DRAFT

MANAGEMENT PLAN

for the

VLBA SPACECRAFT NAVIGATION PILOT PROJECT

2003 May 15

1 INTRODUCTION

1.1 Summary

The National Radio Astronomy Observatory (NRAO), a facility of the National Science Foundation (NSF), will conduct a pilot study of the suitability of the Very Long Baseline Array (VLBA) for providing high-precision angular position measurements to enhance the navigation of spacecraft operated by the National Aeronautics and Space Administration (NASA).

NASA will provide funding for this study through the [NASA Program Executive for the Deep Space Network]. Further, NASA will provide access to various automated information services required by NRAO in carrying out the pilot study.

NRAO will carry out a number of VLBA test observations of several NASA spacecraft, already launched or to be launched during the study period. Through evaluation of these tests, NRAO will determine all upgrades to existing VLBA subsystems which would be required to support routine spacecraft navigation observations. Further, NRAO will estimate the precision that can be achieved in the measurement of spacecraft angular positions, and the probability of a successful outcome from an individual measurement, under a variety of spacecraft parameters and observing conditions.

NRAO will collaborate with the NASA spacecraft navigation team designated by the [NASA Program Executive for the Deep Space Network], to determine the optimal interface for providing high-precision angular position measurements to that team, and to evaluate jointly the enhancement achievable in spacecraft orbit determination through the incorporation of high-precision angular position measurements from the VLBA.

NRAO will develop a plan for implementing a 33-GHz observing capability at the ten VLBA stations.

1.2 Overview of VLBA Spacecraft Navigation Measurements

The pilot study described in this Management Plan is the first phase of a proposed implementation on the VLBA of a 33-GHz spacecraft navigation capability. The results will be essential inputs to the design of the later phases. This sub-section provides a brief introduction to the VLBA and its phase-referencing differential astrometry technique, for the information of readers unfamiliar with these concepts.

The VLBA is a very-long-baseline interferometer (VLBI) instrument, the only facility in the world dedicated to observations using this technique. It combines signals from point-like radio sources – including, in this case, a spacecraft downlink transmitter – as received at each of its ten stations, to produce simultaneous samples of the interferometer fringe visibility function on the array's 45 baselines. Image-restoration procedures can then be used to produce an image of the spacecraft transmitter. The spacecraft transmitter will appear as a point source, even with the extremely high angular resolution achieved by the array. The position of this image can be measured with high precision. A number of such measurements can then be provided to NASA's spacecraft navigation organization as additional, strong constraints on their orbit solutions.

This approach may be contrasted with the VLBI measurement technique currently used for spacecraft navigation on the DSN. "Delta-DOR" measures a high-precision delay on a single baseline, and requires special transmitter modes to resolve ambiguities. The VLBA, in contrast, obtains data from 45 baselines at once, using just the downlink signal itself, and actually images the transmitter at a precise celestial position. Since the VLBA approach requires no special modes or side tones, it will be possible to make these measurements in an "eavesdropping" mode, whenever a downlink is scheduled.

High-precision angular position measurements require an extremely careful calibration of atmospheric effects on radiowave propagation. This is done using a phase-referencing technique, in which observations of reference sources, typically quasars, alternate rapidly with observations of the spacecraft. The quasar measurements essentially measure the atmospheric contribution to the interferometer phase for each station, which can then be removed from the spacecraft observations. The VLBA was designed expressly to support such differential astrometry measurements. A number of its capabilities were optimized to facilitate the phase-referencing technique, which could not be implemented successfully using the radio telescope equipment available before the construction of the VLBA. In particular, the VLBA is able to switch between target and reference sources on timescales of tens of seconds, faster than the timescale on which atmospheric propagation varies.

Phase referencing is most effective when the reference source or sources are close to the target source in the sky, optimally within about a degree. A catalog of reference sources must thus be developed, and must include quite weak sources in order to achieve the required density on the sky.

The VLBA is not currently instrumented at 33 GHz, the frequency band to which NASA plans to move its deep-space telemetry. Accordingly, it will be necessary to implement receiving systems, and to use them first to develop a reference catalog, before spacecraft navigation measurements can be made in this band.

Based on extrapolations from other frequency bands, NRAO believes it is realistic to establish an angular precision goal of 0.5 nano-radian for each individual spacecraft position measurement. Validating this goal is a major focus of the Project.

The VLBA schedules most of its observations on a "dynamic" basis, depending on weather and equipment status. This approach will facilitate the insertion of brief spacecraft navigation measurements into the observing schedule, with minimal impact on the VLBA's astronomical observing program, and offers substantial immunity from weather-related data losses.

2 OVERVIEW of the PILOT PROJECT

2.1 Organization and Management

The title of the Project described herein is the VLBA Spacecraft Navigation Pilot Project. It is the first phase of a proposed VLBA Spacecraft Navigation Project which, following successful conclusion of the Pilot Project and availability of adequate funding, will implement an operational spacecraft navigation capability on the VLBA.

The Pilot Project will be managed at NRAO by a Project Manager to be designated by the Director of NRAO. The NRAO Project Manager will coordinate with the [NASA Program Executive for the Deep Space Network], or his/her designee, on organizational matters. Separate liaison contacts may be designated for organizational and technical coordination. The scope of the Project is sufficiently limited that no secondary management structures are expected to be required.

The NRAO Project Manager will be the principal point of contact at NRAO for all Project activities. He or she will be responsible for producing the reports described in Section 4 below, and for maintaining this document on behalf of NRAO should a need for revisions arise.

It is anticipated that the NRAO Project Manager will also participate centrally in developing the appropriate Management Plans for subsequent phases of the overall VLBA Spacecraft Navigation Project.

2.2 Coordination with NASA Spacecraft Navigation

The [NASA Program Executive for the Deep Space Network] has designated the [JPL spacecraft navigation team] as NASA's principal technical experts with whom the Pilot Project will collaborate in all areas relating to the interface and application of VLBA spacecraft navigation measurements to spacecraft navigation. Biweekly meetings will be held among the [NASA Program Executive for the Deep Space Network], NRAO Project personnel, and members of the [JPL spacecraft navigation team], to review progress toward Project goals.

2.3 Funding

Funding for NRAO activities under this Management Plan will be made available through the [NASA Program Executive for the Deep Space Network]. The Appendix contains the Project budget. NRAO will provide a record of actual expenditures at the end of each Federal fiscal year during the Project's existence, and at the termination of its activities.

2.4 Schedule

Project activities will be initiated as soon as all three of the following conditions occur: funding becomes available to NRAO; access to spacecraft downlink schedules becomes available; and access to spacecraft orbit models becomes available. All Project activities will be completed within 8 months of that date, with a final report to follow soon thereafter.

3 TASKS

3.1 Feasibility Studies

a] For NASA to be able to determine the value of VLBA spacecraft navigation measurements to its mission, it must know the angular precision achievable in such measurements individually, under a variety of circumstances, and the overall enhancement that such measurements could bring to the results produced by NASA spacecraft navigation organizations. NRAO will investigate the angular precision of individual spacecraft navigation observations with respect to all the variables listed below. NRAO will collaborate with the [JPL spacecraft navigation team] designated in Section 2.2, to determine the overall enhancement achievable by using VLBA spacecraft navigation measurements. Both investigations will include an analysis of possible sources of error.

b] For NRAO to be able to present a realistic budget proposal for routine spacecraft navigation observations, it must know the likelihood of a successful individual measurement under the same variety of circumstances. NRAO will investigate the success rate in a series of test measurements, with respect to all the variables listed below.

Variables to be Considered:

- *Spacecraft Signal Power.* The power emitted by spacecraft downlink transmitters, and their distance, both vary significantly. The integration time required with the VLBA's 25-m antennas will vary accordingly.

- *Spacecraft Transmitter Switching.* Some spacecraft operate their downlink transmitters continuously; others only energize the transmitter when a downlink has been commanded. For those in the latter group, some are known to suffer severe drifts in the downlink carrier frequency during the first several minutes that the transmitter is operating.

- *Spacecraft Attitude Control.* Some spacecraft operate their thrusters frequently to maintain attitude control. This has the potential to disturb a VLBA spacecraft navigation measurement, but also offers an opportunity where such measurements could have a greater positive impact than otherwise on the overall spacecraft orbit determination.

- *Atmospheric Conditions.* The technique NRAO proposes to apply in producing high precision measurements of spacecraft angular positions can be degraded by unfavorable atmospheric conditions at some of the observing stations. Sufficiently many test observations will have to be carried out to quantify this impact. Since the tests will be carried out at 8.4 GHz (X band), while routine measurements are desired at 33 GHz (Ka band) eventually, it will be necessary to extrapolate to this higher frequency. Tests on purely astronomical sources may be necessary to facilitate this extrapolation.

- *Density of Reference Sources.* The measurement technique can also be degraded if one or more reference sources are not available in close angular proximity to the target spacecraft. Sufficiently many test observations will have to be carried out to estimate the required areal density on the sky. The required proximity also depends on the elevation angle at which the observations are made. Thus, tests must also include observations in many different parts of the sky. As in the case of studying atmospheric conditions, it will be necessary to extrapolate results from 8.4 to 33 GHz. Tests on purely astronomical sources may be necessary to facilitate this extrapolation.

- *Number and Distribution of VLBA Stations.* Spacecraft navigation measurements could be performed with a subset of the entire VLBA, with some degradation in accuracy. Omitting certain VLBA stations could lead to more rapid delivery of the results.

3.2 Optimal Observable

The most natural output from VLBA spacecraft navigation observations is likely to be a positional offset of the spacecraft relative to the orbit model used in correlation. It is not clear whether this would be a correspondingly natural input to the procedures used in NASA's orbit determination techniques. It has been suggested that multiple baseline-based delays be provided instead. This would require substantial sophistication in the orbit modeling to exploit the multi-baseline results available from the VLBA. NRAO will collaborate with the [JPL spacecraft navigation team] designated in Section 2.2, to determine the optimal interface for providing high-precision angular position measurements to those teams.

3.3 Implementation Studies

A number of subsystems of the VLBA instrument would have to be upgraded to make spacecraft navigation measurements possible at all, or to make them feasible in routine operations. NRAO will identify all such upgrades, and the requirements for their full implementation at a level sufficient for routine operations. During the pilot study, however, these upgrades may be implemented only in a provisional fashion. The following upgrades are already known to be required, but it is possible that the pilot study will identify others, which then will also be studied.

a] Observation Scheduling. NRAO will determine how best to upgrade its dynamic scheduling procedures to facilitate routine spacecraft navigation observations on the VLBA, while minimizing their impact on the VLBA's astronomical observing programs. The [NASA Program Executive for the Deep Space Network] will arrange for access by Project personnel to the downlink schedule for each spacecraft to be observed. For tests during the pilot study, a graphical display of this information will suffice.

For routine operations, the same information must be available in a form more suitable to automated processing. The pilot study will determine the best approach for transferring this information, but implementation is not necessary until a later phase. NASA will identify its internal organization with which NRAO will consult to make this determination.

b] Station Pointing. NRAO will determine the upgrades to its software that will be required to point the VLBA antennas at any given spacecraft, to within a small fraction of a beamwidth. It is assumed that the spacecraft orbit models used for this purpose will be the same as those required, at much higher precision, for item *[c]* immediately below.

c] Correlator Model. NRAO will determine the upgrades to its software that will be required to correlate observations of any given spacecraft in the VLBA correlator. NASA will identify its internal spacecraft navigation organization which will provide the required spacecraft orbit models.

d] Correlator Data Format. NRAO will ensure that the data products that could be delivered to NASA from routine spacecraft navigation observations will provide complete accountability as to how the observations have been processed. NRAO will determine and implement all upgrades to the VLBA correlator's output data format, and all corresponding upgrades to its standard image processing software, that may be necessary for this purpose.

e] 33-GHz Receiving Systems. NRAO will study the requirements for implementing a 33-GHz observing capability on the VLBA, including feeds, low-noise amplifiers, and receiver systems. It will also be necessary to study the placement of the receiving system in the VLBA antenna's feed circle, and the possible requirement for expanding the cryogenic cooling capacity. Preliminary design work will be carried sufficiently far that realistic cost estimates can be included in a subsequent proposal to actually perform the implementation.

3.4 Rapid Response Studies

NRAO will study several options for accelerating delivery of spacecraft navigation data to NASA orbit-determination organizations. The delivery timescale is dominated currently by the requirement for physical shipment of magnetic tapes from the VLBA stations to the correlator. Thus, the principal effort under this task will be to evaluate the costs and time savings achievable using rapid-delivery services. These results should serve as an upper limit to what will be achievable with more modern recording media.

In addition, NRAO will study what eventually may be achieved using real-time or near-real-time data transmission over broad-band networks. It is anticipated that such transmission will become feasible for VLBI within the next five years. The pilot study will summarize the current state of "e-VLBI" and compile expert projections for its eventual implementation, to aid planning by the [NASA Program Executive for the Deep Space Network], but it will not be possible to include any major investigation, nor any tests, within the limited scope of the pilot study.

4 DELIVERABLES

4.1 Quarterly Reports

NRAO will deliver to the [NASA Program Executive for the Deep Space Network], within two weeks of the end of each calendar quarter during the Project's existence, a report detailing the activities carried out during the preceding quarter and the progress toward each task goal.

4.2 Final Report

NRAO will deliver to the [NASA Program Executive for the Deep Space Network], within two months after the Project completion date specified in Section 2.4 above, a complete report of the pilot study results, including, if appropriate, recommendations for full-scale implementation of a spacecraft navigation capability on the VLBA.

The final report will include the following items:

- A detailed assessment of the angular precision of individual spacecraft navigation measurement, and of the overall enhancement that such measurements could bring to NASA's spacecraft navigation capabilities.
- A detailed assessment of the probability of a successful spacecraft navigation measurement in a variety of circumstances.
- A recommendation for the observable quantity which is best suited for transferring the results of VLBA spacecraft navigation measurements to NASA's orbit-determination operations.
- A discussion of NRAO's requirements for integrating spacecraft navigation observations into the VLBA's astronomical observing program.
- A detailed description of the upgrades to VLBA subsystems that will be required in order to perform spacecraft navigation observations, of multiple spacecraft in multiple areas of the sky, and a detailed cost estimate and schedule for implementation of these upgrades.
- A discussion of options, and an estimate of costs and timescales, for NRAO to deliver spacecraft navigation data to NASA on a rapid-response basis.
- A detailed plan for implementation of a 33-GHz observing capability on the VLBA.

5 BUDGET

The budget for the Pilot Project consists primarily of personnel costs. Table 1 shows the job titles for each type of NRAO staff member involved in the Project, and the total planned allocation of time for each job title, in work-years. NRAO may assign employees to this Project who are foreign nationals, with the concurrence of the [NASA Program Executive for the Deep Space Network].

Table 2 shows the total cost of personnel compensation for the work effort detailed in Table 1, including NRAO's standard employee benefit charges. Also included are:

- Upgrades to NRAO scientists' computer equipment, required to support analysis of the numerous tests necessary to meet the pilot study's goals.
- Shipping charges for the rapid-response tests described in Section 3.4.
- Travel in connection with the collaborations described in Sections 3.1 and 3.2, and for occasional face-to-face meetings of the NRAO Project Manager (and, possibly, other Project personnel) with the [NASA Program Executive for the Deep Space Network]. Travel between New Mexico (VLBA operations center) and Virginia (NRAO Central Development Lab) for planning of the 33 GHz capability also is included.

NRAO's standard Common Cost Recovery rate is applied to the total.

Table 1: Personnel

Job Title	Function	Work-years
Scientist	Project manager	0.50
Scientist	Test planning & analysis	0.55
Scientist	Scheduling/pointing software upgrade	0.10
Scientist	Correlator software upgrade	0.10
Scientist	33-GHz implementation study	0.25
Receiver Engineer	33-GHz implementation study	0.25
Software Engineer	Software upgrade	0.25
Operations Manager	Operations upgrade study	0.10
Lead Operator	Operations upgrades study	0.10
Tape Librarian	Operations upgrades study	0.10
Total work-years		2.30

Table 2: Budget

VLBA Spacecraft Navigation Pilot Project

Draft Budget

Amounts in Dollars

Personnel Compensation	168,309			
Benefits	54,700			
Subtotal: Personnel		223,009		
Materials & Services				
Computer equipment	4,500			
Shipping	5,000			
Subtotal: M&S		9,500		
Travel		25,000		
Total Project Direct Costs			257,509	
Indirect Costs			176,651	
TOTAL PROJECT BUDGET				434,160