Final Report for Contract NAS5-32331

Support of the Laboratory for Terrestrial Physics for Dynamics of the Solid Earth (DOSE)

January 8, 1993 – January 31, 2001

This final report for contract NAS5-32331 summarizes the accomplishments during the contract period. Under the contract NVI, Inc. provided support to the VLBI group at NASA's Goddard Space Flight Center. The contract covered a period of approximately eight years during which geodetic and astrometric VLBI evolved through several major changes. This report is divided into four sections which correspond to major task areas in the contract: A) Coordination and Scheduling, B) Field System, C) Station Support, and D) Analysis and Research and Development.

A. Coordination and Scheduling

Master Schedules (1993–2001). NVI coordinated and posted the Master Observing Schedules for each year of the contract. These schedules coordinated all geodetic and astrometric sessions conducted by the international VLBI community. Several meetings were held each year to discuss what sessions should be observed and what science the group was trying to achieve for the next observing year. After a decision was made, NVI contacted the stations about their availability for the upcoming year. After coordination with the stations, the new master schedule was posted electronically. During the year NVI coordinated updates and changes to the master schedule. 2000–2001: NVI created master files for years prior to 1993 and modified the 1979 through 1997 Master Observing Schedules to have the same format as the 1998 through 2001 Master Observing Schedules so that the older databases could be submitted to IVS. The *excat* program was created and maintained to keep track of all observing sessions in an experiment catalog.

Correlator Tracking Report (1993–1997). NVI created and update the monthly Correlator Tracking and Analysis reports to keep track of session processing at Bonn, Haystack, and Washington Correlators. The Correlator Tracking and Analysis reports were discontinued in 1998 since most of the information was now in the master schedule.

Tape Shipping Plan (1995–2001). NVI developed the Tape Shipping Plan in an attempt to reduce tape shipping costs. The plan was to have each of the three correlators supply tapes to specific stations instead of to all the stations of a specific session. From information provided by the three correlators, NVI determined which stations each correlator should supply with tapes. The report has been maintained and updated quarterly.

Experiment Setup (1993–1999). NVI setup NASA-sponsored observing sessions to be processed at the Washington Correlator for prepassing. The setup was discontinued when the Mark IV correlator was installed at the Washington Correlator because of the change in procedures. NVI downloaded and reviewed log files and then copied the log files to the appropriate area to be reviewed by the analysts.

Mars Spacecraft Observing (1997–1998). NVI worked with GSFC and USNO personnel to coordinate a series of VLBI sessions to observe spacecraft en route to Mars and after landing on the surface. These observations have the potential to provide new information about the orientation and rotation of Mars.

DSN Coordination (1993-2001): NVI prepared the Mission Requirements Request (MRR) for geodetic VLBI observations using DSN antennas and submitted it to NASA Headquarters. We worked jointly with JPL personnel to develop the Detailed Mission Requirements (DMR). NVI continued to coordinate with JPL personnel for scheduling observing time on DSN antennas throughout the contract. The most recent DSN interaction is with the CSOC staff.

Equipment Deployment and Upgrades (1993–1996). NVI maintained an equipment deployment plan to show where the data acquisition terminals, recorders, and computers will be shipped and the duration of the stay at each location. NVI coordinated with Haystack, USNO, and NOAA personnel on a plan for gradually upgrading all VLBI stations from Mark III to Mark IV capability.

CONT94, CONT95, CONT96 (1993–1996). NVI coordinated the CONT94 sessions that were observed in January, 1994. GPS antennas were installed at Green Bank, Fort Davis, and Los Alamos to record data during the CONT94 sessions. NVI coordinated the CONT95 sessions observed during August, 1995. NVI coordinated the CONT96 sessions observed during September, October and November, 1996. The three series of observations required coordination and proposal writing to obtain time on the VLBA antennas. The CONT94 results have proven to be one of the most widely used data series because of the high quality of the data available for a continuous two-week period.

Scheduling (1993–2001). NVI generated detailed observing schedule files for all NASA-sponsored sessions during the contract period. We made the schedules with *sked*, made station files using *drudg*, and posted and/or distributed the files. As of the late 1990s, most stations were making their own files using *drudg*. NVI wrote a notes file to accompany each schedule. NVI coordinated and made schedules for numerous fringes tests as needed to verify station performance, new equipment status, or station implementation.

***Sked* Development (1993–2001).** NVI created an automatic scheduling program by merging the German-developed *autosked* and the original *sked*. The new routines were incorporated into *sked* and a new cursor-based user interface for setting options was written. In 1995 the standard schedule file format was expanded to include more detailed

information about station LOs and channel assignments. This provided the ability to assign tracks and video converters to different channels for more flexible specification of recording modes. In 1997-9 support for reading and writing VEX files was added. In the field, this allowed astronomy schedules to be read and processed for data acquisition control. At the correlator, files could be prepared for processing with the new Mark IV correlator which requires a VEX format file as input.

CORE Program (1996–2001). NVI supported the initiative of the Goddard VLBI group to concentrate on Earth orientation measurements through the CORE (Continuous Observations of the Rotation of the Earth) program. We organized the community's proposal to NASA in response to the NRA, and then coordinated the CORE observing program that continued through the end of the contract. We initiated the CORE-A and CORE-B sessions to evaluate concepts proposed for the program, and coordinated the evolution of the program to the current CORE-1 and CORE-3 sessions. The CORE program has been a strong focal point for the international VLBI community.

IVS Formation (1998–1999). NVI participated in discussions about the formation of an international organization, similar to IGS. We served on the Steering Committee which guided the process of formation of the organization. We helped write the draft Terms of Reference and coordinated its review by an international committee and the selection of a name for the organization: IVS (International VLBI Service). We assisted with writing the call for proposals and the proposal evaluation by the Steering Committee. Goddard proposed to support seven components and we assisted with writing these proposals. NVI coordinated elections of the initial Directing Board and proposals for the coordinators. Two NVI staff members were appointed to the Board, one as Network Coordinator and one as Director of the Coordinating Center.

IVS Coordinating Center (1999–2001). NVI. designed and created the web site for IVS and launched it on the IVS inauguration day, as well as the ivsmail e-mail service. The web site and e-mail service were continually supported since then. NVI supported the IVS Coordinating Center by publication of the first and second Annual Reports, coordination of the first General Meeting, publication of meeting proceedings, and coordination of an Analysis Workshop and a Technical Operations Workshop.

Web Support and Documentation (1995–2001). NVI designed, implemented, and maintained the first web site for the Goddard VLBI group, with links to our data holdings, *solve* documentation, Field System documentation, *sked* software and documentation, master schedules, and brochure. NVI developed a linked master schedule with a web page for each session, and developed a processing system for log files to extract useful information and display it on each page. We wrote and continually maintained and published the documentation for the *sked* system and the Field System.

VLBI Brochure (1995). NVI worked with GSFC staff to generate a VLBI brochure titled "VLBI: Measuring Our Changing Earth". We wrote text, gathered photographs, generated images, and worked with the graphics artist to create a visually and technically impressive 12-page brochure. The brochure was distributed widely in the geodetic,

astrometric, and geophysical communities and received high praise for its presentation of VLBI.

B. Field System

Port FS to Linux (1995). NVI led a major initiative porting the Field System (FS) to the Linux Operating System. Previously the FS had been usable only under proprietary realtime operation systems. While Linux is not a realtime operating system, its performance on inexpensive PC hardware is sufficient to support the FS. By removing the need for an expensive proprietary operating system, the cost for using the Field System was greatly reduced. This led to a continued viability of the FS and its being used for observations by all VLBI stations in the world except a few such as the VLBA which used specially designed software that is coupled to their specialized hardware. This led to significant worldwide harmonization of operations at stations that are used both for geodesy and astronomy.

Computer Check-out (1995–2001). NVI verified correct configuration and compatibility of computers for VLBI use bought by cooperating institutions. Use of a standardized Linux kernel and the FS at all stations greatly harmonized VLBI observations. In order to help maintain the significant harmonization, new computers that were bought to run the FS were checked out to verify that they worked with the standard kernel. If they did not, either the problematic components were replaced or the standard kernel was upgraded to handle the new hardware. The stability provided by the standardization of hardware and its verification helped reduce the software maintenance costs by providing a relatively uniform platform for the software to run on.

Developed a Remotely Installable Linux Kernel for FS Use (1995–1998). NVI helped coordinate development of the operational kernel placing special emphasis on making it easy to install. Since the FS is used as an operational system it was important to develop a reliably installable and stable operating system platform. In collaboration with personnel from Metäshovi Observatory in Finland, NVI helped develop a specially packaged kernel. The features of this kernel included: loadable from a standard Linux distribution, downloadable from the network, includes a stable set of utilities and packages for use with the FS. The initial version of this system was based on Slackware 2.3.0. Two subsequent versions were based on Debian 2.0. The use of these standard kernels allowed the FS to be used in a stable and well tested environment at the vast majority of stations using the FS. This facilitated more reliable operation and easier overall network maintenance.

Liaison with the EVN (1995–2001). NVI maintained close contact with the European VLBI Network (EVN). In addition to collaborating on FS development and support, many of the geodetic stations are part of the EVN, so maintaining harmonious operating procedures and relations with the EVN is important for geodesy. In addition to remote collaboration, NVI attended the bi-annual Technical Working Group (TWG), later Technical Operations Group (TOG), meetings.

Developed support for Mark IV recorders and racks (1996). NVI enhanced the FS to support Mark IV racks and recorders as well as VLBA4 racks and recorders. The operation of VLBA racks and recorders was made more harmonious with Mark IV operations as well.

Developed support for systems including K4 components (1997–1999). NVI developed support for K4 systems and systems that use a hybrid of K4 and Mark IV and VLBA components. This improved the performance of Kashima26 system in international programs. It enabled the Tsukuba32 system to participate in international observations

Developed support for sequential use of dual longitudinal recorders (1999). NVI developed support for sequential use of dual longitudinal recorders. This greatly reduced operations costs at two sites where there was insufficient man-power to change tapes overnight.

C. Station Support

Antenna Software (1993–1996). NVI developed sidereal tracking software for the new antennas built by RSI at Kokee Park, Green Bank, and Ny Ålesund. The interface specification was developed in collaboration with RSI to ensure that it would meet the needs for geodetic VLBI and would be the same at each of the three sites. The software was tested at Kokee Park which was the first of three antennas that was built. It was used subsequently at Green Bank and Ny Ålesund with essentially no modifications. NVI also developed sidereal tracking software for the new TIW antenna at Richmond.

Stations Visits (1993–2001). NVI visited Fairbanks, Kokee Park, Ny Ålesund, Noto, Westford, and MV3 to review operations, provide additional training, and upgrade and fine tune software. This sort of visit is useful both for providing "refresher" training and maintaining contacts with site personnel, but also for detecting problems that may not be visible to the stations because they developed gradually and the personnel have adapted to them. An example of this is that one station had developed an intermittent problem with antenna communication, which they were able to fix whenever it happened. However, a simple software fix eliminated the problem entirely.

Implementation of Simeiz (1994). NVI assisted in bringing the VLBI station at Simeiz, Ukraine online. Support was developed for the antenna there as well as specialized local hardware. The site staff were trained in operation of the system.

Training and Antenna Interfaces at Kashima34, Kashima26, and Tsukuba32 (1997–1999). NVI provided training and software development in order to facilitate international observations with Japanese telescopes. Software work included FS installation and customization and antenna interface development at these stations.

TeamChina (1998, 2000). NVI participated in the two TeamChina missions that helped improve the performance of the Chinese VLBI stations. Each trip included approximately one week at each of the Shanghai and Urumqi VLBI stations. NVI provided operational training and developed antenna interfaces.

IVS Network Coordination (1999–2001). NVI supplied the Network Coordinator for the International VLBI Service (IVS). The Coordinator is responsible for monitoring network station performance and representing the stations to the IVS Directing Board.

D. Analysis

User Partial/User Program Capability in *solve* (1993). NVI implemented the user_partial and user_program features in the Goddard VLBI analysis software. Before the implementation of user_partial, it was not possible for a researcher to estimate arbitrary parameters of interest without making extensive modifications to the analysis code in order to make a special purpose version of the code for each application. User_program is the companion feature that was developed to apply the estimated values of user parameters from one solution in later solutions.

Tropospheric Delay Modeling Using Data Assimilation Models (1993, 1997). NVI examined the performance of different standard mapping functions in the VLBI analysis system to determine the optimum choice. Since these standard mapping functions have no meteorological input, NVI then investigated the possibility of correcting tropospheric delay models using 6-hour data from a globally gridded meteorological data assimilation model. Site mapping functions were determined by interpolating model profiles to the VLBI site. Testing of this procedure in the VLBI analysis resulted in the expected improvement in baseline length repeatability.

Atmospheric Pressure Loading Model (1994). NVI investigated the effect of atmospheric pressure loading on VLBI data. Atmospheric pressure loading admittances were estimated from the VLBI data. For most of the frequently observed sites, these admittances were in agreement with admittances determined from a full convolution model for which a loading Green's function is convolved with weather model surface pressure fields. A model using the pressure loading admittances was implemented in the VLBI software.

Gradient Modeling (1995, 1996). NVI investigated the estimation of tropospheric gradient delay parameters in VLBI analysis. The effect of estimation of these parameters was very significant. Site position and baseline repeatabilities were improved. The precision of Earth orientation parameter estimates was improved by 30-40%. Terrestrial and celestial reference frame errors were reduced. It was also found that VLBI estimates of mean site gradient parameters were reasonably well correlated with mean site gradients estimated from global weather model data.

High Frequency EOP (1995, 2000). NVI developed an ocean tidal EOP model based on analysis of the long series of VLBI data from1979-1999. UT1 and polar motion tidal amplitudes were determined for more than 40 tidal frequencies. A smaller set of the largest amplitudes are in good agreement with amplitudes derived from Topex altimeter data. NVI has also compared VLBI amplitudes with those derived with GPS and SLR. Comparison of the VLBI model predictions with existing series of hourly VLBI measurements does not indicate that there are significant anharmonic EOP variations, although they are not ruled out.

Earth Orientation Parameter (EOP) Kalman Filter (1997). NVI developed a Kalman filter to determine an optimal continuous daily EOP series from the discontinuous series of EOP daily offsets estimated from 24-hour VLBI sessions. This is now the standard way of producing an a priori EOP series for later *solve* solutions. In addition an LOD (length of day) series is produced that can also be used for geophysical research applications.

New Set of VLBI Reference Frame Constraints (1998). NVI developed a new more generalized set of constraints for fixing the VLBI reference frame. This replaced the older more awkward constraints that were previously used. The new system applies no net translation and rotation constraints to the estimated positions and velocities of the terrestrial reference frame and no net rotation constraints to the source positions of the celestial reference frame.

Correlation of VLBI LOD and El Nino (1998). NVI investigated the VLBI LOD series and its correlation with atmospheric angular momentum (AAM). The one-day LOD series was determined from VLBI session estimates by Kalman filtering. The seasonal LOD variations and the long term drift of LOD with respect to AAM were removed to investigate interannual variations. It was found that this signal was highly correlated with the El Nino/ La Nino cycle described by El Nino Southern Oscillation indices.

Implementation of f-solve (2000). NVI completed implementation of a new version of the VLBI analysis program. By using faster algorithms and low level routines, a typical terrestrial reference frame solution can be done faster by a factor of 4-5. The code was then successfully modified to a newer faster machine, resulting in a total factor of 20-25 improvement. In addition to making the software faster, numerous improvements have been introduced including new possible options and types of analysis.

Ocean Loading Models (2000–2001). NVI has investigated the use of different ocean tidal models to derive ocean loading coefficients for VLBI analysis. The conclusion of this work is that the newer and better models do not in general improve the VLBI results. Alternatively, ocean loading coefficients were estimated directly from the VLBI data. There are significant differences between the current loading model and the estimated coefficient model indicating likely error in the current model.

Operational Analysis Utility (*opa*) (2000). NVI developed and implemented the program *opa*. It provides an efficient interface to various programs of Mark IV VLBI

analysis system, which are used during operational data analysis of experiments after completion of the interactive analysis. OPA allows the user to select operations from the menu and then executes all requested operations in automatic mode.

CORE Program (1997-2000). NVI played a major role in the planning and development of the CORE program that is planned to be operational by about the end of 2002. The performance of a set of simultaneous pre-CORE experiments from 1997-2000 have been analyzed to determine the observed precision of the measurements and to determine the sensitivity of EOP results on the observing network These results are being used to determine the best CORE observing strategy.