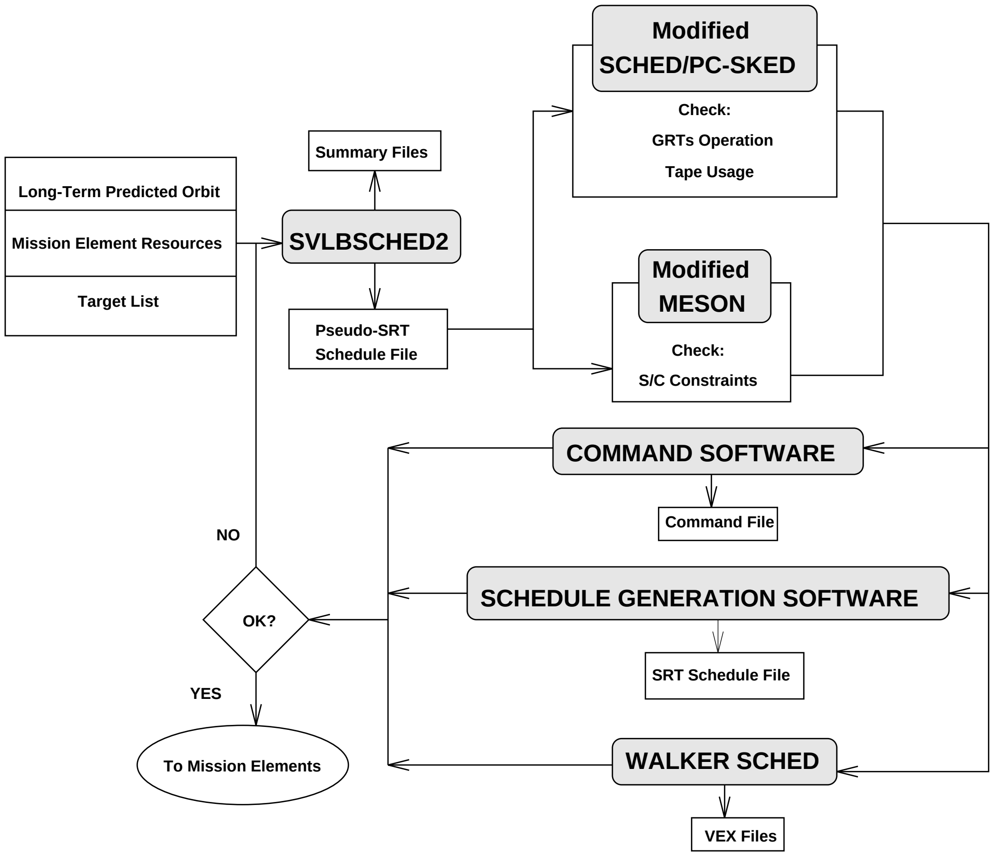


Figure 9-3: Space VLBI Scheduling Process

9.2 Ground Tracking Station Operations

Figure 9-4 shows the uplink and downlink products associated with the NRAO and 11-m DSN tracking stations. The data flow is as follows:

• A **space radio telescope schedule file** is delivered to the U. S. Space VLBI Project and the Green Bank tracking station approximately one week prior to the requested pass.

• The **schedule tables** (pertains only the 11-m DSN stations) are delivered to the DSN NSS approximately one week prior to the requested pass.

The U. S. Space VLBI Project will receive several data streams from each 11-m DSN stations, that will be processed into the required VSOG data products. These pre-VSOG data streams are:

• **Monitor data** (this also includes some correlator input log file information and phase

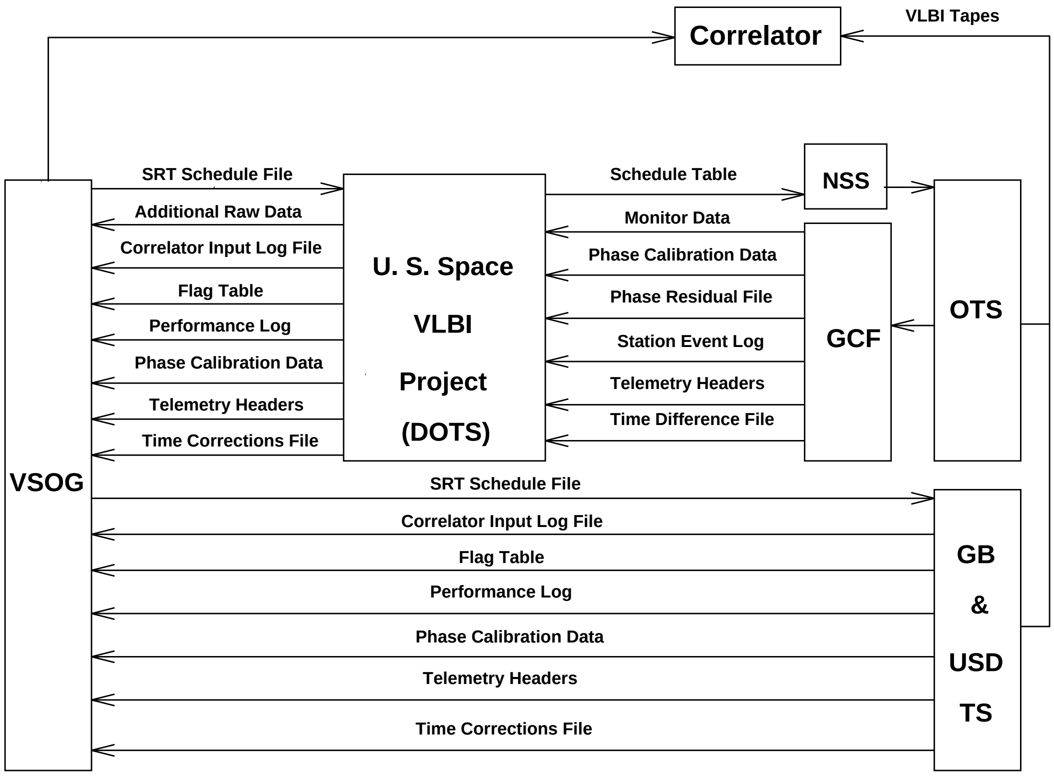


Figure 9-4: Tracking Station Data Flow

calibration data) is delivered in near-real and post-pass time to the U. S. Space VLBI Project.[2]

- **Phase calibration data**[3] is delivered post-pass to the U. S. Space VLBI Project.
- A **phase residual file** is delivered post-pass to the U. S. Space VLBI Project.
- **Telemetry headers** are delivered in near-real-time to the U. S. Space VLBI Project.
- A **time difference file** is delivered post-pass to the U. S. Space VLBI Project.

[2] The post-pass delivery requirement of the same data type is to receive the files by TCP/IP instead of UDP/IP. Currently, the GCF transmits real-time data only by UDP/IP. The file transfer protocol associated with TCP/IP is generally thought to be more reliable, hence the Data Oversight and Transfer System at the U. S. Space VLBI Project may likely retrieve the near-real time data twice.

[3] Although we show the phase calibration data and tracking station log file as two different data streams, they are more likely to be implemented as a data table contained within the monitor data file.

• A **tracking station log** is delivered post-pass to the U. S. Space VLBI Project.

For each tracking pass, which may last from a few minutes to several hours, several products are delivered to the VSOG. For the DSN, these files are generated from those files listed above. For the Green Bank and Usuda tracking stations, they are generated from a comparable set of internal files.

• **Additional raw data** is delivered to the VSOG. This may include selected data streams to be used during in-orbit checkout phase such as the telemetry headers in 10-minute packets, monitor data, and phase residuals.

• A **correlator input log file** is delivered post-pass to the VSOG.

• A **flag table** is delivered post-pass to the VSOG.

• A **performance log** is delivered post-pass to the VSOG.

• **Phase calibration data** is delivered post-pass to the VSOG.

• **Telemetry headers** are delivered in near-real-time and/or post-pass to the VSOG.

• A **time corrections file** is delivered post-pass to the VSOG.

• The **VLBI tapes** are delivered post-pass to the correlator.

9.3 Navigation Team Operations

Figure 9-5 shows the uplink and downlink products associated with the navigation data. The uplink data flow is as follows:

• A **p-file** from the DSN Multi-mission navigation team is delivered prepass to the NSS.

• A **predicts file** from NSS is generated and delivered to the 11-m DSN tracking stations.

• A **predicted orbit** in SPICE SPK format is delivered to the Green Bank tracking station from the DSN Multi-mission navigation team.

• A **predicted orbit** from ISAS is delivered to the Usuda tracking station.

The downlink navigation data flow involves the exchange of navigation data between the navigation groups at ISAS and JPL. This involves the data originating from the Green Bank tracking station, 11-m DSN tracking stations, and the Usuda tracking station. Most of the exchanges will take place 2–3 times a week. The downlink data flow is as follows:

• **Doppler data** is exchanged between the two navigation teams.

• **State vectors** are exchanged between the two navigation teams.

• **S-band data** is delivered to the DSN Multi-mission navigation team.

• An **antenna pointing schedule** is delivered to the DSN Multi-mission navigation team.

- **Maneuver data** is delivered to the DSN Multi-mission navigation team.
- **GPS data** is delivered to the DSN Multi-mission navigation team.
- The **executed sequence of events** is delivered to the DSN Multi-mission navigation team.
- A **reconstructed orbit** from the VSOP navigation team is delivered to the Mitaka correlator.
- A **reconstructed orbit** in SPICE SPK format is delivered from the DSN Multi-mission navigation team to the U. S. Space VLBI Project, and made available to the VLBA correlator (and possibly to other correlators).

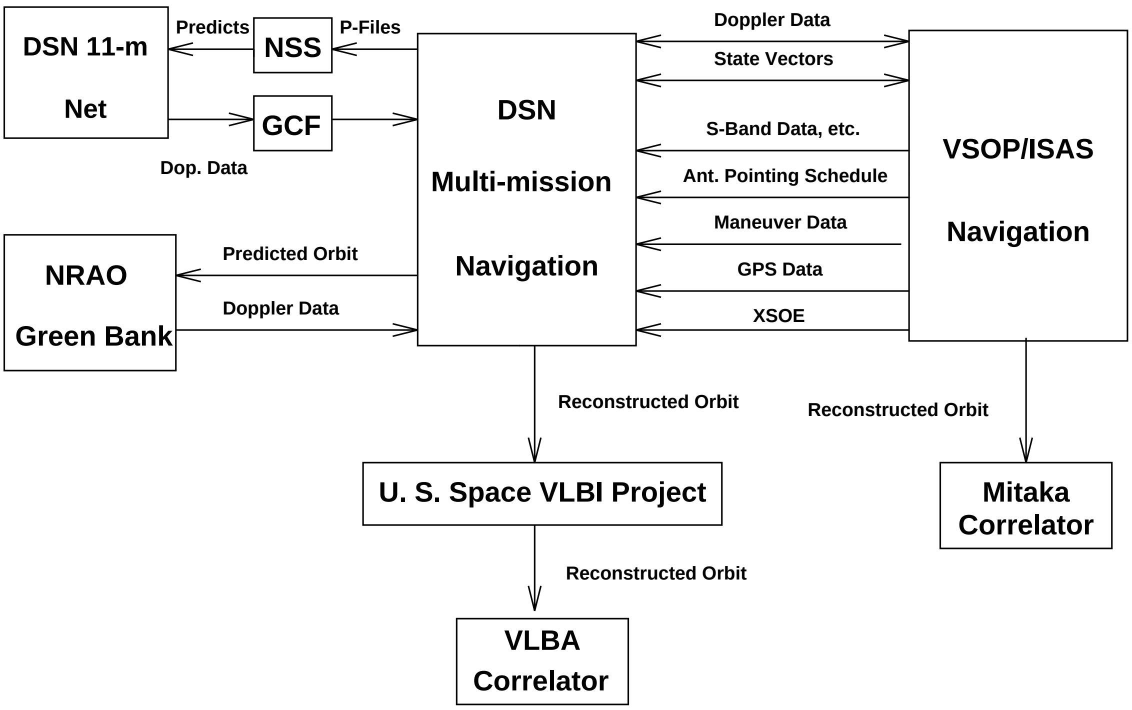


Figure 9-5: Navigation Data Flow

9.4 Ground Radio Telescope Operations

The ground radio telescopes will participate in the space VLBI experiments in a way much similar to ground-VLBI observations. The uplink and downlink products are:

- A **VEX file** will be used to schedule the ground radio telescope.

- A **ground radio telescope log file**, analogous to a correlator input log file, will be delivered post-pass to the VSOG and to the correlator.

- The **VLBI tapes** are delivered post-pass to the correlator.

9.5 Correlator Operations

Because the VSOG is primarily responsible for the science operations, a majority of the tasks associated with the analysis of the space radio telescope, scheduling of mission resources, and preparation of files needed by the correlator will be done by the team members. All the files needed as inputs to the correlators, with the exception of the reconstructed orbit that will be supplied by the navigation teams and the wideband VLBI tapes that will be shipped directly to the correlators, will originate from the VSOG. The products required by the correlator must be delivered within 2 weeks after a given observation. The following products are required by the correlator (see Figure 9-6):

- The **VLBI tapes** are delivered by the ground radio telescopes and tracking stations.

- The **ground radio telescope log files** are delivered by the ground radio telescopes.

- The **merged correlator input log file** is delivered by the VSOG.

- The **time corrections file** is delivered by the VSOG.

- The **reconstructed orbit** is delivered by the navigation team.

Some data quality assurance and fringe checking will be carried out by the correlator. The facility will notify the principal investigator when the correlation process is complete and will send the output data to the principal investigator on appropriate media. Recorded VLBI tapes will be erased after correlation and will be returned to a general pool for redistribution to tracking stations and ground radio telescopes.

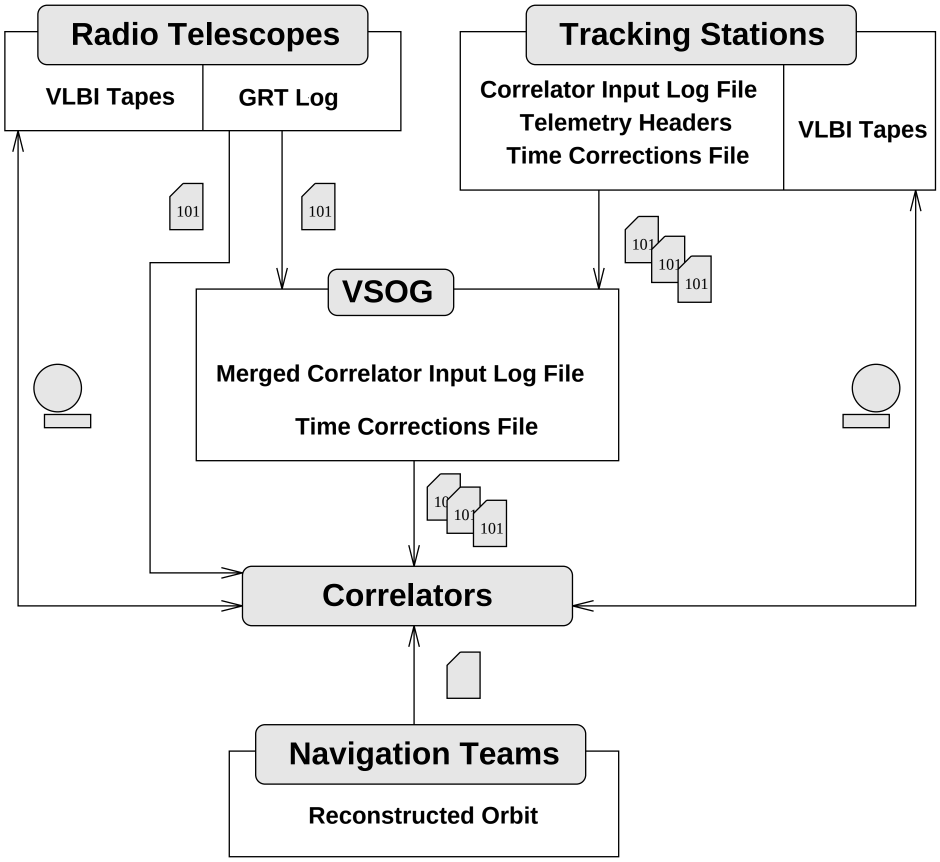


Figure 9-6: Origin of Correlator Input Products

SPACE VLBI DATA TRANSFER

In this chapter and the remainder of the document, we will discuss the processing, transmission, and analysis of space VLBI data. Numerous mission elements will be involved and will have to work together to ensure timely and accurate mission operations. This is further complicated by the fact that the agencies are not physically located at one site or building.

The majority of data products that will flow through the data transfer system are related to navigation, tracking, and ground radio telescope activities. The system itself is not one contiguous pipeline processing (see Figures 9-1–9-6) in the sense that one group generates a product and then passes it on to the next group. Instead, a variety of products will be interchanged on different timelines; all of which are required in some form, as an input to the correlators. Such a data transfer system is complex and the primary requirements are:

- Schedule support for all mission elements;
- Generate, receive, transmit, and process space VLBI data products;
- Archive identified space VLBI data products.

The method for exchange of space VLBI data products will be via anonymous or restricted-access file transfer protocol (ftp) on designated computer sites. There are other options that are currently under consideration, one of which may include an on-demand ISDN line for delivery of products from the U. S. tracking stations to the VSOG, but this has not been implemented or tested. Within the U. S. Space VLBI Project, the Data Oversight and Transfer System (DOTS) is the subsystem responsible for exchanging data between the DSN and external users.

10.1 Ftp Sites

Table 10-1 lists the nodes (with the exception of the ground radio telescope sites) involved in the data exchange process. The table, at present, is not complete but will include the internet protocol (IP) addresses and computer host names. We also intend to reference, when they are formalized, the applicable documents which will describe the directory-tree partitions. Currently, there are several draft documents (and it is understood that these are in the process of being revised) that describe the following sites; they are:

- DOTS: "File Naming Convention and Ftp Structure for DOTS Deliverables - Version 1.1," Wiercigroch (1996a);
- VSOP: "VSOP Filename and Directory Structure for the Tracking Stations," Murata (1995b);

• Space VLBI Sites: "Space VLBI Ftp Sites for Navigation and Tracking Data Exchange," Wiercigroch, Murata, and Langston (1996a).

Table 10-1: Ftp Sites

Site	**Host Name**	**IP Address**
DOTS	TBD	TBD
DSN Navigation	TBD	TBD
Green Bank Tracking Station	ftp.gb.nrao.edu	192.33.116.115
ISAS Navigation	TBD	TBD
VSOG	vsoper1.vsop.isas.ac.jp	133.74.17.21

10.2 Filename Conventions

Murata (1995b) has proposed the file naming conventions for a number of data products pertaining to VSOG operations.[4] In the proposal, the naming of files will be composed of 10 characters designating the data time, followed by a 3 character extension for the file type, and an optional 1 character designating the version. Thus the file name will look like "`YYMMDDHHMM.AAA.v`". This type of naming convention has not yet been adopted by the U. S. Space VLBI Project or the Green Bank tracking station; although a similar (or identical) nomenclature will have straightforward benefits. Thus, the naming of a file is based on the following items:

• Date: The UTC time of the beginning of the tracking pass will determine the "`YYMMDDHHMM`" extension in the file label;

• Contents: The origin and type of data product will determine the "`AAA`" extension in the file label;

• Version number: Multiple versions will determine the "`.v`" extension in the file label.

10.3 Format and Exchange of Data Products

Table 10-2 lists the origin and destination of the data products that will be exchanged among the mission elements. Also included are the interface documents that describe the format and content of the products. Some of the documents refer to internal data exchanges between the DSN and the U. S. Space VLBI Project. Equivalent data products may also exist for the Usuda and Green Bank tracking stations.

[4] There has been recent discussions on changing the file naming convention to the format "`YYMMDDHHMMT.AAA`" where "`T`" denotes a specific tracking station. We intend to formalize the naming convention during the upcoming Space VLBI Work Week in March. The agreed-to file naming conventions and other issues such as data compression will be documented in Wiercigroch, Murata, and Langston (1996b).

Table 10-2: Summary of Format and Exchange of Data Products

Data Product	**Source**	**Destination**	**Section**	**Format**
Amplitude Calibration Data	VSOG	COR & PI	11.1	...
Antenna Pointing Schedule	ISAS NAV	DSN NAV	12.1	ASCII
Command File	SCG	S/C	11.2	...
Correlator Input Log File (partial)	DOTS, GB, & USD	VSOG	13.1	Romney (1996)
Correlator Output	COR	PI	15.1	FITS-format
Experiment Schedule	VSOG	ME	...	...
Long-Term	VSOG	ME	11.4	Ulvestad *et al.* (1995b)
Short-Term	VSOG	ME	11.7	Ulvestad *et al.* (1995b)
Flag Table	DOTS, GB, & USD	VSOG	11.3 & 13.2	Ulvestad *et al.* (1996)
...	VSOG	COR & PI	11.3	Ulvestad *et al.* (1996)
GPS State Vectors	ISAS NAV	DSN NAV	12.3	TBD
Ground Radio Telescope Log File	GRT	VSOG & COR	14.1	VLBA-compatible
Ku-Band Doppler Data	GCF & GB	DSN NAV	12.4	TRK-2-30
...	USD	ISAS NAV	12.4	...
...	DSN/ISAS NAV	ISAS/DSN NAV	12.4	TRK-2-18
Maneuver Data	ISAS NAV	DSN NAV	12.6	ASCII
Merged Correlator Input Log File	VSOG	COR	11.5	...
S2	VSOG	S2 COR	13.7	Carlson *et al.* (1995)
VLBA	VSOG	VLBA COR	11.5	Romney (1996)
Monitor Data	GCF	DOTS	13.3	MON-5-17
NRT Correlator Results	NRT COR	SCG	15.3	...
Orbits	...	...	...	...
Long-Term Predicted Orbit	NAV	VSOG	12.5	...
NASDA Predicted Orbit	NASDA	KSC	12.7	...
Predicted Orbit	ISAS NAV	VSOG	12.10	...
...	DSN NAV	GB	12.10	SPICE SPK
Reconstructed Orbit	DSN NAV	VLBA COR	12.11	SPICE SPK
...	ISAS NAV	VSOP COR	12.11	...
P-File	DSN NAV	NSS	12.9	TRK-2-19
...	ISAS NAV	USD	12.9	...
Performance File	DOTS, GB, & USD	VSOG	13.4	D'Addario (1995)
Phase Calibration Table	DOTS, GB, & USD	VSOG	13.5	Ulvestad & Romney (1996)
...	VSOG	COR & PI	11.6	Ulvestad & Romney (1996)
Phase Residual File	GCF	DOTS	13.6	TRK-2-32
Predicts	NSS	OTS	...	TRK-2-224
S-Band Range Rate Data	ISAS NAV	DSN NAV	12.12	TRK-2-18
...	ISAS NAV	NASDA	12.12	...
Schedule Table	DOTS	NSS	13.8	OPS-6-23
SRT Schedule File	VSOG	DOTS, GB, & USD	11.8	Ulvestad *et al.* (1995b)
State Vectors	DSN/ISAS NAV	ISAS/DSN NAV	12.13	TRK-2-17
Station Event Log File	GCF	DOTS	13.9	MON-5-17
Status Reports	ME	ME	11.11, 12.8, 13.13,	Wiercigroch & Murata (1995)
...	...	...	14.2, & 15.2	...
Telemetry Headers	GCF	DOTS	13.10	TLM-3-22
...	DOTS, GB, & USD	VSOG	13.10	Murata (1995a)
Time Corrections File	DOTS, GB, & USD	VSOG	13.11	D'Addario & Langston (1995)
...	VSOG	COR	13.11	D'Addario & Langston (1995)
Time Difference File	GCF	DOTS	13.12	TRK-2-32
VEX File	VSOG	GRT	11.10	Whitney (1996)
VLBI Tape Information	ME	COR	...	...
S2	ME	S2 COR	15.4	TBD
VLBA	ME	VLBA COR	15.4	TRACK
VSOP	ME	VSOP COR	15.4	TBD
VLBI Tapes	ME	ME	13.14, 14.3, & 15.5	delivery services
...	...	...	...	Ulvestad & Romney (1995)
XSOE	ISAS NAV	DSN NAV	12.2	ASCII

10.4 On-Line Storage Requirement

It has been generally agreed that individual mission elements will be responsible for archiving their original and processed data products. The length of time for these items to remain on-line has not yet been formalized. However, considering the requirement that all data products necessary for correlation will arrive at the correlator within 2 weeks, the correlation process may add an additional 4–6 weeks, and troubleshooting may take place for a significant period thereafter, it is desired to keep data products on-line for 6 months in the early phases of the space VLBI mission.

VSOG PRODUCTS

11.1 Amplitude Calibration Data

1. VSOG to Correlators and PI

Description: The telemetry headers will also contain vital calibration data necessary for the calibration of the space radio telescope and will be essential for the final analysis of the scientific data. The calibration data includes on-board voltages (that will be used for system temperature calculations), spacecraft pointing angles, and boresighting results. As mentioned, this data will be contained in the telemetry headers; so no separate data product will be made available from the tracking stations; the VSOG will have the responsibility for the extraction and analysis of calibration data from the telemetry headers.

Time: File will be submitted no later than 2 weeks after the support period.

11.2 Command File

1. SCG to KSC to Spacecraft

Description: The command file will contain all the necessary commands for the operation of the spacecraft for one day. It will be generated by the SCG approximately one day prior to the scheduled uplink. The command file will be transmitted from ISAS to the Kagoshima Space Centre and uplinked to the spacecraft in real-time; command verification will also be in real-time. Transmission and verification of the command file will only be done during the contact with the 20-m antenna at Kagoshima Space Centre. This will occur approximately once per day. Figure 11-1 shows the process by which the commands are constructed.

Time: File will contain a block of 1 day of time and will be submitted in real-time.

11.3 Flag Table

1. VSOG to Correlators and PI

Description: The tracking stations will supply a flag table to the VSOG, covering the parameters which relate to the tracking station performance. The VSOG will add flags related to spacecraft performance and generate a final flag table for use by the PI. The file may be passed to the PI via the correlator output or may reside on one of the VSOG computer sites for retrieval by the PI.

Time: File will be submitted no later than 2 weeks after the support period.

11.4 Long-Term Experiment Schedule

1. VSOG to Mission Elements

Description: A long-term experiment schedule will be constructed from the approved target list, the available resources, and the requirements for periodic engineering and calibration tests. The long-term experiment schedule will cover approximately 17 months of observing time and will be derived in an iterative process to obtain the maximum science return from the given resources. The file will be revised periodically after launch to account for new information on the orbit of the spacecraft and as additional resources become available. The long-term experiment schedule will be made available to the mission elements and astronomical community.

Time: File will contain a block of 17 months of time and then will be regenerated as necessary to maximize science return.

11.5 Merged Correlator Input Log File

1. VSOG to Correlators

Description: Several data products will be used to assemble what is termed a merged correlator input log file. These data products include information contained in the tracking station logs, calibration data, and results from analysis of the spacecraft performance contained in several additional data products. The correlators currently require a single file for each space VLBI experiment (hence the term merged). This data product will be one of the more time-consuming to generate as it requires several input products and analysis of the space radio telescope performance. Figure 11-2 shows the process by which the merged correlator input log file is constructed.

Time: File will be submitted no later than 2 weeks after the support period.

11.6 Phase Calibration Data

1. VSOG to Correlators and PI

Description: The tracking stations will extract phase-calibration tones from the downlink data and provide the results to the VSOG. The VSOG will add the appropriate frequency information and make the file available to the PI. The file may be passed to the PI via the correlator output or may reside on one of the VSOG computer sites for retrieval by the PI.

Time: File will be submitted no later than 2 weeks after the support period.

11.7 Short-Term Experiment Schedule

1. VSOG to Mission Elements

Description: A detailed short-term experiment schedule will be constructed from the long-term experiment schedule and will be considered the final operational observation plan. It will cover 3 months of support and will contain information on which mission elements will provide support for that period. It will contain, for example, source information (e.g. target name and coordinates), co-observing radio telescope and tracking station support information, and final correlator destination. This schedule will also be made available to the astronomical community via the Internet.

Time: File will contain a block of 3 months of time.

11.8 Space Radio Telescope Schedule File

1. VSOG to Green Bank Tracking Station
2. VSOG to U. S. Space VLBI Project
3. VSOG to Usuda Tracking Station

Description: A space radio telescope schedule file will be generated to allocate the tracking stations. It will contain a list of activities (e.g. begin recording of wideband VLBI data) describing the tracking support for 1 week of the mission from Monday through Sunday UTC. The 1 week coverage does not refer to a particular tracking station but to the entire tracking coverage for the mission. The file will first be made available to the tracking stations 4–6 weeks in advance of a requested support period for allocation purposes. The final space radio telescope schedule file will be delivered by Wednesday at 1200 UTC for the following week of support. This advance delivery time will allow the tracking stations to extract information they require to schedule tracking support.

Time: File will contain a block of 7 days of time, from Monday through Sunday (UTC), and will be submitted 4–6 weeks in advance of a requested support period for allocation purposes and 1 week in advance, (by Wednesday at 1200 UTC), for the final schedule.

11.9 Time Corrections File

1. VSOG to Correlators

Description: Each tracking station will produce a time corrections file for each tracking pass. The VSOG will retrieve and collate the required files for an experiment and send them to the designated correlator. Currently, the correlator plans to accept individual files rather than a single merged product.

Time: File will be submitted no later than 2 weeks after the support period.

11.10 VEX File

1. VSOG to Ground Radio Telescopes

Description: The VSOG will produce VEX files that will operate the ground radio telescopes for the given space VLBI experiment. The requirement for the delivery of these files varies from telescope to telescope and is nominally 7 days in advance of support for a given experiment. Most space VLBI experiments will last 1–2 days so these files will have to be produced on a continuous basis.

Time: File will contain a block of time as specified in the approved target list (nominally 1–2 days) and will be submitted 7 days in advance of a requested support period.

11.11 VSOG Status Reports

1. VSOG to Mission Elements

Description: A comprehensive report of the mission status will be written and released by the VSOG. The contents of the report will be focused on mission operations related topics (and so is different than the e-mail newsletter, "VSOP News", which is geared to the astronomical community). Events in the status report may include a summary of the individual mission status reports, calibration and pointing errors, and spacecraft safe holds.

Time: File will contain a block of 2 weeks of time.

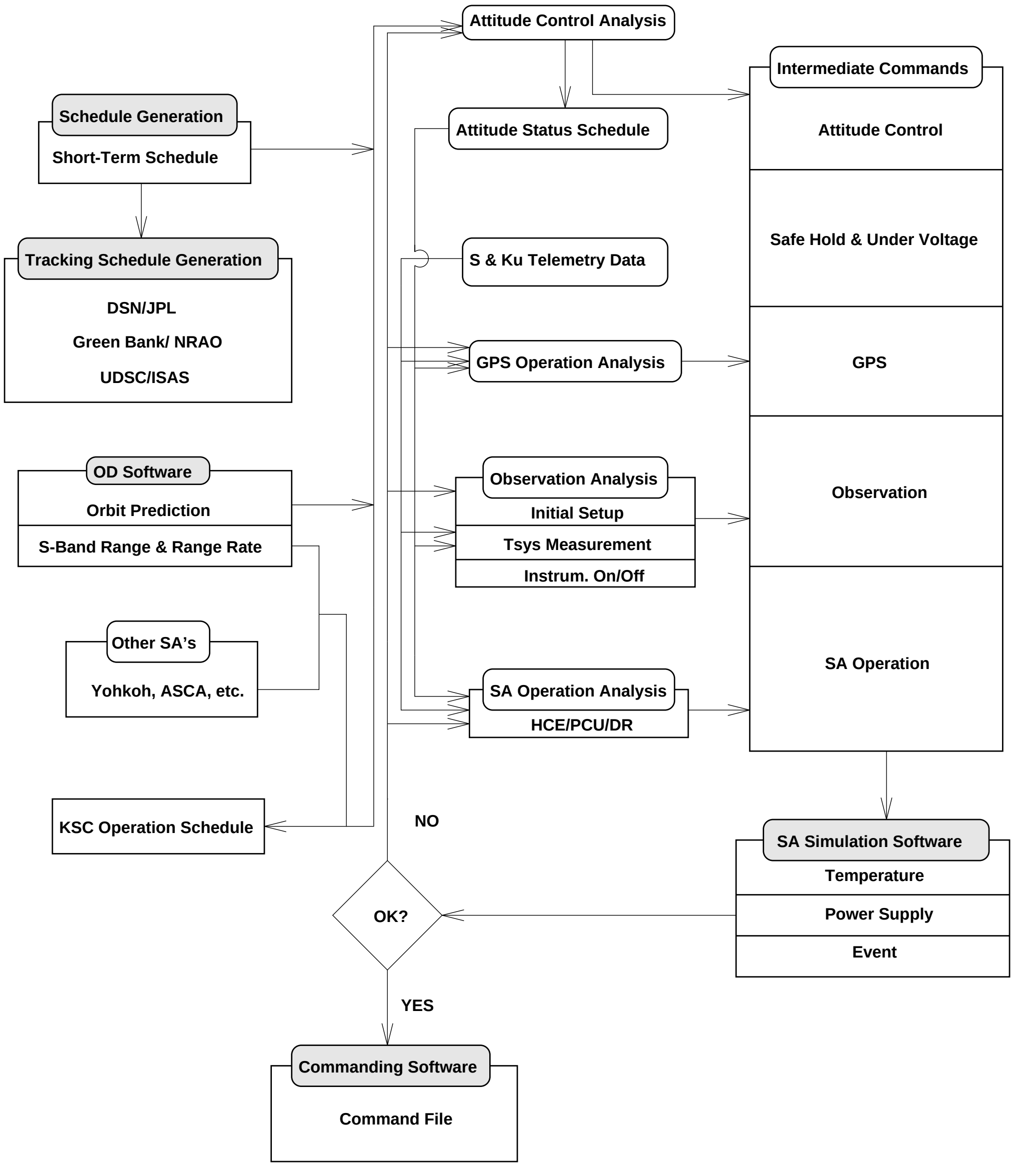


Figure 11-1: Command File Generation

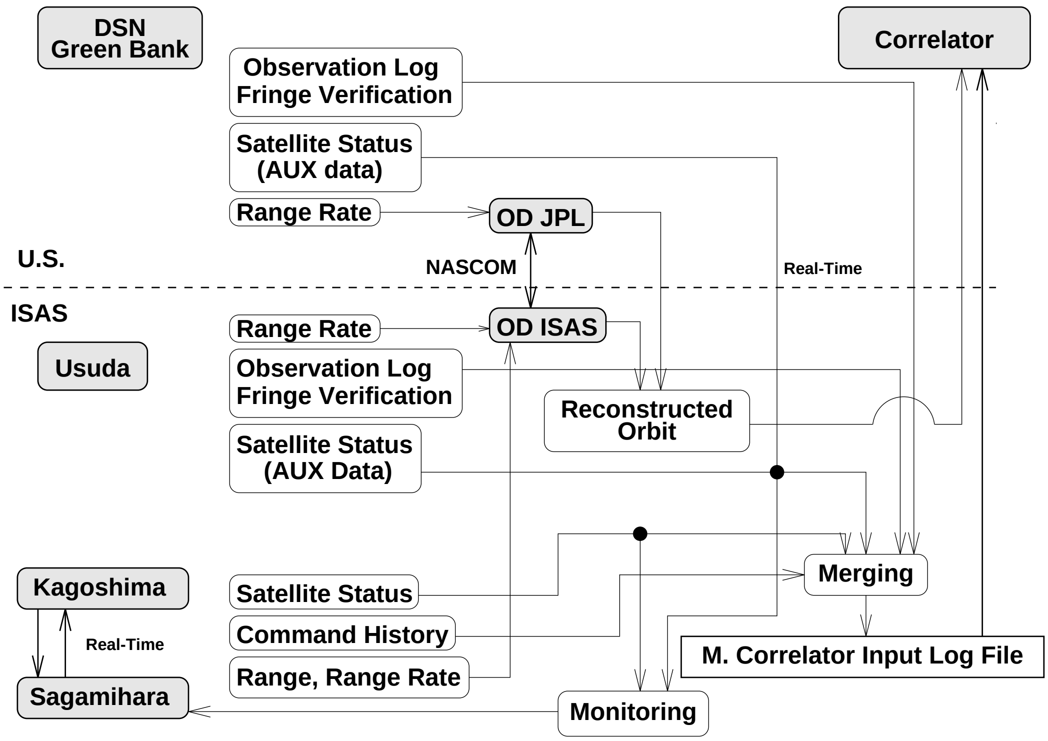


Figure 11-2: Merged Correlator Input Log File Generation

NAVIGATION PRODUCTS

12.1 Antenna Pointing Schedule

1. ISAS Nav to DSN Nav

Description: The antenna pointing schedule is necessary for orbit predictions and includes information on the planned orientation of the spacecraft and solar panels. The DSN navigation team will take detailed solar-pressure effects into consideration in generating the orbit predictions whereas the ISAS navigation team will only include an average solar pressure term in their calculations.

Time: File will be submitted once per week.

12.2 Executed Sequence of Events

1. Spacecraft to KSC to ISAS Nav to DSN Nav

Description: The executed sequence of events will be received by the ISAS navigation team. It will summarize the actual events of the spacecraft (e.g. maneuvers and slews) and will be used as a diagnostic aid when deriving the reconstructed orbit file. The file will be one of the many navigation data products which will be exchanged between the two navigation teams at the DSN and ISAS. This file will be transmitted from the spacecraft during contact at the Kagoshima Space Centre.

Time: File will contain a block of 1 day of time and will be submitted once per week.

12.3 GPS State Vectors

1. KSC to ISAS Nav to DSN Nav

Description: The state vectors generated on-board the spacecraft from the experimental GPS receiver will be downlinked in the S-band telemetry. They will be analyzed by the ISAS navigation team and the results will be sent to DSN navigation team.

Time: File will be submitted TBD per week.

12.4 Ku-Band Doppler Data

1. DSN 11-m Tracking Stations to DSN Nav to ISAS Nav

2. Green Bank Tracking Station to DSN Nav to ISAS Nav
3. Usuda Tracking Station to ISAS Nav to DSN Nav

Description: Ku-band (15-GHz) Doppler data will be transmitted from the U. S. tracking stations to the DSN navigation team and from the Usuda tracking station to the ISAS navigation team in near-real-time. The two navigation groups will exchange the data twice per week.

Time: Near-real time delivery from DSN 11-m and Usuda tracking stations, post-pass delivery from Green Bank tracking station, and delivery once per week between navigation teams.

12.5 Long-Term Predicted Orbit

1. DSN Nav and ISAS Nav to VSOG

Description: The DSN and ISAS navigation teams will work together to generate a long-term predicted orbit that will be delivered to the VSOG. It will be used to generate the long-term schedule. The predicted orbit for the spacecraft is rather coarse, especially over several months, so this data product is only used for approximate scheduling of resources. As a result, a long-term predicted orbit may be generated several times throughout the life of the mission to assist with fine-tuning of the long-term schedule.

Time: File will contain a block of 17 months of time and then will be regenerated as necessary for long-term scheduling.

12.6 Maneuver Data

1. ISAS Nav to DSN Nav

Description: Planned maneuvers of the spacecraft will be delivered to the DSN navigation team. This will be used later in analyzing the Ku-band Doppler data.

Time: File will be submitted as needed.

12.7 NASDA Predicted Orbit

1. NASDA to KSC

Description: The NASDA predicted orbit is determined from S-band range rate data and is used at KSC to acquire the spacecraft.

Time: File will be submitted once per week.

12.8 Navigation Status Reports

1. DSN and ISAS Nav to VSOG

Description: A short summary of navigation activities will be written jointly by the navigation group. It will include a summary of the quality of the orbit processing and anomalies.

Time: File will contain a block of 7 days of time.

12.9 P-File

1. DSN Nav to NSS
2. ISAS Nav to Usuda Tracking Station

Description: The DSN navigation team will supply P-files to the NSS twice per week. These files are the operational predicted orbit because they predict the spacecraft's trajectory one day to one week in advance. The ISAS Nav team will supply a similar file to the Usuda tracking station. For example, a P-file generated on day 1 will cover days 2–8 and the next P-file generated on day 4 will cover days 5–11. These files will be used for tracking station pointing and frequency predictions. Note that the P-files supplied by the DSN and ISAS navigation groups are generated separately.

Time: File will contain a block of 7 days of time and will be submitted 2–3 times per week.

12.10 Predicted Orbit

1. DSN Nav and ISAS Nav to VSOG
2. DSN Nav to Green Bank Tracking Station

Description: The DSN and ISAS navigation teams will work together to generate a predicted orbit for the spacecraft that will be used to generate the space radio telescope schedule file. Since the file will predict the trajectory of the spacecraft 4–6 weeks in advance, it is more accurate than the long-term predicted orbit; but it will still be necessary to submit updates to the tracking stations. The DSN navigation team will also deliver a predicted orbit to the Green Bank Tracking station in SPICE SPK format.

Time: File will contain a block of 7 days of time and will be submitted 4–6 weeks in advance when used in scheduling of mission elements. The file will also be submitted 2–3 times per week when used for tracking the spacecraft.

12.11 Reconstructed Orbit

1. DSN Nav to VLBA Correlator
2. ISAS Nav to VSOP Correlator

Description: A reconstructed orbit will be delivered to the designated correlator. The ISAS navigation team will deliver the file for the Mitaka correlator, whereas the DSN navigation team will have the responsibility for the VLBA correlator. The provider of this item to other correlators has not been determined. The file will periods of several days up to approximately 1 week.

Time: File will contain a block of 1–7 days of time and will be submitted no later than 2 weeks after the completion of the tracking sessions covered by the reconstructed orbit.

12.12 S-Band Range Rate Data

1. KSC to ISAS Nav to DSN Nav
2. ISAS Nav to NASDA

Description: S-band range rate data from the Kagoshima Space Centre will be sent to the ISAS navigation team in real-time. The data will also be made available to the DSN navigation team and to NASDA. NASDA will use it to derive the NASDA predicted orbit. The data is also used to generate the antenna pointing schedule.

Time: File will be submitted twice per week.

12.13 State Vectors

1. DSN/ISAS Nav to ISAS/DSN Nav

Description: The state vectors will be exchanged between navigation groups and are used in comparing the reconstructed orbits.

Time: File will be submitted once per week.

TRACKING STATION PRODUCTS

13.1 Correlator Input Log File (partial)

1. U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG
3. Usuda Tracking Station to SCG to VSOG

Description: A correlator input log file for each tracking pass will be made available to the VSOG. Only partial information will be supplied to the VSOG which must add other information in order to produce the final merged correlator input log file. The files from a number of tracking sessions will be merged into a single correlator input log file by the VSOG, and sent to the correlator for the correlation process.

Time: File will be supplied to the VSOG within 24 hours of the support period but no later than 4 days after the tracking pass.

13.2 Flag Table

1. U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG
3. Usuda Tracking Station to VSOG

Description: The tracking stations will supply a flag table to the VSOG, covering the parameters which relate to the tracking station performance. The VSOG will add flags related to spacecraft performance and generate a final flag table for use by the PI. The file may be passed to the PI via the correlator output or may reside on one of the VSOG computer sites for retrieval by the PI.

Time: File will be submitted within 24 hours after the support period but no later than 4 days after the tracking pass.

13.3 Monitor Data

1. DSN 11-m Tracking Stations to GCF to U. S. Space VLBI Project to VSOG

Description: Monitor data will be supplied to the U. S. Space VLBI Project for each pass by the DSN 11-m stations. The monitor data contains packets of telemetry describing the antenna, boresight, transmitter, tracking and receiver, telemetry, prepass, and subsystem performance. Phase calibration data and some items required for the performance files is contained within this product.

Time: Data will be made available in near-real time to the U. S. Space VLBI Project and the VSOG. In addition, a complete file will be supplied post-pass to the U. S. Space VLBI Project within 24 hours after the support period.

13.4 Performance File

1. U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG
3. Usuda Tracking Station to SCG to VSOG

Description: Auxiliary information that is not needed by the correlator but has been requested by the VSOG is called a performance file. This file will contain information about tracking station performance and may be constructed from a number of internal data products. The generation of this file is secondary to the space VLBI data flow as it is not considered vital for the correlator process.

Time: File will be supplied to the VSOG within 24 hours of the support period

13.5 Phase Calibration Data

1. U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG
3. Usuda Tracking Station to VSOG

Description: Phase calibration tones will be extracted and supplied to the VSOG via a separate phase calibration table, one per tracking session.

Time: File will be supplied to the VSOG within 24 hours of the support period but no later than 4 days after the tracking pass.

13.6 Phase Residual File

1. DSN 11-m Tracking Stations to GCF to U. S. Space VLBI Project

Description: Measurements of the residuals on the two-way phase link caused by effects such as errors in the predicted orbit and atmospheric propagation effects are called phase residuals. The DSN 11-m tracking stations will provide this product in a series of phase polynomials and residuals to these polynomials, to the U. S. Space VLBI Project. The time difference file along with the phase residual file will be processed to create the time corrections file.

Time: File will be submitted within 24 hours after the support period.

13.7 S2 Correlator Log Input File

1. DSN 11-m Tracking Station to VSOG to S2 Correlator

Description: A S-2 correlator input log file for each tracking pass will be made available to the VSOG when the S2 recorders in the tracking station are being used. Only partial information will be supplied to the VSOG which must add other information in order to produce the final merged S2 correlator input log file. For those experiments involving S2 recorders, The logs and S2 tapes will be sent to the Canadian correlator for further processing.

Time: File will be supplied to the VSOG within 24 hours of the support period

13.8 Schedule Table

1. U. S. Space VLBI Project to DSN-NSS
2. Green Bank Tracking Station
3. Usuda Tracking Station

Description: Information will be extracted from the space radio telescope schedule file specific to each tracking station. Each tracking station will extract, translate, and format the necessary information to operate its facilities. The DSN-NSS currently requires these files 4–6 weeks in advance of a requested support period and so this is the limiting time factor. The remaining two tracking stations have the capability to accept these files 1–2 days in advance of a requested support period. It may be possible in the future that this product may have a shorter time delivery requirement for the DSN 11-m tracking stations allowing a more flexible and accurate scheduling process.

Time: File will contain a block of 7 days of time and will be submitted no later than Wednesdays 1200 PT for support starting the following UTC Monday.

13.9 Station Event Log File

1. DSN 11-m Tracking Stations to GCF to U. S. Space VLBI Project

Description: The station event logs contain information on the performance of the tracking stations. Not all of this information is required by the VSOG, so it will be processed on-site to extract the relevant data. The data that is extracted is later used in some part in producing the correlator log input file and the performance log.

Time: File will be submitted within 24 hours after the support period.

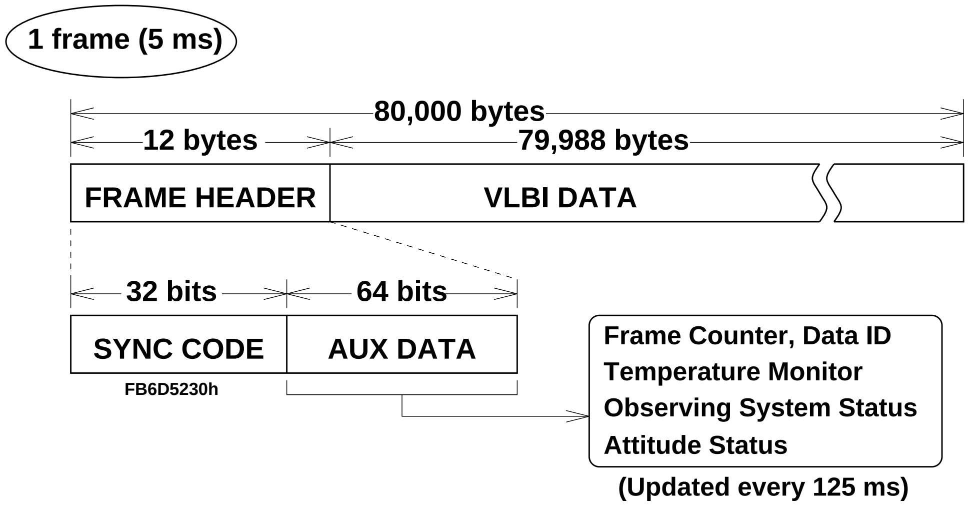
13.10 Telemetry Headers

1. DSN 11-m Tracking Stations to GCF to U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG

3. Usuda Tracking Station to VSOG

Description: Telemetry headers will be used by the VSOG to monitor the health and safety of the spacecraft. (The telemetry headers also contain vital scientific data needed by the VSOG to generate the merged correlator input log file.) The delivery of this product is of primary importance in the overall space VLBI data transfer flow. It is the responsibility of the VSOG to retrieve and analyze these files. The telemetry headers from the DSN 11-m and Usuda tracking stations will be made available to the VSOG less than one hour (near-real time) after reception at the tracking station; whereas the Green Bank tracking station will, in addition, process and interpret the telemetry headers in real-time. Some intermediate processing of these telemetry headers will occur on-site; this includes the stripping of the first 5 bytes of the frame and the packaging of the telemetry headers into a file covering 10 minutes. The telemetry headers for each tracking pass will be made available as one file after the pass has been completed and the 10 minute files will be deleted. The contents of the telemetry headers are shown in Figure 13-1.

Time: File will contain 10 minutes of tracking time and will be available during a tracking pass no later than 1 hour after the support period. A second file will contain the entire tracking pass length and will be available no later than 4 hours after the support period.



AUX data **64 bits / 0.125 sec = 512 bps**

Total AUX data of 1 link operation (4 hours)

= 512 bps x 4 hrs x 3600 sec/hrs / (8 bytes/bit) = 900 kbps

VLBI data **79,988 bytes x 8 (byte/bit) / 0.005 sec = 128 Mbps**

Figure 13-1: Data Contents of Ku Telemetry Headers

13.11 Time Corrections File

1. U. S. Space VLBI Project to VSOG
2. Green Bank Tracking Station to VSOG
3. Usuda Tracking Station to VSOG

Description: A time correction file will be constructed from the phase residual file and time difference file measured for each tracking pass. These files will be made available to the VSOG which will make the files available to the correlator. These data products are used for correcting the time tags on the wideband VLBI data.

Time: File will be supplied to the VSOG within 24 hours of the support period but no later than 4 days after the tracking pass.

13.12 Time Difference File

1. DSN 11-m Tracking Stations to GCF to U. S. Space VLBI Project

Description: Time differences between the tracking station clock and the one-second pulse in the telemetry data will be supplied to the U. S. Space VLBI Project by the DSN 11-m stations.

Time: File will be submitted within 24 hours after the support period.

13.13 Tracking Station Status Reports

1. Ground Tracking Stations to VSOG

Description: Status reports will be generated by each tracking station on a regular basis, nominally once a week, and submitted to the VSOG. The VSOG will have the responsibility of reviewing the reports and making recommendations to ensure the optimal performance of each mission element. These status reports from the mission elements will allow the VSOG to optimize the scheduling and execution of space VLBI experiments.

Time: File will contain a block of 7 days of time.

13.14 VLBI Tapes

1. Ground Tracking Stations to Correlators

Description: The wideband VLBI data will be recorded on VLBI tapes which will be dismounted from the recorder when the tapes have reached their capacity or after three elapsed days, whichever comes first. These tapes must arrive at the designated correlator within 2 weeks after being dismounted.

Time: Tape will be submitted no later than 2 weeks after the final support period included on the tape.

Chapter 14

GROUND RADIO TELESCOPE PRODUCTS

14.1 Ground Radio Telescope Log File

1. Ground Radio Telescopes to Correlators
2. Ground Radio Telescopes to VSOG

Description: Co-observing ground radio telescopes will each generate a log file similar to those for ground-based VLBI experiments. This log file will be made available to the designated correlator and to the VSOG.

Time: File will be submitted no later than 4 days after the support period.

14.2 Ground Radio Telescope Status Reports

1. GVWG to VSOG

Description: Status reports will be generated by the GVWG on a regular basis, nominally once a week, and submitted to the VSOG. The VSOG will have the responsibility of reviewing the reports and making recommendations to ensure the optimal performance of each mission element. These status reports from the mission elements will allow the VSOG to optimize the scheduling and execution of space VLBI experiments.

Time: File will contain a block of 7 days of time.

14.3 VLBI Tapes

1. Ground Radio Telescopes to Correlators

Description: The wideband VLBI data will be recorded on VLBI tapes of the type appropriate for the scheduled correlator for a given support session. These tapes must arrive at the designated correlator within 2 weeks after the observing session.

Time: Tape will be received at the correlator no later than 2 weeks after the support period.

Chapter 15

CORRELATOR PRODUCTS

15.1 Correlator Output

1. Correlators to Principal Investigators

Description: The correlation process will take place after the necessary files have been received. Nominally, the process will be completed within 6 weeks after the receipt of the required input, but may take longer for certain space VLBI experiments. The correlator will notify the principal investigator on the status of the correlation process and will supply the required files and documentation after the correlation is complete. The output files will be in FITS format.

Time: Output data will be available no later than 8 weeks after the support period.

15.2 Correlator Status Reports

1. Correlators to VSOG

Description: Each correlator will inform the VSOG of the status of correlating the space VLBI experiments. These status reports may include any anomalies noted in using the reconstructed orbit and delays in processing experiments.

Time: File will contain a block of 7 days of time.

15.3 Near-Real-Time Correlator Results

1. Usuda Near-Real-Time Correlator to SCG

Description: During the mission, it will be necessary to have periodic and quick checks of the space radio telescope performance using the near-real-time correlator at Usuda. In most cases, this will involve the Usuda tracking station and one or more Japanese telescopes (nominally the Usuda 64-m, Nobeyama 45-m, or the Kashima 34-m). Other telescopes may participate but this will involve international tape shipment and tape copying. The results from the correlation process will be used for pointing and calibration analysis. The data will be delivered to the SCG for detailed analysis.

Time: Periodic with results reported within days of experiment.

15.4 VLBI Tape Management

1. Correlators to Mission Elements
2. Mission Elements to Correlators

Description: Each correlator will maintain a data base including the status of all wideband tapes unit its control. The data base will be kept current by personnel at all mission elements, who have the responsibility to enter all changes in tape status (e.g. shipped, received, or recorded) at their mission element.

Time: Updates to TRACK for VLBA tapes or TBD for S2 and VSOP tapes when changes occur in status.

15.5 VLBI Tapes

1. Correlators to Ground Tracking Stations
2. Correlators to Ground Radio Telescopes

Description: After the correlation process, the wideband VLBI tapes will be erased and distributed into the global tape pool. It will be the responsibility of the correlators to distribute these tapes to ensure that the sites will have enough tapes to support space VLBI experiments.

Time: Tapes will be distributed to the global tape pool and sent out to mission elements at least once per week.

SPACE VLBI ACRONYMS

ASC	Astro Space Center
AGN	Active Galactic Nuclei
DOTS	Data Oversight & Transfer System
DSN	Deep Space Network
DRAO	Dominion Radio Astronomical Observatory
EVN	European VLBI Network
ftp	file transfer protocol
FWHM	Full Width Half Maximum
GB	Green Bank Tracking Station
GCF	Ground Communications Facility
GPS	Global Positioning System
GRT	Ground Radio Telescope
GVWG	Global VLBI Working Group
IMOG	International Mission Operations Group
IP	Internet Protocol
ISAS	Institute of Space and Astronautical Science
ISTS	Institute for Space and Terrestrial Science
JIVE	Joint Institute for VLBI in Europe
JPL	Jet Propulsion Laboratory
KSC	Kagoshima Space Centre
Mbps	Megabits per second
ME	Mission Element
NAO	National Astronomical Observatory
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
NAV	Navigation Groups
NFRA	Netherlands Foundation for Research in Astronomy
NRAO	National Radio Astronomy Observatory
NRT	Near-Real-Time
NSS	Network Support Subsystem
OTS	Orbiting VLBI Tracking Subsystem (DSN 11-m)
PI	Principal Investigator
PT	Pacific Time
S2-PT	S2 Playback Terminal
S2-RT	S2 Record Terminal
SCG	Satellite Control Group
SEFD	System Equivalent Flux Density
SRT	Space Radio Telescope
TS	Tracking Station
U. S.	United States
USD	Usuda Tracking Station

UTC	Universal Coordinated Time
VEX	VLBI Experiment
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VSOG	VSOP Science Operations Group
VSOP	VLBI Space Observatory Programme
VSOPT	VSOP Terminal Recording System
WSRT	Westerbork Synthesis Radio Telescope
XSOE	Executed Sequence of Events

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