NAVIGATION OF SPACE VLBI MISSIONS: RADIOASTRON AND VSOP

Jordan Ellis

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

N94-23926

Abstract

In the mid 1990s, Russian and Japanese space agencies will each place into highly elliptic earth orbit a radio telescope consisting of a a large antenna and radio astronomy receivers. Very Long Baseline Interferometry (VLBI) techniques will be used to obtain high resolution images of radio sources observed by the space and ground based antennas. Stringent navigation accuracy requirements are imposed on the Space VLBI missions by the need to transfer an ultra stable ground reference frequency standard to the spacecraft and by the demands of the VLBI correlation process. Orbit determination for the missions will be the joint responsibility of navigation centers in the U.S., Russia and Japan with orbit estimates based on combining tracking data from NASA, Russian and Japanese sites. This paper describes the operational plans, the inter-agency coordination and data exchange between the navigation centers required for space VLBI navigation.

Key words: Space VLBI, Navigation, Cross-support

1. Introduction

Very Long Baseline Interferometry (VLBI) techniques from ground based antennas have been extensively used to map celestial radio sources. For earth based antennas, the angular resolution is limited by the maximum baseline between radio telescopes which is effectively the diameter of the earth. Longer baselines and thus greatly increased resolution and sensitivity can be attained by placing one of the antennas in earth orbit. In the 1995-96 time frame, Russian and Japanese space agencies each plan to orbit a dedicated radio telescope. The space radio telescopes will observe astronomical radio sources simultaneously with a world wide network of ground radio telescopes. Correlation of the signals received by the space and ground antennas is expected to yield high resolution images of the observed source.

Japan's Institute of Space and Astronautical Science (ISAS) is planning to orbit a 7.2 meter antenna in August '95 using the new M-V booster. The Japanese mission VSOP will be in a 1000 by 20,000 km orbit with a 6.06 hour period and a 31 degrees inclination. In late '95 or early '96, the Russian Astro Science Center (ASC) will orbit a radio telescope with a 10 meter antenna. The Russian spacecraft Radioastron will be placed into a 28 hour orbit with a perigee height of 4000 km, an apogee of 76,800 km and an inclination of 51.5 degrees.

The U.S. will participate in the VLBI science in exchange for tracking and navigation services by the Deep Space Network (DSN) and co-observation and correlation by facilities of the National Radio Astronomy Observatory (NRAO). Extensive international collaboration between the space agencies and between the multi-national VLBI community will be required to maximize the science return. Schedules for an international network of VLBI radio telescopes will be coordinated to ensure the ground antennas and spacecraft antenna are simultaneously observing the same sources. An international network of ground tracking stations will also support both spacecraft. The tracking stations will record science data downlinked in real time from the orbiting satellites, transfer a stable phase reference and collect two-way doppler for navigation.

Navigation of the Space VLBI (SVLBI) missions is unique in the sense that they are both highly elliptic earth orbiters-with relatively stringent navigation requirements for orbit prediction and orbit reconstruction. Orbit determination will be the joint responsiblity of navigation centers in the U.S., Russia and Japan. The primary data type available for navigation is two-way doppler which is generated by the reference phase transfer operation. Since orbit determination for each spacecraft is dependent on using tracking data from several tracking sites, cross-support from the international ground network is essential for meeting accuracy requirements.

This paper describes the operational plans at the U.S. navigation center and the inter-agency coordination and data exchange between the navigation centers required for SVLBI navigation. Elements of this plan include agreements on navigation requirements, tracking strategies, common reference frames and astrodynamics constants; and formulation of compatibility tests to demonstrate the consistency of spacecraft dynamic models, observational models, tracking station locations and orbit estimation techniques. The navigation centers are expected to exchange orbit solutions, tracking data and an assessment of the orbit accuracy. The Mission Control Centers will provide the planned and actual maneuver and antenna pointing data required for modelling the spacecraft dynamics.

2. Navigation Requirements

The Space VLBI missions have science and operational objectives which translate into navigation requirements that are more stringent than those typically encountered for highly elliptic earth orbiters. For the space VLBI missions, there is a need to continuously uplink an ultra-stable ground reference frequency standard to the satellites to provide a phase stable reference for the on-board receiver. A time varying uplink frequency

is transmitted to the spacecraft which is corrected for the predicted doppler shift so that a nearly constant frequency is received at the spacecraft. This signal is coherently retransmitted by the spacecraft to the tracking site where a predicted downlink shift is removed from the received signal to minimize ground receiver tracking loop degradation.

Doppler shifts are computed from the predicted orbit solutions. Accuracy requirements for the predicted orbit arise due to constraints on the maximum round trip phase residual error which can be sampled. The 400 Hz sampling rate used at the NASA tracking stations translates into a maximum downlink frequency error of 175 Hz (3 sigma).

Correlation of the VLBI data received by the orbiting satellites and the ground VLBI network imposes another more stringent level of accuracy requirements on the post flight orbit knowledge. Specific accuracy requirements for the reconstructed orbits are dependent on the characteristics of the VLBI correlator.

Table 1 Navigation Requirements

	Radioastron	VSOP
Predicts		
Position	480 m	170 m
Velocity	46 cm/s	27 cm/s
Knowledge		
Position	90 m	45 m
Velocity	1 cm/s	2 cm/s
Acceleration	6.8×10^{-8} m/s^2	3.0×10^{-8} m/s^2

Table 1 summarizes the (one sigma) accuracy requirements which have been by formulated by R. Linfield (Ref 1) assuming specifications for the NRAO/VLBA correlator and the DSN tracking stations. Requirements are expressed as one sigma errors in one dimension. The predicted velocity error represents the component along the tracking station to satellite line of sight and the position error the component along the projection of the velocity vector in the plane of sky. A minimum altitude of 2500 km is assumed for VSOP based on visibility constraints. Reconstruction accuracies are defined for component along the direction to the observed radio source.

3. Tracking System Plans

3.1 Tracking Stations

The VLBI experiment requires lengthy uninterrupted reception of a radio signal at the radio telescope receiving sites. During the VLBI sessions, uplink phase control must be maintained for the ground to spacecraft link. This requirement for continuous contact motivates the use of a world wide tracking network to support science data acquisition, phase transfer and acquisition of radio metric data throughout the orbit.

A combination of Russian, Japanese and NASA tracking stations will provide operations support for the two space VLBI missions. A four station Orbiting VLBI Network is being implemented by NASA. This network includes

a new 11 meter antenna at each of the DSN complexes at Goldstone, Madrid and Canberra; and conversion of an existing 14 meter antenna at the NRAO site at Green Bank. The Russian space agency is upgrading a 32 meter antenna at Ussuriisk to track Radioastron, and ISAS is planning a dedicated antenna at Usuda for tracking VSOP.

The advantages of cross-support from the multi-national network is apparent when considering the station view periods for the space VLBI missions. Radioastron is injected into an orbit with a perigee in the southern hemisphere to maximize coverage from Russian sites.

Since the rate of precession of periapsis is less than 8 degrees/year, (and node less than 15 degrees/year) station view periods for Radioastron are reasonably constant and repeat with a 6 day cycle. During this cycle, the spacecraft is visible only 53 percent of the time from Ussuriisk. The addition of the four NASA stations increases the coverage to 97 percent. Perigee is primarily visible from Canberra.

For VSOP, the situation is very different; perigee is initially in the northern hemisphere to facilitate communication with the booster stage. However the argument of periapsis precesses at a rate of 0.96 degrees/day. Consequently, view periods will change significantly throughout the year. Canberra has the longest view periods after launch and the northern stations 6 months later.

3.2 Tracking Data Characteristics

Each tracking station will be equipped to receive the wideband signal from the spacecraft, transmit a phase reference signal, receive the coherent downlink and generate doppler data for navigation. The Radioastron mission will use a two-way coherent X-band link for phase control and Ku-band for wideband data downlink; the Japanese will use Ku-band for both functions. The NASA stations will accomodate both uplink frequency bands, while the national stations will support only the frequency band for their respective spacecraft.

All stations are expected to be capable of generating two-way coherent doppler for use by navigation. Doppler is routinely collected during the phase transfer process. Consequently nearly continuous coverage is available for the 28 hour Radioastron orbit; and typically 12-22 hours of daily coverage is available for VSOP.

A two-way doppler compensated phase which has predicted uplink and downlink doppler shifts removed is recorded at the receiving stations. Use of this observable for navigation requires recovery of the actual doppler shift and knowledge of the uplink frequency. Since the uplink frequency may change 400 times per second, a two-way doppler shift is constructed based on a pseudo constant uplink. The predicted uplink and downlink doppler shifts are added to the measured phase residual and the resulting doppler shift is normalized to a known constant uplink frequency. NASA stations are expected to generate two-way coherent doppler with a random error of 0.1mm/sec (1 sigma) for a 60 second count time

and a systematic bias of $0.1mm/sec$. The latter is due to the phase reconstruction procedure.

In addition to the two-way doppler generated during the phase transfer process, other data types may be available for determining the orbit. A C-band radio link is used for spacecraft operations by the Radioastron Mission Control Center which is located in Eupatoria. During the daily commanding sessions, three 8-10 minute passes of two-way C-band range and doppler are typically scheduled. ISAS will command and receive spacecraft engineering data from VSOP using an S-band link from Kagoshima. Nearly continuous two-way range and doppler will be received during these passes. VSOP will also carry a GPS receiver which can directly provide estimates of the orbit during GPS visibility periods. However,the GPS receiver is considered primarily a technology demonstration.

4. Navigation Covariance Study Results

Independent navigation studies were conducted by the three agencies to determine tracking strategies for satisfying accuracy requirements and identifying dynamic and observational modelling errors limiting the navigation performance (Refs 2-5). Orbit determination accuracies were evaluated for different data strategies, assuming unmodelled errors due to solar pressure, attitude control accelerations, earth's geopotential, station locations, doppler bias and media effects. The studies confirmed the feasibility of satisfying requirements using primarily the extensive two-way doppler collected throughout each orbit as part of the phase transfer process.

A brief summary of the principal conclusions are as follows:

1. For Radioastron, navigation accuracy requirements are satisfied with a tracking span that includes at least 22 hours of X-band doppler data for one 28 hour orbit collected from at least two sites. Data from only a single site is not adequate. Orbit accuracies are considerably enhanced if tracking data can be collected in the vicinity of periapsis (ie $\pm3hrs$) where the dynamic changes are a maximum. This criteria can be met with C-band ranging passes during commanding sessions or doppler data from Canberra.

2. The VSOP requirements are met by processing doppler data collected for a 24 hour span covering four orbits. Typically, the data span may include up to 4.5 hours per orbit or 18 hours for a 24 hour span. It should be emphasized that the requirements need only be satisfied for segments of the orbit where it is feasible to collect VLBI data. This is fortunate since predicts requirements are more stringent at lower altitudes and would be difficult to satisfy below 2500 km.

3. The dominant unmodeled errors are due to solar pressure acceleration errors, and errors introduced by station locations and the doppler bias. Plans are being formulated by the navigation agencies to reduce the effect of these error sources. Comprehensive solar pressure models have been developed and an effort is underway to measure the reflectivity properties. An operational interface has been established to utilize the science viewing schedule for predicting the orientation of the spacecraft antenna which in turn influences the solar pressure effects. Efforts are also underway to use GPS and VLBI techniques to determine the location of the tracking stations in a consistent reference frame. Improved station location estimates of Ussuriisk and Usuda will be determined from VLBI observations between antennas at these sites and at DSN sites

5. Navigation Support Plans

5.1 Agency Roles

Orbit determination will be the joint responsibility of navigation centers in the U.S., Russia and Japan. The Flight Control Center in Kalliningrad and JPL's Multimission Navigation Center in Pasadena will share responsibility for determining the Radioastron orbits using data from the Russian tracking sites and from the four NASA sites. Similarly, the JPL navigation center and the ISAS navigation center in Sagamihira will be responsible for orbit determination for VSOP using data from the Japanese and NASA sites. GPS based solutions may also be available for VSOP.

Orbit solutions, independently determined by each center, will be exchanged, solution differences resolved and the accuracy of the solutions evaluated. The overall objective of this exchange is demonstrate the consistency of the solutions computed by each agency. It is expected that each navigation center will be responsible for providing predicted orbits for use at their respective tracking sites and reconstructed orbits for use at their national VLBI correlation center.

5.2 JPL Operations Plans

JPL navigation will independently determine Radioastron and VSOP orbits using tracking data from all supporting sites. Predicted orbits for a seven day period will be computed twice per week and distributed to the DSN tracking sites for acquisition and phase transfer. Orbit files will be delivered using the standard DSN interface. State vectors will also be provided to the Russian and Japanese navigation centers.

Post flight (reconstructed) orbits will be computed bi-weekly using all available tracking data. The resulting ephemerides will be delivered to the U.S. Space VLBI project center for distribution to the NRAO VLBI correlator and to other potential users. Ephemerides will be distributed in a standard portable format using JPL's Navigation Ancillary Information Facility to prepare the files. Figure 1 illustrates the navigation data flow for the JPL center.

Reconstructed orbit solutions for Radioastron will cover one 28 hour orbit period and will be determined by fitting data collected during a 28-32 hour span. VSOP orbits will be based on fitting data over four orbits. The correlation activity is also expected to provide the navigation centers with an independent assessment of the orbit accuracies.
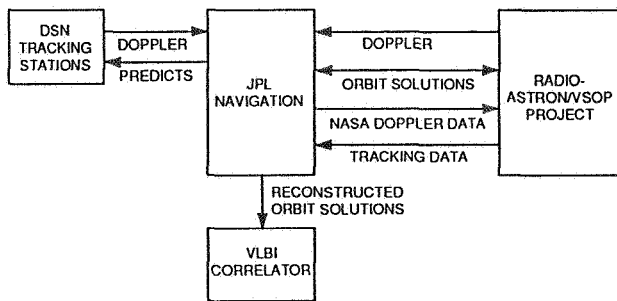
Fig 1. DSN Navigation Data Flow

5.3 Data Exchange Plans

This multiagency orbit determination requires extensive coordination between the navigation centers and the Mission Control Centers. Long term planning information on spacecraft events that affect the spacecraft dynamics will be provided by the Mission Control Centers. This includes maneuver plans, a schedule of radio sources to be viewed, and spacecraft antenna and solar panel orientation data. A 30 day schedule will be transmitted twice per month for use in the computation of predicted orbits.

The navigation centers will exchange state vectors and all tracking data collected by their respective sites twice per week. Tracking data will be corrected for troposphere and ionosphere effects before transmission. Updates of actual antenna pointing and maneuver data will be also be distributed at this time. JPL navigation deliverables will be stored in a data base maintained by the U.S. Space VLBI Project which will be accessible by external users.

6. Compatibility Test Plans

A key task in this cooperative navigation effort was to define a standard set of constants, dynamic models and reference frames to be used by the navigation centers. At the outset, the agencies agreed to adopt the J2000 reference frame, a DE200 planetary ephemeris and a GEM T2 geopotential model. Astrodynamics constants, time transformations, solid earth and ocean tidal models are to be based on the standards in IERS Technical Note (1989).

A series of studies were initiated to identify dynamic effects which must be modeled to satisfy accuracy requirements and to demonstrate the compatibility of the trajectory propagation procedures. It was agreed to include Newtonian point mass accelerations for planets and moon, relativistic perturbation accelerations for the Sun and Earth, a geopotential of at least order 17 and solid earth and ocean tides and solar radiation pressure. Atmospheric drag effects will also be modeled for VSOP.

Procedures for modeling the solar radiation pressure accelerations due to the spacecraft antenna, solar panels and bus have been adopted and results of the software implementation are currently being compared. The Lavochkin Association is tasked to determine the reflectivity properties of the components of the Radioastron spacecraft. ISAS will provide similar data for VSOP.

A three stage compatibility test program is being pursued to demonstrate that consistent orbit determination results can be obtained by the three navigation teams. This plan is similar to the one followed by the U.S. and Russian navigation centers in preparation for supporting the Mars PHOBOS mission. The first phase entails detailed testing of the dynamic models assumptions by comparing results of trajectory propagation. The second phase will be to validate the observational modelling assumptions used for processing the exchanged radio metric data. Detailed debugging type comparisons will be made of all the intermediate quantities generated in the computation of a single computed observable. Data for a representative earth orbiter will also be processed by each facility and data residuals compared. The final test is an end-to-end test designed to demonstrate the consistency of the estimation procedures and to validate the data exchange formats and procedures.

Concluding Remarks

With expected mission lifetimes of 3-5 years, the space VLBI missions represent one of the most intensive and long term applications of the concept of cross-support. It is only with the support from an international ground network and the collaborative efforts of the multi-agency navigation centers that full benefits of the mission science may be realized.

References

1. Linfield, R. "Orbit Determination Requirements for VSOP and Radioastron" JPL Internal Memo, June 6,1991.

2. Ellis, J., and Estefan, J.A. "An Assessment of Soviet Capabilities for Radioastron Navigation", JPL IOM 314.7-119, Feb.25, 1991.

3. Pavlov, V et al, "Spectr-R Mission Control Organization", S.A.Lavochkin Association, ASC, JPL,BC , March 1992.

4. Estefan,J., Christensen, C. and Ellis, J., "Japanese and DSN Orbit Prediction Capability for the VSOP Mission", JPL IOM 314.5-1551, July 1,1991.

5. Ichikawa, T., "Japanese VSOP Navigation and Orbit Determination", ISAS presentation at VSOP Working Group Meeting, Tokyo, June 1992,