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# INTERNATIONAL MISSION PLANNING FOR SPACE VERY LONG BASELINE INTERFEROMETRY

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## ABSTRACT

Two spacecraft dedicated to Very Long Baseline Interferometry (VLBI) will be launched in 1996 and 1997 to make observations using baselines between the space telescopes and many of the world's ground radio telescopes. The Japanese Institute of Space and Astronautical Science (ISAS) will launch VSOP (VLBI Space Observatory Programme) in September 1996, while the Russian Astro Space Center (ASC) is scheduled to launch RadioAstron in 1997. Both spacecraft will observe radio sources at frequencies near 1.7, 4.8, and 22 GHz; RadioAstron will also observe at 0.33 GHz. The baselines between space and ground telescopes will provide 3–10 times the resolution available for ground VLBI at the same observing frequencies. Ground tracking stations on four continents will supply the required precise frequency reference to each spacecraft, measure the two-way residual phase and Doppler on the ground-space link, and record 128 Megabit/s of VLBI data downlinked from the spacecraft. The spacecraft data are meaningless without cross-correlation against the data from Earth-bound telescopes, which must take place at special-purpose VLBI correlation facilities. Therefore, participation by most of the world's radio observatories is needed to achieve substantial science return from VSOP and RadioAstron. The collaboration of several major space agencies and the ground observatories, which generally follow very different models for allocation of observing time and for routine operations, leads to great complexity in mission planning and in day-to-day operations. This paper describes some of those complications and the strategies being developed to assure productive scientific missions.

*For the International Space VLBI Team

## INTRODUCTION TO SPACE VLBI

The Very Long Baseline Interferometry (VLBI) technique (e.g., Thompson, Moran, & Swenson 1986) has been used for over 25 years to maximize the angular resolution of radio-emitting astronomical objects. Widely separated radio telescopes simultaneously observe the same radio source at the same frequency. The data are digitized and recorded at a rate of over 100 Megabit/s on wideband videotapes or cassettes. A highly accurate clock at each telescope is used to time-tag the data. Following an observation, the recorded data are physically transported to a special-purpose correlation facility; information about the observing conditions, recording, and calibration at each telescope also is transmitted to the VLBI correlator. Cross-correlation of data from each pair of radio telescopes is performed to derive the source "visibility" as a function of baseline length and orientation. The collection of source visibilities then is used by the radio astronomer to model or map the radio source and derive various astrophysical parameters.

At a given observing frequency, the resolution of ground-based VLBI is limited by the physical dimensions of the Earth. At the common VLBI observing frequency of 5 GHz, a 10,000-km baseline corresponds to an interferometer fringe spacing of about 1.2 milliarcseconds. Higher resolution can be obtained either by using a higher observing frequency or by placing one telescope of a VLBI system in space, first suggested seriously in the late 1970s (e.g., Preston, Hagar, & Finley 1976; Burke & Roberts 1979). Since different source components dominate at different frequencies, and brightness-temperature measurements depend on the physical baseline length rather than the angular resolution, the two approaches to higher resolution can be viewed as complementary.

Space VLBI (SVLBI) observations present challenges beyond those found in ground-based VLBI experiments. Cross-correlation requires an accurate model for the relative signal delay (and its derivatives) for each telescope pair. When one telescope is in space, this requirement translates to a need for highly accurate orbit determination. The observing frequencies and time of reception for each data sample must be accurately known, requiring a frequency reference on the spacecraft that is comparable in quality to a hydrogen maser. This reference can be generated by transferring the stability of an Earth-based frequency standard from each tracking station to the spacecraft; residuals from the two-way link are recorded for use at the correlator. Because VLBI data must be recorded at a rate of more than 100 Megabit/s for extended periods, a wideband downlink is necessary. Finally, the ancillary data required for correlation must be constructed from a combination of spacecraft telemetry and tracking-station logs.

The technology required for SVLBI was demonstrated in a series of observations carried out from 1986 through 1988 (Levy et al. 1986, 1989; Linfield et al. 1989, 1990). In those experiments, the Tracking and Data Relay Satellite System (TDRSS) was used together with large radio telescopes in Japan and Australia to observe a number of radio sources at frequencies of 2.3 GHz and 15 GHz. Interference fringes were found on baselines as long as 2.15 Earth diameters (close to the maximum baseline sampled), and crude models were made of the observed radio sources. The successful observations demonstrated the technical feasibility and scientific potential of SVLBI observations, and have led directly to the dedicated SVLBI satellites that are scheduled for launch in the next several years.

## VSOP AND RADIOASTRON MISSIONS

The VLBI Space Observatory Programme (VSOP) satellite will be launched in September 1996 by the Japanese Institute of Space and Astronautical Science (ISAS). The RadioAstron spacecraft, part of the Spectrum series of missions under development in Russia, is being built by the Astro Space Center (ASC) and the Lavochkin Association and is scheduled for launch in 1997. Each spacecraft will carry an 8–10 meter deployable radio telescope together with receivers capable of making observations at standard VLBI frequencies in the gigahertz range. The nominal mission lifetimes are approximately 3 years. VSOP will be in an elliptical orbit with an apogee height of about 22,000 km, while RadioAstron will be in an elliptical orbit with an apogee height of about 77,000 km. Table 1 summarizes a number of the features of the missions, while Figures 1 and 2 are sketches of the two spacecraft. The primary scientific goals of both spacecraft will be the imaging and modeling of the nuclei of active galaxies (quasars, BL Lacertae objects, and radio galaxies) as well as investigations of OH and $H_2O$ maser emission within our own Galaxy. Although the operational lifetimes of the two spacecraft are expected to overlap, they will operate independently in the sense that they generally will not observe the same sources simultaneously.

Table 1. SVLBI Mission Characteristics

| Mission | VSOP | RadioAstron |
|---|---|---|
| Telescope | 8 m | 10 m |
| Mass | 800 kg | 5000 kg |
| Data Rate | 128 Mb/s | 128 Mb/s |
| Frequency | 22 GHz<br>4.8 GHz<br>1.7 GHz | 22 GHz<br>4.8 GHz<br>1.7 GHz<br>0.33 GHz |
| Perigee Ht. | 1,000 km | 4,000 km |
| Apogee Ht. | 22,000 km | 77,000 km |
| Period | 6.6 hr | 28 hr |
| Inclination | 31° | 51° |

Both spacecraft will make use of an uplink tone near 8 GHz (RadioAstron) or 15 GHz (VSOP) to establish the on-board frequency reference. On-board transponders will enable round-trip links with the ground tracking stations. The two-way phase on this link will be used to establish the error in the spacecraft frequency standard and to derive Doppler data needed for accurate orbit determination. Each spacecraft will downlink the wideband VLBI data at 15 GHz. For further descriptions of the RadioAstron and VSOP missions, see Kardashev and Slysh (1988) and Hirosawa (1991), respectively.

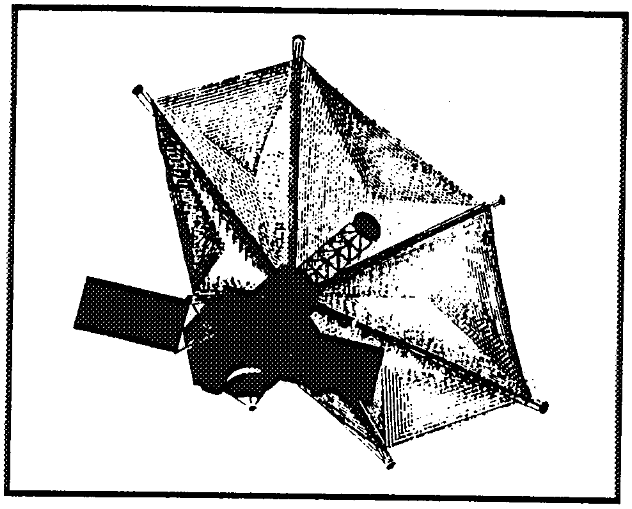

Figure 1. Sketch of VSOP spacecraft.

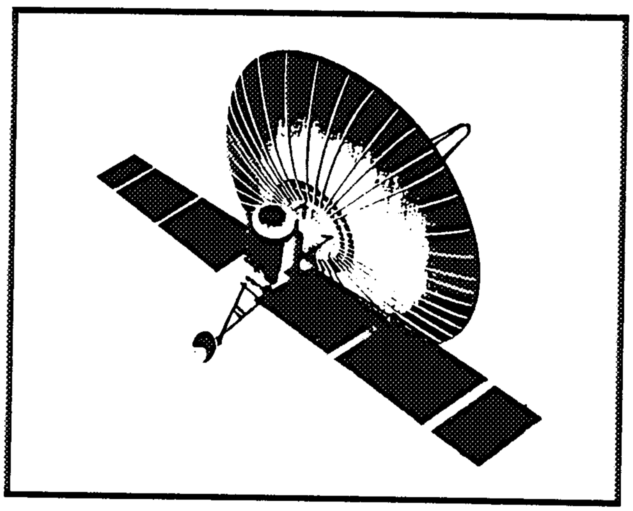

Figure 2. Sketch of RadioAstron spacecraft.

Because of the need to maintain a two-way phase link and a wideband data link during observations, scientific data can be gathered only when a spacecraft is in direct contact with a ground tracking station. Furthermore, the quality of the scientific results depends critically on the sampling of the aperture plane by the space-ground baselines, so a globally distributed tracking network is crucial to the success of VSOP and RadioAstron. Therefore, the U.S. National Aeronautics and Space Administration (NASA) is funding four ground stations that will be dedicated to tracking the two spacecraft. Three new 11-m antennas will be built, one each at the NASA tracking complexes in California, Spain, and Australia. A fourth station will be at the National Radio Astronomy Observatory (NRAO) facility in Green Bank, West Virginia, and will make use of an existing 14-m antenna. In addition, VSOP will be tracked by a new 10-m antenna to be built at Usuda, Japan, while RadioAstron will be tracked by a 32-m antenna at Ussuriisk (near Vladivostok), Russia, and possibly by another antenna near Moscow.

## INTERNATIONAL PARTICIPATION IN VSOP AND RADIOASTRON

The spacecraft tracking described above is only one aspect of the substantial international participation in the VSOP and RadioAstron missions. The flight receivers for RadioAstron are being built by Finland (22 GHz), the European Space Agency (4.8 GHz), Australia (1.7 GHz), and collaboratively by India and Russia (0.33 GHz). Highly accurate orbit determination will be provided by Japanese and Russian agencies and by NASA's Deep Space Network (DSN).

A required element unique to SVLBI is the participation of large networks of ground radio observatories, most of which are independent of the agencies building and tracking the spacecraft. Some of these ground observatories not affiliated with space agencies include the Very Long Baseline Array, the Very Large Array, and the 100-m Green Bank Telescope now under construction, all operated by NRAO; the members of the European VLBI Network, consisting of telescopes in England, Germany, the Netherlands, Sweden, Italy, and China, as well as associate members in Poland, Ukraine, Russia, Finland, Germany, and France; the Australia Telescope National Facility; Nobeyama Radio Observatory (Japan); the Communications Research Laboratory (Japan); Hobart Observatory (Australia); Hartebeesthoek Observatory (South Africa); and the Giant Metre Wave Radio Telescope (India). Other participating radio telescopes more closely related to the space agencies include the 70-m antennas of the NASA DSN, the 64-m ISAS antenna at Usuda, and the 70-m antennas located in Russia (Ussuriisk) and in the Ukraine (Evpatoria). Each observatory has its own method of allocating time among a variety of scientific requests, including VLBI and a host of other radio astronomical programs. Although the ground telescopes are required for any science return from VSOP and RadioAstron, most are not under the control of the space missions. Therefore, a significant aspect of the planning for VSOP and RadioAstron has been the process of negotiation between the space missions and ground observatories, wherein the needs of the missions are balanced with the other scientific priorities of the observatories.

The primary bodies established for the scientific management of the missions are the RadioAstron International Scientific Council (RISC) and the VSOP International Scientific Council (VISC). Each is co-chaired by a representative of the Russian (RISC) or Japanese (VISC) project and a representative of the outside international community. The RISC and VISC contain representatives of the Russian and Japanese projects, foreign space agencies, and other participating organizations (including ground observatories). Because VSOP and RadioAstron face many of the same problems and must share resources such as tracking stations, ground telescopes, and correlation facilities, there is considerable overlap between the membership of the VISC and the RISC. Each organization meets formally twice per year, with additional informal discussions held during other international meetings.

## SCIENTIFIC ACCESS AND GROUND OBSERVATORY PARTICIPATION

The policies for granting observing time on VSOP and RadioAstron are the subject of ongoing discussions that will be completed only when the announcements of opportunity are formally released. The standard practice for space astrophysical observatories has been to reserve some fraction (up to 100%) of the observing time for those individuals and organizations that have built the spacecraft or contributed scientific instruments. This reserved time often is used to carry out key science programs that are the primary goals of the missions. In contrast, the long-standing practice of most radio observatories is one of open access based solely on scientific peer review and independent of an individual's organizational or national affiliation; they typically have little or no reserved time. However, it is not possible to schedule SVLBI programs without some guarantee that particular time periods will be made available to the space missions by the ground observatories, since the scientific return of any specific observation depends critically on the distribution of the participating ground telescopes.

For both VSOP and RadioAstron, the agreements that have been made to date specify an open peer-review process based on scientific merit and technical feasibility of each proposal. Scientific referees will be selected from among nominees provided by the participating organizations. A few key science programs (e.g., a survey for high brightness temperature, or monitoring of superluminal motions) will be listed in the announcements of opportunity. Many of the members of the key science teams may be selected based on their proposals. Representatives of organizations that have made substantial contributions to the spacecraft and mission development also may be added to the key science teams by the RISC and the VISC.

The Global VLBI Working Group, consisting of the directors of major radio observatories or their representatives, has negotiated ground-telescope participation with the space missions. Based on the general philosophy of access for the highest quality science, many ground observatories have now made commitments of some fraction of their observing time for at least the first year of the SVLBI missions. The expectation is that those commitments will be renewed if the quality of the science return during the first year is commensurate with that of the other science being done by these observatories. Typical commitments from the majority of the world's major radio observatories range from 10% to 30% of their total observing time in a year. In most cases, the commitments have been made to a general SVLBI pool of observing time that would cover both missions, with the understanding that the missions will divide that time as scientifically appropriate. Despite the substantial commitments of time from ground observatories, the need for significant numbers of telescopes to observe for a large part of a day in order to produce a single SVLBI image implies that the scientific return of the missions may be limited by the lack of ground telescopes, particularly if both spacecraft are in orbit simultaneously. Extensive observing simulations are in progress to determine the minimum numbers of ground telescopes required to make observations of different types. Ultimately, it may be up to the investigators, the scientific reviewers, the international science councils, and the scheduler(s) to determine the scientific tradeoffs between a large number of observations employing a minimal number of telescopes and a smaller number of observations using more ground telescopes.

## SCIENTIFIC SIMULATIONS AND SCHEDULING

The planning of the missions and analysis of the scientific return has benefited tremendously from the development of a variety of software packages that simulate different aspects of the missions. Simulation packages have been developed by D. Murphy at the Jet Propulsion Laboratory (JPL); R. Taylor and G. Young at the University of Calgary; H. Kobayashi and collaborators at ISAS; L. Gurvits, V. Yakimov, and collaborators at ASC; and I. Fejes and collaborators at the Institute of Geodesy, Cartography, and Remote Sensing in Hungary. (See Fejes et al. 1994, and Murphy et al. 1994.) One of the most important functions of the software is to simulate the aperture-plane coverage for different combinations of tracking stations and ground telescopes, given the known spacecraft constraints. The packages can produce plots of the aperture-plane coverage as a function of source position or time for an assumed set of participating ground telescopes, and some also analyze the detection thresholds and image quality for those coverages for an assumed source model. Two early successes of the JPL simulations were the realizations that the VSOP telemetry antenna mask and a RadioAstron radiator constraint significantly reduced the missions' scientific returns; subsequent redesigns reduced or removed those constraints.

The continuing development of the simulation software has two main goals. The first goal is to use simulations as an aid in scheduling the missions. The software would be used to analyze the technical feasibility of proposals and the possible tracking scenarios. Analyses of the aperture-plane coverage as a function of time (particularly important for the rapidly precessing orbit of VSOP) will be used to find the optimum time to schedule a particular scientific observation. As an example, Figure 3 shows the synthesized aperture for a 5-GHz observation of 3C 345 using the combination of VSOP and the 10 VLBA telescopes at three different epochs separated by six months each (from the software written by D. Murphy). This diagram plots the east-west and north-south components of all sampled interferometer baselines. The top and bottom panels show changes in the synthesized aperture over time due to precession of the spacecraft orbit. The middle panel has no space-ground baselines because the radio source lies within 70° of the Sun and cannot be observed by the spacecraft. Two major differences between space-ground and ground-only VLBI are readily apparent: (1) the projected baselines for the ground telescopes alone (see middle panel) are much shorter than the space-ground baselines; and (2) the ground baselines (inner portion of all three panels) do not change from month to month.

The second use for the simulation software will be as an aid to the prospective user. The user software and associated user guides will be integral parts of the announcements of opportunity. It currently is thought that the main software packages to be used in proposal preparation will be those developed at JPL and at the University of Calgary. These packages will be used as a tool to familiarize the prospective user with the complexities of the SVLBI missions. Details of particular observations then can be simulated, enabling a stronger proposal to be written. The tools will also reduce the number of technically infeasible observations that are proposed, thus reducing the workload in the proposal evaluation process.

A strawman scheduling program has been developed by D. Meier of JPL (Meier 1994) to determine the need for ground radio telescopes in support of SVLBI observations. After making assumptions about the minimum number of telescopes needed for particular types of observations, the total requirements on the world's ground radio telescopes have been analyzed for the case when either VSOP or RadioAstron is flying alone, or when the two are in operation simultaneously. These requirements were of great use in the aforementioned negotiations for guaranteed ground radio telescope time.

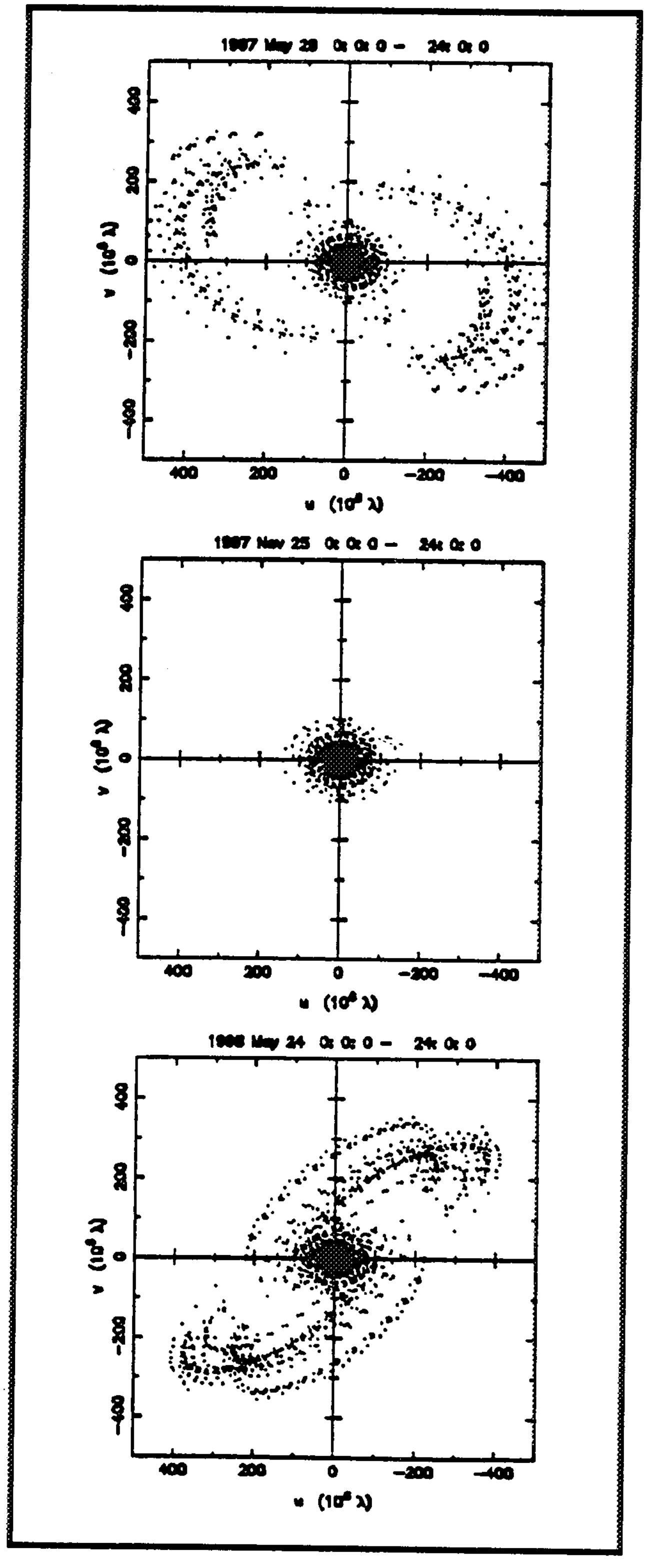


Figure 3. Aperture-plane coverage for 5-GHz observations of 3C 345 at 6-month intervals, using VSOP and the VLBA. Projected baselines are given in units of millions of wavelengths.

Additional software will be used to create the scientific observing schedule. This software would require inputs such as the source coordinates, the set of ground telescopes available at a particular frequency, and the quality of the aperture plane coverage as a function of time (based on the simulation software). The output would be an observing program that would achieve a high scientific return for a given set of constraints on ground and space resources. Because of the need to finalize the precise commitments of the ground telescopes, this schedule would be produced up to one year in advance of the appropriate observation period, but the scheduling procedures also must be flexible enough to accommodate contingencies aboard the spacecraft or at any of the supporting ground facilities.

## MISSION OPERATIONS

The details of the operations of VSOP and RadioAstron have been entrusted to two parallel groups, the RadioAstron Science Operations Group (RSOG) and the VSOP Science Operations Group (VSOG). The groups' membership consists largely of representatives of the space agencies operating the spacecraft, but also includes affiliated international members such as the developers of the simulation software and (ultimately) representatives of the key science teams. The responsibilities of the RSOG and VSOG include preparation of the announcements of opportunity, development of simulation and scheduling software, production of both scientific and detailed schedules, allocation of ground resources, coordination of the daily operations of all international mission elements, calibration of the space radio telescope data, and overall mission performance assessment. Much of the work on simulations and scheduling has been, and will continue to be, performed under the auspices of the VSOG and RSOG. In the end, the scientific success or failure of VSOP and RadioAstron will depend on the effectiveness of the VSOG and RSOG in coordinating all the international participants.

The VSOG and RSOG have concentrated heavily on the duties involved with pre-launch science planning. Recently, a subgroup to both the VSOG and RSOG was formed in order to coordinate pre-launch planning of mission operations. This team includes representatives of the different space agencies, tracking stations, and correlation facilities. Its key responsibility is the development of the detailed interfaces and procedures needed for exchange of data such as schedules, phase residuals, and correlator input logs. It also participates in development of plans for the in-orbit checkout phases and in generating agreements on the operational responsibilities of all mission elements.

A key aspect of the mission operations for SVLBI is the development of a reliable international system for data transfer. Schedule files and required updates must be made available in a timely fashion. A variety of tracking, telemetry, and VLBI data must take different, sometimes circuitous paths before arriving at the correlation facilities. The relative paucity of operations personnel implies that all data-transfer tasks must be automated as much as possible. Details of the international data transfer system for SVLBI, including the generation of correlator input files, are presented at this conference in a paper by Wiercigroch (1994).

## ORBIT DETERMINATION

The primary means of orbit determination for VSOP and RadioAstron will be the two-way Doppler data derived from the 15-GHz and 8-GHz links between tracking stations and spacecraft. These data will be supplemented by range and range-rate data from the spacecraft command stations. Accurate predicted orbits are needed for the tracking stations to follow the spacecraft and to keep the two-way phase residuals at an acceptably low level. More accurate spacecraft trajectories, with position and velocity errors less than 100 meters and 1 cm/s, respectively, are required for the correlator models. In addition, acceleration errors much smaller than $10^{-7}$ m/s$^2$ are needed to enable long coherent integration times. Covariance analyses have revealed that the most difficult problem will be that of achieving the velocity and acceleration requirements near spacecraft perigee.

The two-way Doppler data used for orbit determination must be derived using a two-way phase link that is a new feature for both VSOP and RadioAstron. The tracking stations under construction by different agencies have different implementations for that link and the derivation of the Doppler data. It remains to be seen whether they will yield data of comparable quality in order to produce the accurate orbit required for data correlation.

## DATA ANALYSIS

VLBI data are recorded in real time, with the recordings brought together later for pairwise cross-correlation at a special purpose correlator. The VLBI correlators use models of delay and delay-rate to determine the window used for cross-correlation; fits to the correlator output are used to determine the location of the interference fringes and to derive visibility functions from the output data. The permitted values of delay and delay-rate must be considerably larger in SVLBI than for ground-only VLBI because of the longer baseline and higher relative speed between space and ground telescopes. Since one element is not fixed to the Earth, a new correlator interface must be built to include a spacecraft trajectory in the model. Measurements of the residual phase on the link between tracking station and spacecraft must be input at least 10 times per second in order to account for frequency variations caused by effects such as orbit errors and propagation of the uplink tone through the Earth's troposphere and ionosphere. Each VLBI correlator is a one-of-a-kind system of hardware, firmware, and software, and presents a unique technical challenge to the processing of SVLBI data.

The standard software used for analyzing much of the world's radio interferometry data is the Astronomical Image Processing System (AIPS), developed by NRAO; VLBI data are also processed using other software such as that developed at the California Institute of Technology. AIPS is being upgraded by NRAO in order to be capable of processing SVLBI data. New routines are being written to improve the detection of weak interference fringes and to follow those fringes forward or backward in time. Special-purpose software also is being written to enable improved modeling of the radio sources. Tests of some parts of this software have been performed using the experimental SVLBI data obtained with TDRSS, and more are anticipated in the future.

Problems associated with proposing SVLBI observations and analyzing the resulting data will be considerably more formidable than those associated with ground VLBI. Therefore, the international participants in the SVLBI missions need to provide as much assistance as possible to the scientists interested in using those missions. The simulation software described previously is an important part of the response to this challenge. On-line information, workshops, and articles in newsletters and the scientific literature also are being developed in order to assist prospective users. User support in analyzing SVLBI observations using the AIPS software will be made available by NRAO at their facility in New Mexico. Other mission participants will provide more limited support of data analysis.

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# Mission Management



* *Presented in Poster Session*

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