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INTERNATIONAL DATA TRANSFER FOR SPACE VERY LONG BASELINE INTERFEROMETRY

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ABSTRACT

Space Very Long Baseline Interferometry (SVLBI) experiments using a TDRSS satellite have successfully demonstrated the capability of using spacecraft to extend the effective baseline length of VLBI observations beyond the diameter of the Earth, thereby improving the resolution for imaging of active galactic nuclei at centimeter wavelengths. As a result, two spacecraft dedicated to SVLBI, VSOP (Japan) and RadioAstron (Russia), are scheduled to be launched into high Earth orbit in 1996 and 1997. The success of these missions depends on the cooperation of the international community in providing support from ground tracking stations, ground radio telescopes, and correlation facilities. The timely exchange and monitoring of data among the participants requires a well-designed and automated international data transfer system. In this paper, we will discuss the design requirements, data types and flows, and the operational responsibilities associated with the SVLBI data transfer system.

INTRODUCTION TO THE SVLBI DATA TRANSFER SYSTEM

The number of facilities that play a role in any space mission is no longer restricted by institutional or national boundaries. A large majority of missions now involve international consortia, due to the immense cost and complexity of designing and operating a space mission and the desire to jointly benefit from space exploration. The ground-based technique of Very Long Baseline Interferometry (VLBI) has always required substantial international coordination, and the extension of VLBI to include one or more orbiting radio telescopes requires a similar effort.

Two spacecraft, VSOP (VLBI Space Observatory Programme) and RadioAstron, are being developed for use as orbiting observatories dedicated to making Space VLBI (SVLBI) observations at centimeter wavelengths. VSOP (Hirabayashi 1991; Hirosawa 1991), scheduled for launch in 1996, is a project of the Japanese Institute of Space and Astronautical Science (ISAS). RadioAstron (Kardashev and Slysh 1988), a project led by the Russian Astro Space Center (ASC), is due to be launched in 1997.

The success of the SVLBI missions depends strongly on the cooperation of a large number of international organizations, some of which are directly involved in radio astronomy, while others are contributing or funding hardware and software support. The international mission planning for SVLBI is presented in a paper by Ulvestad (1994) at this conference. The nominal operation and scheduling of experiments for the missions will take place at ISAS for VSOP and at ASC for RadioAstron. The tracking of the spacecraft will be performed by six tracking stations located worldwide and operated by four different organizations. They include three 11-m antennas under construction by NASA at the Deep Space Network (DSN) facilities located at Goldstone (United States), Madrid (Spain), and Tidbinbilla (Australia). A 14-m antenna will be operated by the National Radio Astronomy Observatory (NRAO) in West Virginia (United States). All four antennas will be capable of tracking either VSOP or RadioAstron. Additional tracking coverage will be provided by a 10-m antenna at Usuda, Japan (VSOP only) and a 32-m antenna at Ussuriisk, Russia (RadioAstron only). Tracking sessions at each site typically may occur two or three times a day and may last from a few minutes to more than 12 hours. Other ground radio telescopes that will provide co-observing support with RadioAstron and VSOP include (but are not limited to) the Very Long Baseline Array (VLBA), the European VLBI Network, and the Australia Telescope National Facility. Correlation facilities located in Australia, Canada, Japan, the Netherlands, Russia, and the United States are being constructed or modified to accept the necessary files and data for correlation.

An integral part of the SVLBI missions will be the implementation of an international data transfer system that will retrieve and accept data files, monitor intermediate data products, and provide or construct the necessary files for final processing at the designated correlation facility. The major nodes of this data transfer system will be operated by ISAS, ASC, NRAO, and the Jet Propulsion Laboratory (JPL); these organizations are also responsible for all the tracking stations, and hence will provide all the space data. Processing of intermediate data products will be as automated as possible. Retrieval and redistribution of all data (except for the wideband VLBI data), will be via the Internet, utilizing standard file-transfer protocols.

The top-level requirements on the data transfer system are as follows:

1. Provide access to the detailed schedule files for all mission elements (principally ground telescopes and tracking stations) in a timely fashion.

2. Facilitate spacecraft performance monitoring by providing access to the telemetry data obtained from tracking stations.

3. Provide all spacecraft telemetry data required for the calibration of the space radio telescope.

4. Exchange navigation data required for high-accuracy orbit determination and subsequent VLBI data correlation.

5. Provide the VLBI correlators with all tracking-station information necessary for data processing.

UPLINK DATA TYPES

The types of data that are associated with the data transfer system can be grouped into two categories: files necessary to schedule and perform an experiment ("uplink") and the data necessary to correlate an experiment ("downlink"). Each data type (described below) may be the responsibility of disparate groups and, in many cases, depends on information provided by other organizations. In the following subsections, we will describe the files associated with the uplink processes necessary to prepare for a SVLBI experiment.

Schedule Files

A short-term schedule generated from the approved scientific program for VSOP and RadioAstron will be supplied by the VSOP Science Operations Group (VSOG) and RadioAstron Science Operations Group (RSOG) for VSOP and RadioAstron respectively. These two groups (known collectively as the SOGs) have the additional responsibility to provide a conflict-free schedule if both spacecraft are flying simultaneously. Each schedule will be divided into segments covering one week of mission operations and will describe all spacecraft and tracking-station activities in sufficient detail to allow each mission element to perform its required duties. A separate file following standard formats developed for ground VLBI will be made available to the ground radio telescopes. The initial schedule will be made available to the SVLBI data transfer system approximately five weeks in advance of the requested support period. It may be modified slightly up until a few days before the support is required.

The schedule file obtained from the SOGs will be maintained on multiple nodes of the data transfer system. These nodes will act as information servers to supporting ground radio telescopes and tracking stations. Negotiations are under way to finalize the contents and detailed formats of the schedule files and the method of procurement. It will be the responsibility of the personnel at the supporting facilities to retrieve each schedule file from the data transfer system, to extract all information needed to operate their facility, and to translate that information into the actual commands required for their mission element.

Predicted Orbit Files

An accurate predicted spacecraft trajectory is an important element of the uplink process. This trajectory is necessary not only for pointing ground tracking antennas, but also for generating an accurate frequency reference for VLBI observations. Predicted orbits will be generated by navigation teams associated with the DSN (for both spacecraft), ISAS (for VSOP only), and ASC (for RadioAstron only).

UPLINK DATA FLOW

Figure 1 shows a portion of the uplink data flow. Short-term schedule files covering a one-week time period are generated by the VSOG and RSOG for VSOP and RadioAstron, respectively. These schedule files must be conflict-free with respect to tracking and ground radio telescope support. They are made available to the SVLBI data transfer system nodes such as the one at JPL, where they may be accessed by supporting facilities. Information specific to ground tracking stations will be extracted and reformatted from the schedule file into the required operational commands. Ground radio telescopes will extract all the information needed to operate their facilities from a separate schedule file. In the case of the predicted spacecraft trajectory, navigation teams internal to each organization will construct the orbit and supply it directly to their own tracking stations. The predicted orbit also will be supplied from the JPL orbit determination group to the NRAO tracking station via the data-transfer node operated by the JPL Project. Figure 1 does not show all the details of the data flow within the data transfer system. Rather, the basic data types and pathways are indicated.

DOWNLINK DATA TYPES

The numerous data types created during and after an experiment, collectively known as "post-pass" data, include the VLBI data recorded on video cassettes or instrumentation tapes at each tracking station and telescope, near-real-time data used in monitoring the spacecraft and tracking station performance, and various other data supplied by the tracking stations following each tracking session. The latter data include two-way phase residuals from the link between the tracking stations and spacecraft, Doppler data, calibration information from the downlink headers, and tracking-station logs which contain information about performance and recording parameters. These data must be extracted, processed, and supplied to the SOGs or the navigation teams on a regular (approximately daily) basis. Further processing, analysis, and combination of data is required to generate all the inputs needed for experiment processing at a correlation facility; all the final data products must be available to the correlators within 2–3 weeks after an observation. The logistics of a SVLBI experiment may involve mixtures of two spacecraft, four types of tracking station, three VLBI recording systems, a large number of ground telescopes, and up to six correlation facilities, providing an overwhelming number of possible data formats and combinations. Therefore, one of the biggest challenges for the international data transfer system is to define common procedures and interfaces for data handling. The subsections below discuss a few of the specific activities and problems associated with the different data types.

Wideband VLBI Data

The VLBI data are recorded in real time at each site and are later brought together at a special purpose processing correlation facility. The bulk of the tracking stations and telescopes will be equipped with VLBA-compatible recording systems. They will record data on tapes which can hold up to 10–12 hours of data at 128 Megabit/s and cost over $1,000 per tape. Since a nominal SVLBI experiment may use 10 or more telescopes and may last 24 (or more) hours, the high cost makes it impossible to archive the raw data for all (or any) ground or SVLBI experiments. (A 1-month tape supply for 10 telescopes costs over $600,000.) Instead, it is standard practice to correlate the experiments, provide a quality check of the data, and then to erase the tapes and distribute them into a general pool used by the world's radio telescopes. The data transfer system must provide all ancillary data in a timely fashion so that delays in processing do not lead to a requirement for purchasing additional tapes.

Science Headers

The header sections of the downlinked wideband VLBI data blocks contain information about the health and safety of the spacecraft,

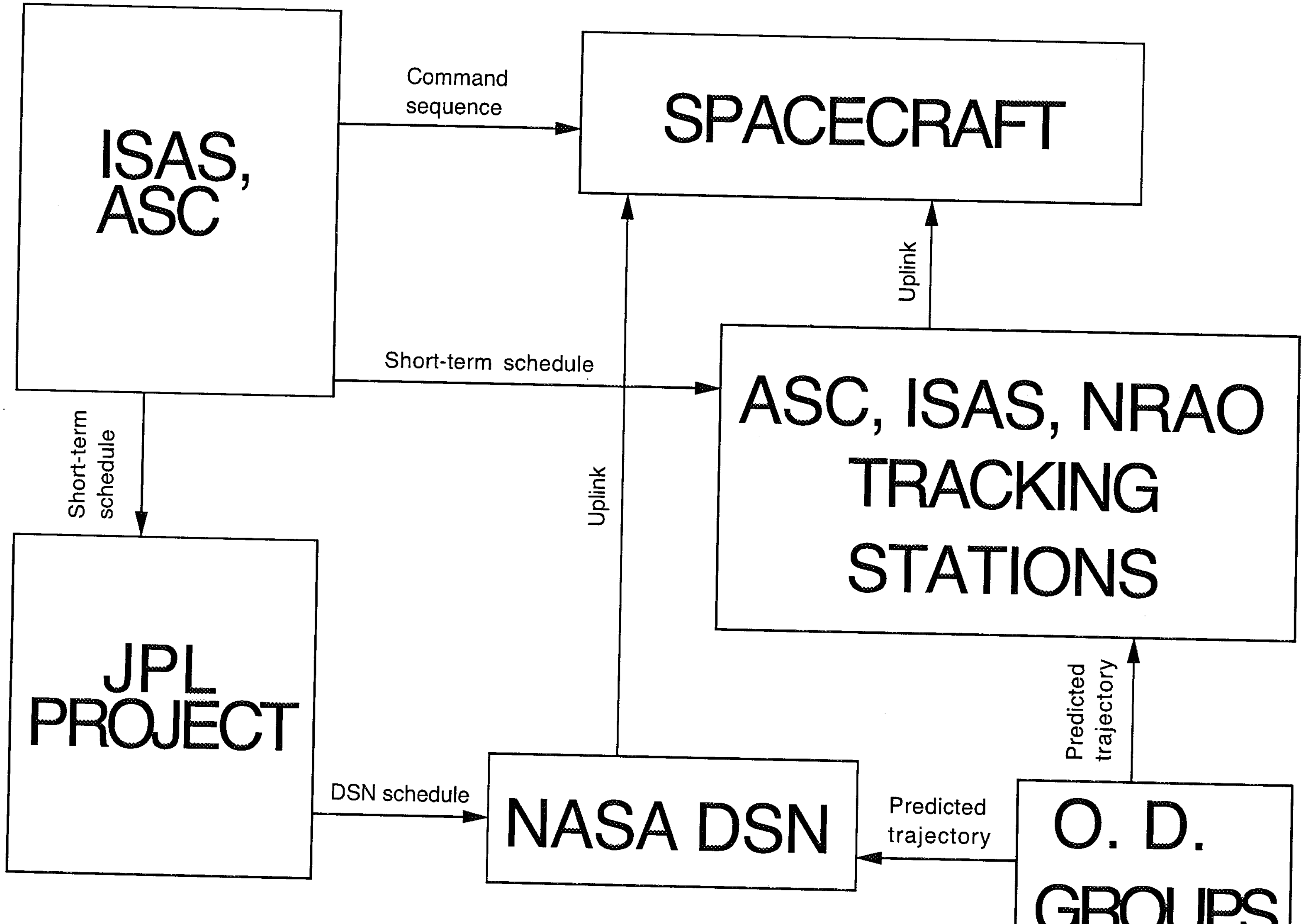

Figure 1. SVLBI Uplink

so some examination of these data in near-real-time is required. These headers will be extracted from the telemetry stream by each tracking station and made available to the spacecraft operators in a number of ways. The DSN tracking stations will extract portions of the headers and make them available to Russia or Japan in near-real-time, via the JPL data transfer node; these data will be available for monitoring of the health and safety of the spacecraft. The NRAO tracking station will check the values of some of the spacecraft parameters and report anomalous conditions to the SOGs in near-real-time. The Russian and Japanese tracking stations will extract the spacecraft monitor data and provide it directly to the appropriate spacecraft control teams.

The science headers also contain data critical to space radio telescope calibration. These data will be extracted and made available to the SOGs in a manner similar to that for spacecraft health data, either during (DSN) or after (NRAO) each tracking session. Extracted calibration data supplied by the Russian and Japanese tracking stations will be delivered to the appropriate SOG.

Observing Logs

Station log files describing the performance of the tracking stations and events that occurred during each session will be delivered to the data transfer system. These logs contain information on how the VLBI data were recorded, and are essential to the correlation process. The data will be assembled by the RSOG and VSOG and will be merged into the correlator input files (see below).

Phase Residuals and Reconstructed Orbit Files

A phase link between the tracking station and spacecraft is needed to provide an accurate on-board frequency reference (e.g. Edwards 1987; Levy et al. 1989; D'Addario 1991). Phase residuals from the two-way link must be tabulated at a rate of 10 Hz or greater to correct for orbit errors and the propagation of the signal through the Earth's troposphere and ionosphere. They are necessary for correcting the time and frequency information used by the correlator. Phase residuals from each type of tracking station are derived in a different manner, but each station must supply equivalent information. The phase residuals will be supplied to the data transfer system, and retrieved by the SOGs for provision to the correlators. A common interface required for the different tracking stations and correlators is under development.

The phase link also will be used to generate two-way Doppler data. Each tracking station will deliver Doppler data in near-real time to the appropriate navigation teams, who will derive a final reconstructed orbit. The reconstructed orbit must meet stringent accuracy requirements for VLBI correlation. It may be delivered to the data transfer system as much as 3 weeks after an observation.

Correlator Input Files

In order to process a SVLBI experiment, a correlator must receive the following via the data transfer system: (1) VLBI data, (2) the reconstructed spacecraft orbit, (3) phase residuals, and (4) the correlator input log file. The last file is created by the SOGs based on the tracking-station logs, calibration data, and spacecraft performance information. A model of delay and delay-rate is used to search for the location of interference fringes (if any) in the cross-correlation data for each antenna pair. The correlator output data is then delivered to the principal investigator and may be used to derive visibility functions and various astrophysical parameters. This data is archived at the correlator facility.

DOWNLINK DATA FLOW

Figure 2 shows a portion of the downlink data flow associated with a SVLBI experiment. As with Figure 1, this diagram over-simplifies the data paths within the data transfer system. Near-real-time and post-pass data generated by various agencies must ultimately be collected and processed by the SOGs before being passed to the correlator. The operation of tracking stations by different agencies necessitates independent flow of data to the SOGs and correlators. Due to the complex data flow, the final correlation of data may begin only when all the necessary data has been supplied to the correlator, which may take as long as 3–4 weeks after a SVLBI experiment.

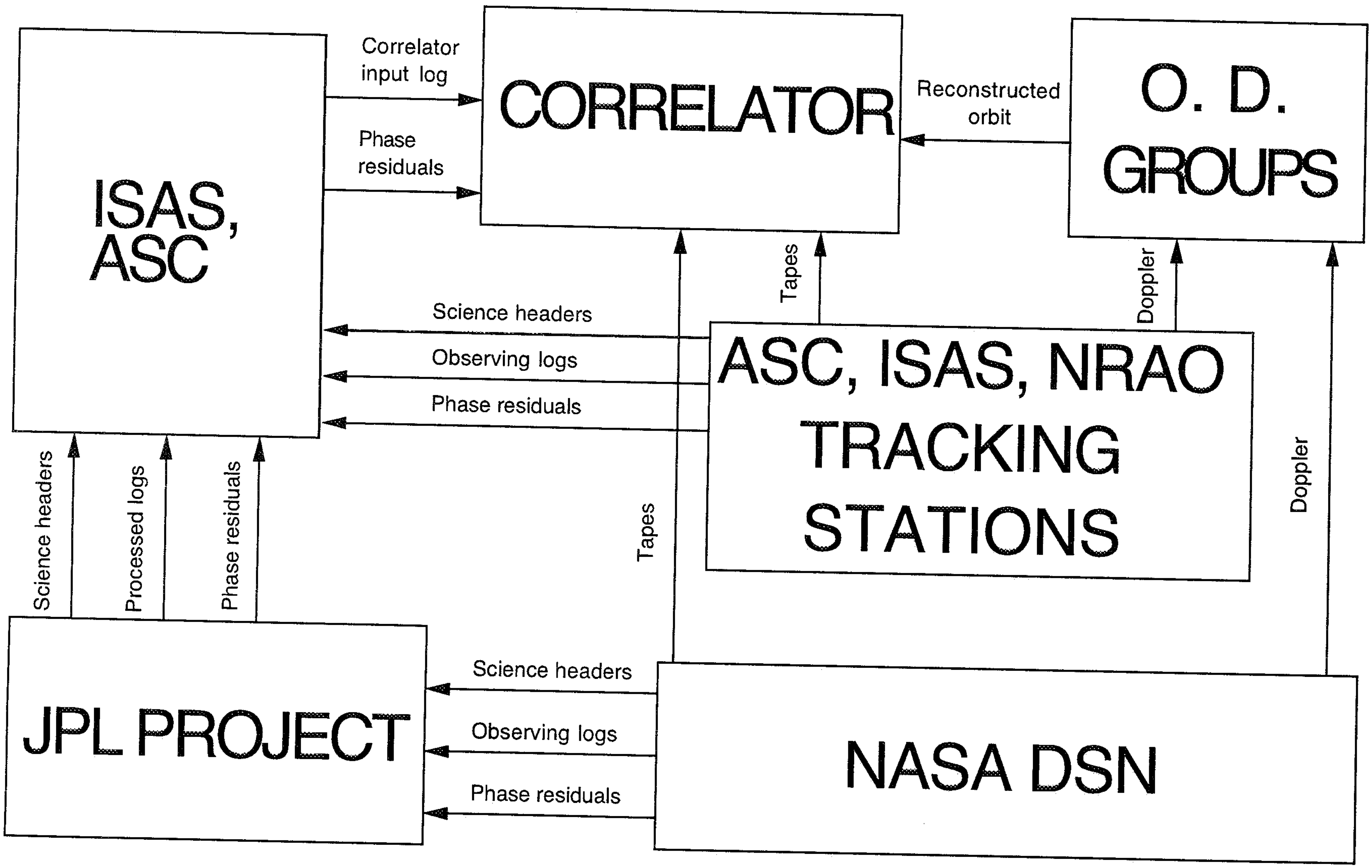

Figure 2. SVLBI Downlink

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