SAGE – Small Advanced Geodetic eVLBI System

A. E. Niell, A. R. Whitney, B. E. Corey, J. M. Gipson, W. E. Himwich,
C. A. Kodak, C. Ma, N. R. Vandenberg, W. T. Wildes

9 September 2004

1. Summary

In this report we study the possibility of replacing the current set of antennas used for geodetic VLBI with small, low-cost, high-efficiency wide-band systems using state-of-the-art technology. The study indicates that such systems are feasible and will be able to yield results which are as good or better than current systems can produce. Two candidate antenna systems are examined, one 6m diameter and one 12m diameter, with attendant first-order estimates for development and deployment costs, as well as a projected development schedule. We recommend that a detailed 6-month study phase, followed by a prototyping phase, be undertaken to put such a system into operation. This would then be followed by deployment to multiple sites for routine operation.

2. Objectives

The Solid Earth Science Working Group (http://solidearth.jpl.nasa.gov) has recommended guidelines for the NASA Solid Earth program for the next 20 years. The fundamental measurements needed to achieve the objectives must be based on a well-defined reference frame for which the accuracy goal is sub-millimeter position and sub-millimeter per year velocities globally. These accuracies will come from an integrated system of VLBI, GPS, and SLR networks, but the VLBI contribution is unique for the Celestial Reference Frame and for Earth rotation and nutation.

The current geodetic VLBI network utilizes a variety of dissimilar antennas, many of them built decades ago, for purposes ranging from communications and radio astronomy to dedicated geodetic measurements. As such, this collection of geodetic antennas has proven costly to maintain and inefficient to operate. Furthermore, non-uniformity among the antennas and systems causes antenna-specific systematic errors that are difficult to uncover and correct. Despite these difficulties, the current array of antennas has performed admirably well and has provided essential results for the geophysical community over many years.

To support the long-term program and goals prescribed by the NASA Earth Science program a new dedicated network of uniform, low-cost, high-accuracy VLBI antenna and data systems is needed. The anticipated features of these systems are small, fast antennas, high rate data recording and transmission using the latest fiber technology, and near real-time correlation and analysis. Such systems will be more efficient and less costly to operate, including the possibility for full unattended operation, with the resultant geodetic results expected to be improved as well.

In order to evaluate possible system components, we propose to initiate a test-bed for these technologies by developing a two-antenna (single baseline) system which, in the final phase, would be used to demonstrate intensive monitoring of EOP.

Based on a successful demonstration of these systems, construction and deployment of new systems by the larger geodetic VLBI community could be pursued.

3. Background

Working Group 3 of the International VLBI Service (IVS), also known as 'VLBI2010', is currently evaluating the requirements for the next generation geodetic VLBI system. The effort was initiated at this time for several reasons:

1. Many of today's geodetic-VLBI systems are aging, inefficient and expensive to operate, and are unable to provide data of best quality much of the time.
2. Observation using very wide data bandwidths has been made possible and much less expensive by the adoption of modern and inexpensive computer-based hardware.
3. With wider data bandwidths, much smaller, faster, and cheaper antennas may be able to replace today's large and expensive antennas.
4. Though the dual-band S/X systems have been quite successful over the years, increased RFI problems, particularly at S-band at some stations, have compromised results; moving to higher RF frequencies may help both to alleviate RFI problems and improve the precision of observables.
5. Significant advances in digital signal processing hold the prospect of replacing VLBI backend devices (video converters, samplers, and interfaces) with much more capable and cost effective alternatives.
6. The rapid rise of global high-speed networks presents the possibility to bring data from the antenna to the correlator in real-time or near-real-time in order to improve the value of the geodetic results.

The confluence of these factors leads us to propose construction of a new prototype geodetic-VLBI station, dubbed SAGE (Small Advanced Geodetic e-VLBI system), which might form the basis for the next generation of geodetic stations to be deployed around the world. Construction and operation of these antennas would serve to demonstrate these new technologies and to address some of the goals recommended by WG3. Among these goals are:

- Demonstrate that the desired delay precision of 4 psec can be achieved for a sufficient number of sources
- Determine the best way to utilize available frequencies if not limited to specific bands (as for the current S/X systems)
- Test and evaluate digital back end systems, if possible
- Evaluate innovative ways to utilize the phase and delay calibration system, and develop such a system for the proposed higher frequencies
- Demonstrate high-rate continuous transmission of data by fiber
- Develop software and procedures for (near) real time determination of EOP and product delivery
- Develop new algorithms for analysis of wideband data when processed with the current Mk4 correlator
- Investigate development of software correlator
- Develop control system software (Field System) for reliable unattended operation

4. Required precision of delay measurements

Although the WG3 report is not complete at this writing, progress reports and preliminary drafts of the sub-groups establish that the target delay precision should be approximately 4 picoseconds per observation in order to achieve approximately 1 mm precision in a twenty-four hour observing session. This is based on scaling the observation uncertainties from the CONT94 experiments by the factor needed to reduce the vertical position uncertainty to 1 mm, taking into account that unmodeled noise comparable to the observation uncertainty is expected. However, for current observing strategies and capabilities, realistic atmosphere and clock-like errors will inflate the vertical uncertainty to almost three millimeters even for the target delay error. It is possible that this degradation of the position accuracy will be reduced by a) the much more rapid sampling of the atmosphere and clocks that will be possible by the proposed small, rapidly slewing antennas and high data rate observations, and b) the use of Numerical Weather Models to constrain the atmosphere uncertainties.

5. SAGE System requirements

The following SAGE system requirements are adopted from preliminary drafts of the sub-groups of WG3.

Base requirements (anticipated from the WG3 study):

- Antenna efficiency: > 60%
- RF frequency range: 1.2 – 34 GHz desired
- S/X capability is required for compatibility with current systems during overlap period
- T_{sys}: <~50K
- Channel bandwidth: 16 MHz (Mk4 compatible)
- Data rate: 2 Gigabits per second (maximum practical with Mk4 correlator)
- Antenna motion: ±270° in azimuth; from 3° (or 5°) to 90° in elevation
- Slew rates: >3° per second (180° in 1 minute)

6. Available sources

In order to demonstrate the inherent precision of the SAGE system it is desirable to use a source catalogue with sufficiently accurate positions that the delay uncertainty does not contribute significantly to the RMS postfit delay residual. For the proposed demonstration on the 600 km Westford-GGAO baseline (see Section 12) the uncertainty in the source position should be less than 0.2 mas to achieve a delay error of less than ~4 psec.

Table 1, derived from the WG3 Observing Strategy sub-group report, shows the minimum source flux necessary to achieve a signal-to-noise ratio of 24 for various integration times for both a pair of 6m antennas and a pair of 12m antennas. An SNR of ~24 is judged to be minimum acceptable for the desired level of performance (see WG3 Observing Strategy sub-group report).

Int time	6m	12m
30s	1.30 Jy	0.33 Jy
60s	0.92 Jy	0.23 Jy
120s	0.65 Jy	0.16 Jy
240s	0.46 Jy	0.12 Jy

Table 1: Minimum correlated flux density (Jy) for a pair of 6m or 12m antennas with e=60%, T_{sys}=45K and a data collection rate of 2 Gbps/antenna

The other requirement is that the sources be strong enough at the resolution given by the antenna separation, and for both X- and S-band, that sufficient signal-to-noise ratio (SNR) be obtained to achieve the 4 psec delay precision.

Based on investigations and analysis of existing geodetic source catalogs, these requirements are met. Furthermore, source catalogs are being continually expanded and systematically monitored, thus assuring a sufficient supply of adequate sources for future programs.

7. Options Investigated

Based on the stated 4 psec measurement-precision requirement, we have explored various options to construct a new low-cost VLBI observing station. Our projection is that a 6m-class antenna with a 2 Gbps data rate to the correlator can provide the necessary sensitivity for the core set of radio sources used for geodetic VLBI, as described above. On the other hand, a 12m antenna would provide greater sensitivity and versatility for investigating future needs and performance.

We have identified two antenna systems that are either being reproduced, under construction, or under contract for construction, that may be suitable for SAGE. They are, respectively, the ATA 6m antenna of the SETI Institute and a12m prototype for the NASA Deep Space Array Network being built for JPL by Patriot Antenna Systems.

7.1. ATA system

7.1.1. ATA antenna

Our attention for a 6m class antenna is focused on the antenna and feed system that has been developed for the Allen Telescope Array (ATA) at the SETI Institute (Figure 1). The ATA is developing these antennas to be both high performance and low cost. The plan is to ultimately deploy 350 of these 6m offset Gregorian dishes in an array at the Hat Creek Observatory in California.

Three ATA antennas are currently in place with twenty-nine more under construction. On completion of these an order will be placed for additional reflector surfaces to bring the total to 206. By taking advantage of the extensive work already done for this development by the ATA, we believe that we can save both significant time and expense for the geodetic-VLBI application.

In the following paragraphs, we will briefly address each of the major sub-systems required for such a system.

The RF performance of the ATA 6-m antenna system indicates that the efficiency and system temperatures that have been demonstrated will allow observation of a sufficient number of radio sources with the necessary delay precision to significantly surpass the current level of geodetic VLBI precision in a 24-hour session for a network of nine globally distributed antennas. While the preliminary goal set by WG3 is for frequency coverage from 1.2 GHz (GPS) to 34 GHz (DSN S/C tracking), the ATA antenna covers 0.5 to 11 GHz. However, as discussed in the WG3 report, there are advantages to keeping the observing frequencies as low as possible while obtaining the desired delay uncertainty:

1. antenna efficiency and pointing accuracy are more easily achieved;
2. receivers generally have lower temperatures for the same cost;
3. correlated flux densities are generally greater, although sources may be more complex.

The WG3 report will also recommend that antennas be capable of making observations as low as 5° in elevation. Low elevation observations provide greater separation of the vertical from the clock and atmosphere delay, but at the same time increase the sensitivity to errors in the atmosphere mapping function. As constructed the ATA antenna will go down to only 15° elevation, at which point the backup structure encounters the pedestal. To go lower will require a larger offset of the antenna from the azimuth axis, thus requiring a stronger and therefore more expensive mount. Although such a mount can undoubtedly be designed, it will certainly raise the cost of the system. With higher sensitivity (which might be attained with a 12-m antenna) and rapid slewing, a 15° minimum elevation might be sufficient to meet the geodetic measurement goals, but the 6m antenna with this limitation is likely to be marginal.

The feed/LNA output provides orthogonal linear polarizations. For the long baselines of the geodetic applications linear polarization is a disadvantage for two reasons. First, the angle of the incoming radio waves will be different at the two sites due to differential Faraday rotation, primarily from the ionosphere, leading to decorrelation. Second, the parallactic angle of the feeds will be different for az-el antennas. To recover the full signal it will be necessary to correlate all four combinations of linear polarization, XX/YY/XY/YX, from the pair of antennas (or the two combinations of linear with circular when observing with the existing geodetic systems). Then, to extract the phases, delays, and amplitudes for the geodetic application, either the separate correlations must be combined in the astronomy software package, AIPS++, or additional post-correlation software must be developed. For the current Mark4 correlator, the correlations can be done in one pass for up to four antennas since the additional polarizations can be treated as additional baselines.

The phase center of the unique log-periodic broadband feed is frequency dependent. The position is remotely adjustable over a distance of thirteen inches. For SETI the focus is set for a frequency of 6 GHz, resulting in loss of sensitivity below 4 GHz and above 8 GHz. The sensitivity loss is about 10% at 2 GHz and 11 GHz. The corresponding reduction in sensitivity for the VLBI observations is about 20%. The effect of these losses on the delay observable could be partially compensated, in principle, by putting relatively more bandwidth in these outer frequency ranges.

7.1.2. ATA Receiver to IF

The ATA system will be equipped with an integrated feed and cooled receiver that provides continuous frequency coverage from 0.5 GHz to 11 GHz with a system temperature of about 45K. In ATA memo 64 (Frequency Coverage of the ATA Front-end, David R. DeBoer et al) the system temperature and gain of the feed and receiver combination is shown to degrade only slightly up to about 14 GHz, thus opening the possibility for wider bandwidth coverage and more option for avoiding RFI.

A block diagram of the ATA analog electronics from feed through the digitizer is shown in Figure 2. Each antenna has a dual-linear feed, inside of which are the cooled LNA, variable-gain post-amplifier, gain equalizer, and band-defining filter for each polarization. No frequency translation is done at the antenna. The two RF signals spanning approximately 0.5-11.2 GHz are transmitted via optical fiber to the RF converters. Each RF converter can translate up to four ~1-GHz-wide chunks of RF spectrum to L-band frequencies (1-2 GHz). These L-band IF signals are then down-converted to baseband in an I/Q mixer (I = in-phase, Q = quadrature), low-pass filtered, and digitized in an 8-bit sampler at 155 MS/s.

The best place to tap off the ATA signal and send it to the VLBI equipment appears to be after the RF converter, when the signal is at L-band. A simple, relatively inexpensive downconverter (a few hundred $US, not including the LO) could translate each IF signal to the frequency range appropriate to a Mark 4 data acquisition terminal (DAT) (100-500 MHz, or 100-900 MHz for an IF3-equipped DAT) or to a digital BBC, should the latter become available on the time scale of this project. Before adopting this approach, however, it must be verified that the LO phase noise in the RF converter is sufficiently low to support VLBI observations.

7.1.3. Conclusions for ATA 6m antenna

In summary, the ATA 6m design comes with the following advantages:

- Low cost due to mass production
- Comes complete with RF/IF system
- Wide continuous RF bandwidth (0.5 GHz to 11 GHz)

and with the following disadvantages:

- Relatively low sensitivity
- 15° low-elevation limit
- Linearly polarized feed system
- One-piece antenna construction may pose difficult transportation problems

Due to its low cost, the ATA 6m system worthy of further study despite its 15° elevation limit. If the elevation limit can be overcome by a new mount design of modest development and replication cost, it is possible that the 6m design will be satisfactory. Further study of this antenna is thus warranted.

7.2. JPL 12m design

7.2.1. 12m antenna

The JPL Deep Space Array Network is developing a 12 m antenna system as part of a project to replace its large tracking antennas with arrays of smaller antennas. The 12m antenna will be significantly more sensitive, but also more expensive, than the 6m ATA antenna. The 12m prototype is being built by Patriot Antenna Systems of Albion, MI. It will be a paneled antenna (not a hydroformed single piece surface as used for the ATA) with surface accuracy good enough for operation at 30+ GHz. The system to be built by Patriot will be complete, including sub-reflector, except for primary feed and electronics. Therefore it would be necessary to obtain independently the feed and amplifiers, as well as a backend for the RF to IF conversion.

The azimuth wrap is ±270° from neutral. The elevation range is from zenith down to 5°. The antenna is specified to reach a commanded position in no more than two minutes.

The execution of a geodetic schedule puts extreme demands on the drive system with the need to move rapidly around the sky up to thirty times per hour essentially continuously for an operational system. The robustness of the Patriot design has not been evaluated, but should be sufficient for prototype testing.

7.2.2. 12m feed and amplifiers

A possible feed for the 12m JPL antenna is a broadband dual linear polarization feed for 0.5 to 15 GHz that has been developed by Per-Simon Kildal of Chalmers University in Sweden. A separate feed for 11-34 GHz is under development by Kildal (S. Weinreb).

Low-noise amplifiers are available at several bands up to the 30 GHz range. If we restrict our frequency range to the current S (2.3 GHz) and X-band (8-9 GHz) antennas, plus C-band and Ku band (12 GHz), it may be possible to adapt these amplifiers and the Kildal lower range feed for use with the 12m antenna built by Patriot. Possible issues are the size of the sub-reflector needed to match the Kildal feed beam size and location of the Kildal feed.

7.2.3. Conclusions for JPL 12m antenna

In summary, the JPL 12m design comes with the following advantages:

- Relatively high sensitivity
- Observes down to 5° elevation limit
- Paneled construction for easy transportation of unassembled antenna
- Relatively higher cost

and with the following disadvantages

- More expensive than 6m design
- Linearly polarized feed system
- Feed system less well developed; may need some custom design
- May have to design RF/IF system

7.3. Calibration systems

In order to keep costs down, it would be desirable to initially use the same phase and delay calibration design currently installed in most geodetic-VLBI station. This system provides calibration tones spaced at 1 MHz intervals throughout the RF band which are used to calibrate the phase delay through the receiver and backend system.

Current limitations in the Station Units at Mark 4 correlators allow a maximum of two phase-cal tones to be processed within each observed baseband channel. There is significant benefit in both system calibration and diagnostics if more tones are extracted. This will be possible with the new Mark 5B system, which is expected to be available in early 2005. The Mark 5B will replace the Mark 4 Station Unit at the correlator and allow up to 16 phase-cal tones to be processed in each of the 16 observed baseband channels.

Since the dual linear polarization broadband feeds do not accommodate a directional coupler for injection of the required calibration signals, other designs will have to be considered. On the other hand, the improved stability of an ATA-type front end, and the use of very wide bandwidth on a common fiber, may reduce significantly the need for such calibration. Since the RF/IF system for the 12 m design is not known, the means of calibration should be kept open.

The other type of calibration that is desirable is system gain calibration. This is needed for monitoring antenna sensitivity and for calibrating the strengths of the radio sources that are observed. It is usually accomplished by injecting near the feed the signal from a stable noise diode, then comparing the power with diode on to the power with the diode off. As for the phase calibration, this requires a means of introducing the signal near the beginning of the RF signal chain. The ATA uses a calibration signal transmitted from the subreflector.

In order for either of these systems to be used operationally, a means of generating circular polarization should be found in order to eliminate the additional correlation that is required when using dual linear polarizations.

7.4. Back-end subsystem

Although we anticipate that the initial implementation of SAGE will use current analog backend components (baseband converters [BBCs], sampler module, and Mark5B), better reliability and stability can be achieved by replacing the analog ‘backend’ systems (BBCs and samplers) with fully digital counterparts. Digital backend (DBE) systems will be absolutely uniform and predictable in their performance, effectively eliminating systematic errors currently contributed by analog BBC’s . Additionally, DBE systems will be considerably less costly to manufacture and to maintain than their current analog counterparts.

As a first step, a collaborative effort of European and US engineers has been initiated for the design of digital baseband converters. The goal is to provide fully digital BBCs by the end of 2005.

7.5. Data system

Initially, two Mark 5B recorders will be required at each antenna to achieve the 2 Gbps data rate. However, progress is being made to increase the recording rate of a single Mark 5 system to 2 Gbps, which will incorporate a next generation StreamStor card and the use of SATA disks. Playback, however, will be limited, at least initially, to 1 Gbps.

In the short term, two Mark 5B systems would be used in parallel to record 32 16MHz channels from a set of standard Mark 4 BBC’s (for a total of 2 Gbps). Correlation on the Mark 4 correlator would be done in two passes, with 16 channels correlated in each pass, or by treating each of the two Mark 5B systems as a separate station and correlating in a single pass (up to 8 actual stations maximum). Software upgrades will be required to “stitch” the data together for a fourfit type analysis. The possibility of additional correlations to accommodate the linear polarization must also be taken into consideration.

In order to demonstrate real-time or near-real-time operation, a high-speed network connection to the global network is required to return 'e-VLBI' data to the correlator. Communication at 1 Gbps for Westford and GGAO are now in place (Sep 2004), and a real-time demonstration experiment at 512 Mb/s was recently successfully conducted. Though stations with existing 2 Gbps network connections are rare, the cost of connection continues to fall and more stations will continue to be connected at higher and higher rates.

Data will be transferred according to the developing VSI-E (VLBI Standard Interface – e-VLBI) specification, which is expected to be ratified by the international VLBI community by the end of 2004. In addition, advantage will be taken of new network protocols and algorithms developed at Haystack Observatory under grants from the National Science Foundation that optimize network usage for e-VLBI.

7.6. Antenna control software and field system modifications

A standard package for antenna control will be needed with a new antenna. This will be based either on existing antenna control packages for ALMA or ATA or on one for an existing antenna. This will allow utilization of existing antenna calibration tools of the Field System for the new antennas.

The Field System will be modified to allow it to be used more effectively for remote and unattended operation. The changes will allow concurrent operation of the system both locally and remotely so that a centralized "network operator" can monitor operation of the sites. In addition the facilities for identifying and classifying errors will be expanded so that situations that require local operator intervention will be identified and an alert that assistance is required will be automatically issued to nearby off-site personnel. Both of these changes will decrease the operations costs and should improve the overall reliability of the network.

8. Correlator

The station data will be transmitted to the Mark 4 correlator at Haystack Observatory via high-speed network. The capability has recently been demonstrated to correlate data in both near-real-time (disk buffered using Mk5a) and real-time (diskless). These initial demonstrations were conducted with quickly modified software at the Mark 4 correlator, but operational real-time software must be developed for reliable routine operation.

9. Network connections

High-speed network connections are crucial to the demonstration of sustained real-time or near-real-time operation of the SAGE system. As indicated above, both the Westford and GGAO stations have 1 Gbps connections to the Haystack Mark 4 correlator. The speed of these connections will be increased to greater than 2 Gbps in time for the SAGE demonstration, made possible primarily by NSF funding for e-VLBI research at Haystack.

It is assumed that network connectivity of the required speed will be in place. No request is being made for funding in this SAGE proposal for additional capability in the data transmission from the antennas to the correlator.

10. Data Processing

SAGE data analysis beyond correlation will require software development. In particular, the RF frequency flexibility and extreme RF spanned bandwidths available in the SAGE system may require upgrading of fringe-finding software. Since the current fringe processing software can make use of only two calibration tones in each band (S or X), the extraction of all available 16 phase-cal tones, which will improve the group-delay observable, will require software development.

11. Analysis and product delivery

The availability of near-real-time correlated data from the initial baseline will allow monitoring of UT1-UTC as a prototype application product. Software will be developed to automate the analysis and generation of UT1-UTC. The development will include capabilities for automated quality control and validation of the results before delivery.

12. Recommendations

We recommend that the SAGE project proceed as a three-phase plan:

1. Detailed design
2. Prototype development and testing of 2-antenna SAGE system, with SAGE antennas sited at Westford and GGAO; software development and correlation at Haystack.
3. Deployment of 2-antenna SAGE system for intensive (perhaps continuous) EOP observations

12.1. Phase 1 - System Design

The design phase will consist of the following elements:

- Choose antenna system, including the following:
  - Procurement of the antenna surface?
  - Cost to duplicate mount?
  - RF frequency band selection (S, C, X, Ku, Ka?)
  - Can Kildal 0.5-15 GHz feed be mounted on the antenna structure?
  - Feed selection and design (if necessary)
  - Selection of front-end LNA; both ATA and JPL MMIC LNA's, as well as satellite-communication LNAs, will be evaluated
  - Is JPL MMIC LNA suitable for use with 6m antenna; can we purchase MMIC LNA from JPL supplier?
- Backend design:
  - Use current Mark 4 backend design; availability?
  - Adopt digital BBC design from VLBI community (if available)

12.2. Phase 2 - Prototype development and testing

The prototype development and testing phase of the project will consist of:

- Site selection at Westford and GGAO
- Site development (antenna pad; power, communications; frequency-standard distribution; GPS timing); existing H-maser frequency standards and high-speed network infrastructure will be utilized.
- Procurement of all subsystems and components
- Assembly and testing of individual antenna systems
- Integration of antenna system, backend, data system
- Integration with NASA Field System software
- Testing of individual standalone antenna systems
- Interferometric testing, including observations with the Westford antenna to demonstrate sub-millimeter accuracy (though precision may be limited by the Westford system); testing with both SAGE antennas
- Evaluation of results

In order to fairly evaluate the performance of the SAGE system, it will be necessary to perform extensive tests both with existing VLBI sites as well as with the second SAGE antenna. For testing with existing sites, it will be valuable to maintain the S/X capability in the SAGE system. Tests between the two SAGE antennas will be free to move to the alternate frequency bands supported by the SAGE system. If 6m antennas with 15° elevation limit are chosen and evaluated, the need for an antenna-mount redesign will be addressed and costs estimated.

12.3. Phase 3 - Deployment for Intensive EOP Observations

Following validation of the SAGE prototype systems, one of both of the SAGE systems will be deployed to other sites that are better geographically placed for EOP measurements and that have the necessary existing infrastructure to support them (hydrogen maser, high-speed network connection); at these locations the SAGE systems will conduct intensive real-time (or near-real-time) EOP measurements to prove their suitability in a real-world environment.

13. Schedule

We estimate the following schedule for the work of the three proposed phases of the SAGE project:

Phase 1: Detailed design – 6 months (from NASA approval to proceed and identification of resources)

Phase 2: Prototype development and testing – 18 months

Phase 3: Routine intensive EOP measurements – open-ended

14. Budget

A very rough budget has been developed that will be refined during Phase 1 of the SAGE project.

14.1. Phase 1 - Detailed Design

Detailed system design is estimated to require ~2 person-years at a loaded cost of ~$300K.

14.2. Phase 2 - Prototype development

Until Phase 1 is completed it will be impossible to accurately estimate the costs for prototype development. The following budget numbers are first order estimates for Materials and Services (M&S) that will be refined during Phase 1.

One SAGE system (M&S)

<u>ATA 6m</u>	
Complete with feed/LNA	$100K
<u>Patriot 12m</u>	
Antenna [including installation by Patriot]; (cost is highly dependent on purchase within JPL prototype/implementation cycle)	$100-300K
Feed (not including design)	$5-10K
LNAs for 3 or 4 freqs	$20-40K
Front end to IF	$10-20K
L-band IF converter	$1-2K
<u>Common</u>	
Shipping	$10-20K
Antenna erection	$5-8K
Pad, cabling	$10-15K
Control computer	$2-4K
Networking connection	$5-10K
Two Mark 5B systems	$35K
Mark 5 disk media	$15K
Digital back end (if developed externally in time)	$20K
Phase and delay calibration system	$3-6K
<u>Manpower & Travel</u> (total for Phase 2)	
~5 person-years	$750K
Travel	$10K

Total for two ATA-based 6m systems:	*~$1160-1220K*
Total for two JPL-based 12m systems:	*~$1240-1760K*

Additional manpower may be needed if feed design work is necessary for 12m antenna.

14.3. Phase 3 – Deployment for Intensive EOP measurements

Costs for deployment to sites is highly dependent on the sites selected and is hard to predict at this time. We expect deployment would be to already well developed sites so that incremental personnel costs to operate the SAGE systems would be quite low. Additionally, we assume that a high-speed network infrastructure is already in place. The following numbers are based on educated guesses to move one SAGE system and operate two SAGE systems for one year:

System relocation cost	$10-20K	(unloaded)
Manpower (estimate 0.1 p-y/year/system; 2 systems)	$30K	(loaded)

15. Summary

The results of this report show that a small-diameter high-performance antenna system of low to modest cost can be used in conjunction with multi-Gbps data rates to build a geodetic VLBI system that meets the precision-measurement requirements for the future. We propose a two-year development effort to move from concept to operational reality of a 2-antenna system based on these concepts. We believe this new system, dubbed SAGE, will be instrumental in helping to both improve the science which geodetic VLBI enables and dramatically lower the cost of collecting the necessary measurements.

Acknowledgments

We thank Bill Petrachenko (Natural Resources Canada) for system design studies, as well as the contributors to the IVS Working Group 3 sub-group report series. In addition, we thank Sander Weinreb (JPL) and Dave DeBoer (ATA) for many useful discussions regarding the development of their respective new antenna systems.

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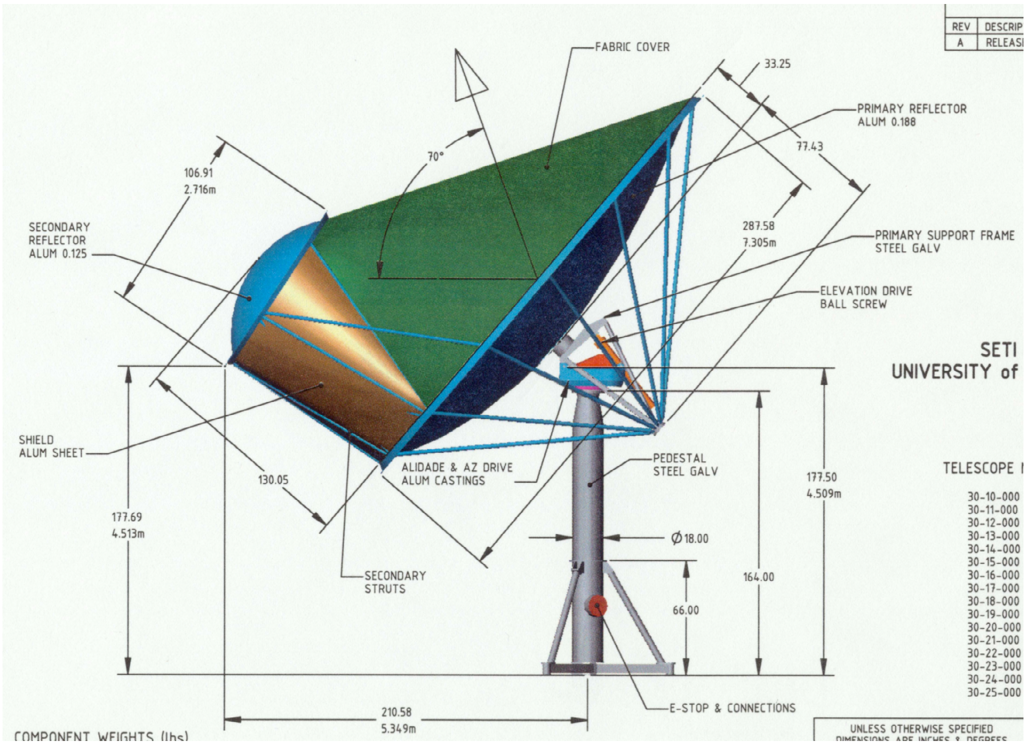

Figure 1: Diagram of ATA 6m antenna

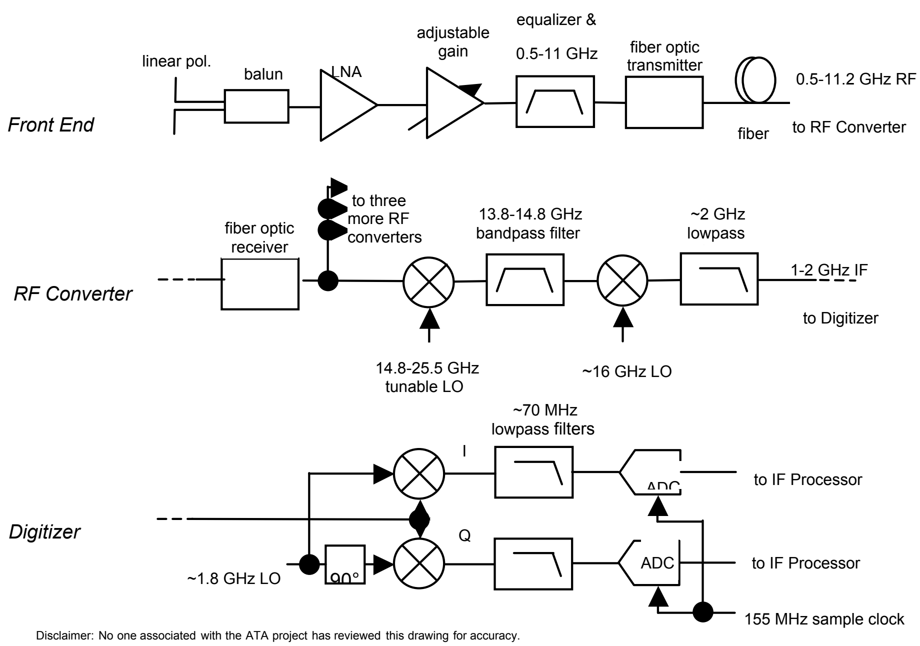

Figure 2: Block diagram of ATA electronics from feed through digitizer