VLBI2010: Current and Future Requirements for Geodetic VLBI Systems

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Abstract

Geodetic VLBI stands at the brink of a new era. Such societally relevant issues as climate change and natural hazards are placing ever increasing demands on performance. This comes at a time when problems with aging antennas, a deteriorating RFI environment, obsolete electronics, and high operating costs are making current levels of accuracy, reliability, and timeliness difficult to sustain. Attaining modern requirements for significantly greater accuracy, continuous data flow, and shortened times to product delivery challenge the continuing progress made by geodetic VLBI over the past 30 years. Fortunately, recent advances in antenna manufacture, digital electronics, and data transmission technology are enabling modes of operation unimaginable only a few years ago. Furthermore, the capital investment and reduced operating costs associated with the new technology make complete renewal of present infrastructure appear cost effective. A new instrument that will meet requirements for decades to come can now be envisioned.

IVS Working Group 3 (WG3) was asked to examine current and future requirements for geodetic VLBI, including all components from antennas to analysis, and to create recommendations for a new generation of VLBI systems. To constrain these recommendations, a new set of criteria by which to measure the next generation geodetic VLBI system was established based on the recommendations for future IVS products detailed in the IVS Working Group 2 Report [23], on the requirements of the Global Geodetic Observing System project of the International Association of Geodesy [7], and on the science driven geodetic goals outlined in the NASA Solid Earth Science Working Group Report [19]. These criteria are:

- 1 mm measurement accuracy on global baselines
- continuous measurements for time series of station positions and Earth orientation parameters
- turnaround time to initial geodetic results of less than 24 hrs.

While the new requirements are significant challenges, it is vital to continue the measurements for which VLBI is the unique space geodetic technique:

- UT1 and nutation
- the celestial reference frame (CRF)

UT1 and the CRF are currently defined by VLBI, and there is no alternative for the foreseeable future.

It is recognized that achieving long term accuracy at the level of 1 mm or better is a daunting task. From the outset WG3 sought approaches for the design of the new system that would enable the following performance enhancing strategies:

- Reduce the random component of the delay-observable error, i.e., the per-observation measurement error, the stochastic properties of the clocks, and the unmodeled variation in the atmosphere
- Reduce systematic errors
- Increase the number of antennas and improve their geographic distribution
- Reduce susceptibility to external radio-frequency interference
- Increase observation density, i.e. the number of observations per unit time
- Develop new observing strategies

All of the above considerations, along with the need for low cost of construction and operation, required a complete examination of all aspects of geodetic VLBI, including equipment, processes, and observational strategies. The results of this examination have led WG3 to make the following recommendations:

- **Design a new observing system based on small antennas.** The new system will be automated and operate unattended and will be based on small (10–12 m diameter), fast-moving, mechanically reliable antennas that can be replicated economically. The observing should be done over a broad, continuous frequency range, perhaps 1–14 GHz, which includes both the current S-band and X-band frequencies for backwards compatibility, but allows much more agility to avoid RFI and more bandwidth to significantly improve delay measurement precision. At the same time, the best of the existing large antennas will be updated for compatibility with the new small-antenna system; this will allow them to co-observe with the small-antenna systems to preserve continuity with the historical record, as well as to improve the CRF measurements made primarily by the large antennas.
- **Transfer data with a combination of high-speed networks and high data-rate disk systems.** Data recording rates and transmission rates are rapidly increasing courtesy of vast investments by the computer and communications industries.
- **Examine the possibilities for new correlator systems** to handle the anticipated higher data rates, including correlation based on commodity PC platforms, possibly widely distributed.
- **Automate and streamline the complete data-analysis pipeline,** enabling rapid turnaround and consistent TRF, CRF, and EOP solutions.

Because the new systems should be fully backwards compatible with the existing systems, the transition from the old to the new systems can be gradual and deliberate, maintaining important continuity of geodetic results and measurements series while dramatically upgrading the quality, precision, and timeliness of new observations. Furthermore, with more of the new VLBI systems co-located with the suite of complementary space-geodetic techniques, the space-geodetic program as a whole will be greatly strengthened.

The above recommendations describe a system that can begin to become reality very soon. This report identifies specific steps that need to be taken next in order to develop, deploy, and bring the system into operation. The next steps include two broad categories of efforts:

- **System studies and simulations:** error budget development, decisions on observing frequencies, optimal distribution of new sites, number of antennas per site, new observing strategies, and a transition plan.
- **Development projects and prototyping:** small antenna system, feed and receiver, cost and schedule, higher data rate system, correlator development, backend development, and data management and analysis software.

Almost all of the recommended next steps can be done in parallel, and WG3 hopes that various IVS components will find the resources to support one or several of these studies and development projects. Results of these studies and projects should be well communicated within the community and coordinated by IVS so that common goals for the new vision are recognized and met.

It is important that IVS make a strong recommendation that some of the resources dedicated today to routine product generation and technology development be directed to address the studies and projects recommended in this report. These studies must move forward so that a detailed plan can be generated, including defensible costs and schedules. Building on the efforts of WG3, the results of these studies and projects will provide the final element required for IVS members to move forward with requests for augmented funding to implement the new vision. We believe that this vision will renew the interest of current funding resources and inspire new interest from universities, industry, and government, based on the exciting possibilities for a more accurate and data-rich geodetic VLBI system.

1. Introduction

The quest for increasing accuracy, continuity, and timeliness of geodetic data as a benefit to both science and society has been at the root of the development of space-geodetic techniques for more than 30 years. VLBI has played, and continues to play, an important role in providing high-precision geodetic data, having improved measurement accuracy and precision from meters in the 1970s to millimeters at the turn of the century. However, the existing worldwide VLBI system, though being continually upgraded, has now nearly reached the limits of its capabilities and requires major renewal in order to provide the 1 mm accuracies demanded in the coming years. In this report, we will examine the role of VLBI in high-precision geodetic measurements, outline the challenges that are currently being faced, and propose a new system (and transition plan) based on small antennas that will achieve the goals set forth by the geodetic community.

1.1. The Importance of High Accuracy Geodesy to Science and Society

High-precision geodesy is central to a broad variety of human activities, including private, commercial and governmental interests, as well as being of broad scientific interest. In everyday life the applications include monitoring of dam and bridge deformation; navigation for commercial airlines; and agriculture (fertilizing by tractor or crop duster). In not-so-every-day life high accuracy geodesy is fundamental to the evaluation of natural hazards with the goal of mitigating the suffering of individuals and reducing the cost to society. Among these applications are monitoring volcano inflation, measuring stress levels for earthquake hazard assessment, and refining our models of sea level change. For the advancement of science, precise geodetic measurements contribute to the fundamental understanding of many aspects of our Earth, including structure and deformations of the crust, mantle, and core, and the magnetic coupling between the inner and outer cores.

Modern geodesy relies on space-based observing systems. The three primary techniques are Very Long Baseline Interferometry (VLBI), the Global Navigation Satellite System (GNSS), and Satellite Laser Ranging (SLR). All three systems provide the basic measurement of the positions of the instruments on the surface of the Earth. These positions define the reference frame for the high-accuracy applications described above. In addition, each technique makes unique and complementary contributions to the overall framework. GNSS provides the high surface density and ready availability of reference positions needed for a practical system. SLR most accurately measures the center of mass of the Earth. VLBI provides the orientation of the Earth in inertial space and the celestial reference frame (CRF).

1.2. Contributions of VLBI

VLBI can accurately measure the geodetic parameters associated with the shape of the Earth and orientation in inertial space. This includes the positions and velocities of the sites occupied by VLBI antennas, UT1-UTC, polar motion, and nutation. In addition, of the three space geodetic techniques, VLBI provides the only access to the inertial reference system through observations of the extragalactic sources that form the CRF. The orientation of the Earth in inertial space, as given by UT1-UTC and nutation, is necessary for accurate satellite orbit determination.

The scale of the Earth-fixed reference frame is accurately determined by VLBI measurements of the relative positions and velocities of the VLBI antennas on the surface of Earth. The changes in position are due to the motion of the tectonic plates, to deformation of the crust near faults, to post-glacial rebound, and even to volcanic activity. The inertial frame is defined by the quasars billions of light years away which form the CRF. A global network of VLBI antennas relates the two frames by measurements of the rotational position of the Earth (UT1-UTC) and measurement of changes in direction of the spin axis in the inertial frame.

A further significant contribution of the VLBI technique is accurate positioning of planetary spacecraft relative to the CRF for interplanetary navigation. A recent application has been the measurement of the change in position of the Huygens lander of the Cassini mission to determine the velocity of winds in the atmosphere of Saturns moon Titan [18].

The historic series of VLBI measurements of the Earths nutations and variation in rotation are unique for investigating the properties of the mantle and core and changes with time [13].

1.3. Challenges of the Current System

The current geodetic VLBI network of antennas has achieved extraordinary success. However, a number of factors are converging which challenge continued progress:

- Most VLBI equipment now in use around the world for geodetic VLBI programs was developed in the 1970s and 1980s. The equipment is being pushed to the limits of performance and is costly to maintain.
- Radio interference at S-band has increased dramatically in the past few years, reducing the sensitivity and increasing the errors in that band at many locations.
- Existing antennas at many sites move slowly, which makes it difficult to provide the rapid whole sky coverage needed for the highest accuracy.
- The location of many antennas is not ideal; a number of gaps in the worldwide distribution leaves the Terrestrial Reference Frame (TRF) incomplete and reduces the sensitivity for measurement of EOP.
- Operational costs remain high due to the fact that unmanned operations are generally not possible.
- Processing time to final results is long, due to shipping times and to the lack of automation of final solution software.

1.4. Recent Developments

Over the past few years there have been several technological developments that will enable significant improvement in the capability of a new geodetic VLBI network, and at a lower cost than would have been possible earlier.

- **lower cost antennas:** The development of large radio-frequency arrays for other projects, such as the Allen Telescope Array (ATA), the Square Kilometer Array (SKA), and the NASA Deep Space Network Array (DSNA), has led to the creation of antennas of a size that is useful for geodesy but at an order of magnitude lower cost.
- **cheaper, higher capability disk technology:** The decreasing cost and increasing rate and capacity of disk media have made it possible to develop and demonstrate inexpensive, high-data-rate recording, with much higher rates to be attainable in the future.
- **global optical-fiber network infrastructure:** The rapid increase in global availability and deployment of optical fiber provides the means of transferring data from antennas directly to the correlators.

- **high-speed digital signal-processing technology:** Advances in digital signal-processing technology will increase the absolute stability, repeatability, and predictability of the signal-processing chain. At the same time the technology can provide much higher data rates for recording and/or transmission, thus permitting the use of smaller antennas.

In addition, a major organizational development, the International VLBI Service for Geodesy and Astrometry (IVS), has enabled a more tightly focused and broadly coordinated global VLBI effort. IVS, organized in 1998 as one of the services of the International Association of Geodesy (IAG), is responsible for coordinating VLBI components operated and provided by its member organizations and for generation and distribution of accurate TRF, CRF, and EOP parameters in a timely manner.

1.5. Goals for the VLBI System

In the same time period that important advances have been achieved in the technology realm, the goals that influence the actions of the space geodetic services have become more focused. In 2001, a review of the existing products and observing programs was carried out by IVS Working Group 2 [23], which clearly defined the goals for IVS products and prescribed an IVS observing program optimized to make best use of the available resources to create these products. The major recommendations of Working Group 2 for IVS products are briefly summarized in Table 1.

The science drivers for geodesy in general have been advanced by the NASA Solid Earth Science Working Group [19]. Additionally, global goals for geodesy as a science are expressed in the scientific rationale of the GGOS project [7]. Combining these science goals with the operational goals laid out by the IVS WG2 report, the requirements for the next-generation VLBI system can be essentially distilled into the following three distinct goals:

- 1 mm position and 1 mm/year velocity for position (TRF)
- Continuous measurements for EOP
- Rapid generation and distribution of the IVS products

These goals, along with both the challenges presented by the current status of the global VLBI system and the opportunities presented by recent technological developments, provide the motivation for the recommendations made in this report.

1.6. Charge to WG3

The IVS Directing Board formed WG3 with the charge to examine current and future requirements for geodetic VLBI systems, including all components from antennas to analysis, and to create a vision and concrete recommendations for a new generation VLBI system that not only meets the goals stated above, but also satisfies the following criteria:

- low cost of construction
- low cost of operation
- prompt analysis and delivery of final results

Among the issues to be explored were:

- small, low-cost, fast-moving antennas

Table 1. Summary of primary goals of IVS Working Group 2.

Category	**Products**	**Accuracy**	**Frequency of solutions**	**Resolution**	**Timeliness**
TRF	x, y, z time series (one solution per session)	2–5 mm	7 d/w	1 day	1 day
	episodic events	2–5 mm	7 d/w	< 1 day	near real time
	annual solution coordinates velocities (multi session)	1–2 mm 0.1–0.3 mm/y	yearly	–	1 month
CRF	radio source coordinates	0.25 mas for as many sources as possible	yearly		1 month
	α, δ time series	0.5 mas	monthly	1 month	1 month
EOP	UT1-UTC	5 μs	7 d/w continuous	10 min	near real time
	$d\varphi$, $d\varepsilon$	25–50 μas	7 d/w	1 day	near real time
	xp, yp	25–50 μas	7 d/w	10 min	near real time
	dxp/dt, dyp/dt	8–10 μas/day	7 d/w	10 min	–
geodynamical parameters	solid Earth tides h, l	0.1%	1 y	1 y	1 month
	ocean loading A, φ	1%	1 y	1 y	1 month
	atmosphere loading	10%	1 y	1 y	1 month
physical parameters	tropospheric parameters zenith delay gradients	1–2 mm 0.3–0.5 mm	7 d/w 7 d/w	10 min 2h	near real time
	ionospheric mapping	0.5 TEC-units	7 d/w	1 h	near real time
	light deflection parameter	0.1%	1 y	all sessions used	1 month

- optimum and practical observing frequencies
- inclusion of existing antennas
- modernization of VLBI data-acquisition systems for higher stability and reliability, wider bandwidth, lower cost
- transmission of data via high-speed network (e-VLBI)
- new observing strategies
- automation of observations; remote monitoring
- possible correlator upgrades

- advances in models and strategies for data analysis
- automation of data processing

For this work, WG3 was asked to draw on the resources of both the astronomy and geodesy VLBI communities to obtain the best ideas and technological advances worldwide, and to examine other relevant developments, such as the SKA and ATA antenna system development. To facilitate the goals of WG3 and to draw the largest possible group of experts into the effort, seven sub-groups were formed, each with members from the broad international VLBI community.

The remainder of this report summarizes the strategies and recommendations that arose from the work of this broad array of expertise. Necessarily, many of the details presented in the sub-group studies are omitted here, though the reader is invited to review them [24].

2. Strategies to Achieve the Goal of 1 mm Accuracy

The existing VLBI network and observing procedures evolved largely from an astronomical background. For the next-generation instrument it is important to consider from the beginning the best strategies to achieve the geodetic objectives. The path to achieving the last two of the goals stated in Section refsec1.5, namely continuous measurements for EOP and rapid generation of products, involves reasonably straightforward technological approaches and will be addressed in Section 3. However, 1 mm position accuracy that is consistent over global distances and long time periods, e.g. decades or more, is unprecedented.

A number of actions can be considered in order to reach the 1 mm accuracy goal. These include reducing both the random and systematic components of the delay observable itself, increasing the number of observations per unit time, increasing the number of antennas and their geographic distribution, reducing susceptibility to external radio frequency interference (RFI), and developing improved observing strategies. We will briefly examine each of these in the sections below.

2.1. Reduce the Random Component of the Delay Observable

The primary contributors to random delay-like errors, which currently limit vertical accuracy to about three millimeters, are the per-observation delay measurement error, the stochastic behavior of the troposphere, and the stochastic behavior of the frequency standard and distribution system. It would be helpful to be able to place hard targets on each of these contributions. Unfortunately, this is more difficult than it might at first appear since the contributions are heavily correlated, and their effects are strongly influenced by other factors, such as the details of the observing schedule, array geometry, etc. Nevertheless, reducing each effect individually will have some beneficial effect.

2.1.1. Reduce the Per-Observation Delay Measurement Error

To improve the instrumental noise limitation on short time scales, a per-observation delay precision of approximately four picoseconds is the target [25]. Three approaches can be considered to achieve this target: 1) increase SNR; 2) increase the frequency spanned within a band by moving to higher frequencies: for example, at Ka band ($\sim$32 GHz) the available bandwidth is several GHz, and the present X-band could be used as the second frequency for ionosphere correction; or 3) use an ATA-style feed [1] to sample more frequencies over the range from about 1 GHz to 14 GHz so that phase-delay ambiguities can be resolved. It has been shown in the Observing Strategies report [25] that the last option can produce a delay measurement uncertainty of about 1.5 ps with a signal-to-noise ratio (SNR) of 24.

2.1.2. Improve the Frequency Reference Standard

The set of hydrogen maser frequency standards in use at existing antenna sites is satisfactory for the current level of accuracy of a few millimeters, but their performance does not appear to be good enough to support 1 mm accuracy, at least with the current observing densities. H-masers of 1970s vintage, many of which are still in use at the existing observing sites, typically have a stability of several parts in 1015 over 1 to 24 hours, while modern laboratory masers are capable of closer to about a few parts in 1016 over the same period [9]. Further investigation is needed to determine the tradeoffs between required frequency standard stability and increased observing density since there is a strong correlation. The frequency-standard issue is examined further in Section 3.

2.1.3. Improve Models and Procedures for Handling the Troposphere

The accuracy with which the troposphere model can be made to approximate the effect of the actual troposphere depends on the accuracy of the model itself and on the density in direction and time with which the troposphere is sampled. Recent developments indicate that sufficient accuracy in the troposphere model is likely to be obtainable by using a meteorological Numerical Weather Model (NWM) to provide either the parameters of an analytic mapping function ([14], [15], [3]) or a numerical relation among observations in different directions.

The troposphere remains one of the most challenging limitations for all space geodetic techniques. It is important to continue efforts to improve modeling and analysis strategies. In addition, information may be added by including a water vapor radiometer at the site, although the benefit has yet to be demonstrated. The impact of the atmosphere might also be reduced by including the desirability of a benign troposphere in the list of site selection criteria for new VLBI sites.

A shortcoming of considering the VLBI system in isolation is that the complementary nature of GNSS and VLBI observations is not explored. In particular, the neutral atmosphere affects the observables of both techniques the same way, and with collocated instruments there will be a very high correlation of the atmosphere delays. The estimation of a common atmosphere should be of great benefit.

2.2. Increase Observation Density

Another approach for reducing the impact of the random delay error is to increase the number of observations per unit time, i.e. the observation density. Simulations and results support this strategy. Increasing the observation density may benefit performance several ways:

- **Improve robustness of adjustments.** Variations in data analysis have a surprisingly large impact on final VLBI results. It is hypothesized that this fragility results from the fact that VLBI solutions are highly parameterized relative to the number of observations. Increasing the observation density will improve this situation.

- **Increase precision through averaging.** Provided that model complexity does not increase more rapidly than observation density, increasing the number of observations will increase the number of degrees of freedom in adjustments. To the extent that the unmodeled errors are independent, final results will become more precise.

- **Permit reduction of unmodeled effects.** As the number of observations increases, it is possible to improve the accuracy of the underlying geophysical and instrumental models. A balance must be maintained between the two competing tendencies of increasing parameterization in order to reduce unmodeled effects and limiting parameterization in order to increase robustness and improve precision.
- **Improve ability to estimate troposphere parameters.** Significantly increasing observation density will allow the troposphere to be sampled at many more values of azimuth and elevation during its characteristic time for variability. To the extent that errors due to unmodeled anisotropy of the atmosphere delay are independent, the added observations will improve final results through averaging.
- **Reduce correlation between the troposphere delays, clock errors, and the vertical component of the baseline.** The creative use of scheduling has been an effective approach for separating the effects of geometry, clocks, and the troposphere in VLBI parameter adjustments. To be effective, the density of observations must be, at the minimum, sufficient to sample the troposphere at several values of elevation and azimuth within the characteristic time for variability (typically approximately twenty minutes). For the current level of sensitivity of the observations, the density is twelve to fifteen observations per hour, which results in formal errors in height of approximately 3 mm. At this sampling density and with the scheduled source elevation distribution, it appears that correlation is greatly reduced between the vertical component and the time-dependent terms of the troposphere and clock, leaving mainly correlation between the vertical component and the constant terms.

2.3. Reduce Systematic Errors

In order to achieve 1 mm long-term accuracy it is necessary that the sum of all systematic errors be less than that. In some cases these systematic effects have a spectral characteristic similar to that of the reference oscillators and are removed as part of the clock terms. In this case the apparent clock performance is degraded. There are four broad areas of systematic error that afflict VLBI:

- instrumental errors (e.g. temperature and voltage dependent errors associated with analog components, polarization impurity, variability in the feeds, etc)
- mechanical errors (e.g. thermal and gravity distortion of the dish, mechanical play in bearings, geological instability, connection to the local geology, etc)
- loading errors (e.g. due to the atmosphere, hydrology, oceans, etc)
- radio-source structure errors

These effects are expected to become significant sources of error when the per-observation measurement error is reduced by a factor of approximately four, as proposed. Therefore either great care must be taken to reduce all known defects considerably, or they must be calibrated in a more complete way than has been accomplished for the existing systems. Obviously, a combination of these approaches would have the greatest effect. Also, the use of identical stations will be beneficial due to common calibrations and antenna models, as well as for cost and efficiency of maintenance.

In the case of instrumental errors, the use of digital signal processing beginning as early as possible in the signal chain will have a significant effect on mitigating the RF/IF/baseband errors.

The requirement placed on mechanical accuracy and stability of antenna structures is extremely stringent. Not only must the structure be stable to a small fraction of a millimeter under all observing conditions, it should maintain this accuracy for decades. Since it is somewhat unrealistic to expect such longevity, monumentation should be included from the beginning to allow connection of the reference point of the antenna to a stable reference marker on the ground.

In the case of source structure error, observing a larger number of sources on a regular basis will result in a more robust connection to the CRF. In particular, more complete time series of source positions will make source variability easier to evaluate, while the effect on geodetic results will be reduced through averaging over a larger ensemble. If this is not sufficient to render the effect negligible, a means of measuring and applying source structure corrections must be considered.

2.4. Increase the Number of VLBI Sites and Improve Their Geographic Distribution

The experience of the GNSS community has demonstrated the value of increasing the number of receiving sites and improving the geographic distribution. The present geodetic VLBI network has a very irregular distribution of antennas over the surface of the Earth; Africa, South America, and Asia are particularly under-represented compared to the other continents. Thus, important considerations for the planning of a new network are the number and locations of the sites needed to achieve the 1 mm goal.

Although the detailed choices for deployment of new stations will be driven by a combination of science, economics, and politics, two quantitative estimates can serve to bound the value for the number of sites.

- The goal of combining GNSS, VLBI, and SLR geodetic networks sets a guideline for the number of VLBI sites. The current uncertainty in GNSS daily horizontal measurements for a global network is approximately 3 to 5 mm and is unlikely to improve significantly. In contrast, the repeatability in regional GNSS networks of $\sim$1000 km is down to approximately 1 to 2 mm. For VLBI the horizontal repeatability of the VLBA antennas has been 1.5 to 3 mm over the past decade, while for the new VLBI system the horizontal accuracy is expected to be better than 1 mm. In order to take advantage of the best attributes of both GNSS and VLBI, the spacing of combined VLBI/GNSS sites should be on the order of 2000 km. Such spacing would require approximately forty sites (Eurasia (14), Africa (7), Australia (2), Antarctica (2), Greenland (1), North America (6), South America (6), Southern Pacific (2)).
- If the minimum goal is set to only three sites per continental land mass (Africa, Eurasia(2), North America, South America, Australia) plus one site in Greenland, one in Antarctica, and one in the southern Pacific, then a network of approximately twenty sites is needed.

Additionally, the minimum number of sites can be assessed from the history of geodetic VLBI measurements. The best results in terms of both site position and EOP uncertainties, confirmed by the repeatability of baseline lengths, are for the sessions that include the ten VLBA antennas and up to ten of the geodetic antennas. Similarly, increasing the number of antennas from eight to sixteen in recent sessions has shown a significant reduction in EOP uncertainty. Thus it would appear that the minimum network size should be at least twenty sites. In order to strengthen complementarity and ties among the space geodetic techniques, as many sites as practical should have collocated GNSS, VLBI, and SLR systems.

For the highest accuracy the global networks must be tied together. Automated systems must be developed to provide continuous measurement of the relative three-dimensional positions of the antennas and telescopes at each site and of their locations relative to the reference position for that complex. This monitoring, which should have an accuracy of better than one millimeter, will make it possible to account for factors such as thermal and mechanical deformation of the mounting structures, as well as local ground motion.

2.5. Reduce Susceptibility to External Interference

Recently, new sources of radio-frequency interference (RFI) have appeared, particularly at S-band. Due to hardware limitations, there is no option for replacing the impacted channels. Therefore, an important objective for a new system must be to provide options for mitigating the effects of RFI. Two options have been considered:

- To continue with the current model of correlating individual channels of data, the new system would offer continuous frequency coverage over a very wide range, for example from 1 GHz to 14 GHz, but the channels and frequencies actually used would be selected as those that are most free from RFI at all sites. This capability has become possible to consider only recently with the development of very wideband feeds and low noise amplifiers, pioneered by the Allen Telescope Array engineering [1].
- An alternative approach would be to record/transmit the entire available RF band, but with a low duty cycle, so that the average data rate yields sufficient SNR. Frequency ranges with RFI may then be excluded from correlation processing on an individual baseline basis, allowing considerable flexibility without having to know the details of RFI at each site. If designed properly, this approach can respond in real time (or after the fact) to changes in the RFI environment, making it more effective against dynamically changing conditions.

Both of these approaches may have implications for the maintenance of the CRF since the effect of varying source structure with frequency must be accommodated.

2.6. Develop New Observing Strategies

A detailed study of possible new and/or augmented observing strategies is contained in the sub-group report on observing strategies [25]. The most important points to be noted from this report are:

- The availability of a global array of small fast-moving antennas will allow many more observations per day than can be currently accomplished, by as much as a factor of 5 or more, resulting in over a thousand observations per day (i.e. on the order of 1 observation/minute).
- The continuing refinement of the precision of the data will lead naturally to improvement in the models underlying the geodetic analysis, which will in turn lead to a continuing evolutionary process in improving observing strategies.
- With low-cost observing systems, it may be possible to place two or more antennas at a site while sharing data recording and transmission resources. Using two antennas at a site

provides the opportunity to substantially increase the observing density by always observing with one antenna while the other is moving. This improved observation density also allows much faster and more diverse sampling of the atmosphere to help reduce systematic atmospheric effects. Alternatively, simultaneous observations of different sources with two or more antennas may reduce clock stability requirements, as well as correlations between atmosphere, clocks, and the local vertical component. Multiple antennas also provide a measure of redundancy in the event one fails.

2.7. Improve Data Analysis

Analysis of both existing data and data to be acquired in the future will benefit from two types of improvement: better models and better strategies. The modeling changes are mentioned in other parts of this report and fall into three general areas:

- geophysical (atmosphere, loading, hydrology)
- astronomical (radio source structure)
- mechanical (thermal and gravitational deformation of the antennas).

In addition, the analysis strategies should also be re-considered. Several proposals are given in the sub-group report on data analysis [30], of which the most important ones are to:

- improve robustness and reliability of VLBI solutions
- develop complete solutions with consistent TRF, EOP, and CRF
- generate rigorous intra-VLBI combinations of complete solutions
- investigate differences in analysis software packages
- obtain phase-delay solutions for all baseline lengths.

3. Recommendations for Next-Generation System

The implementation of the strategies and goals aimed at achieving 1 mm measurement accuracy, as discussed in Section 2, will require the development and deployment of a next-generation VLBI data-acquisition system, including antenna, and a major upgrade of many elements in the VLBI signal and analysis chain. The centerpiece of the new system is a small-antenna observing system, coupled with the use of global high-speed fibers where possible, plus upgrading and automation of tasks from acquisition to final analysis. The key characteristics of this new system are summarized in Table 2. In this section we will review each major VLBI subsystem and make recommendations in accordance with the goals stated in Section 1.

3.1. Design New Observing System Based on Small Antennas

The implementation of a relatively small antenna system to meet the stated goals is a significant departure from present practice of ~20 m diameter systems. Advances in engineering and production allow high-performance antennas in the 10–12 m class to be constructed for far lower cost than the traditional larger antennas. Coupled with advanced high-bandwidth receivers, feeds, and data systems, this new class of small antennas promises to considerably reduce costs,

Table 2. Key characteristics of next-generation VLBI system.

Antenna	~10–12 m dish, 60% efficiency, $> 5°$/sec slew
Feed	Dual polarization; low cross-polarization leakage
Front end	~1 GHz to ~14 GHz continuous RF coverage; T_{sys}~45K
Back end	Digitize signals as early as possible after receiver; channelize into several frequency segments selected from front-end bandwidth, totaling 4 to 8 GHz
Calibration system	Upgraded phase and cable calibration systems
Data rate	2–4 Gbps initially, expanding to 8–16 Gbps, potentially to 32 Gbps
Frequency standard	H-maser
Network design	20–40 antennas, globally distributed, co-located with other space-geodetic techniques, including sufficiently capable existing geodetic VLBI antennas
Data transport	Mixture of disk-based recording and high-speed network transfer
Correlation	Near real time, perhaps distributed among a network of processors
Products	Near real time automated generation of rapid response products, later complete analysis
Data archiving	Data may be retrieved from clearinghouse on any timescale

while at the same time providing better overall system performance. This new observing system can act as a standalone system for many TRF and EOP measurements, and will participate with existing larger antennas for maintenance and improvement of the CRF. The following discussion will examine each of the main elements of this new system.

3.1.1. Antenna Size and Performance

The sub-group report on observing strategies [25] shows that a minimum signal-to-noise ratio (SNR) of ~24 is sufficient to reach the goal of ~4 psec in the group-delay measurement. Figure 1 shows the antenna diameter required to reach this SNR level as a function of source correlated flux density and the number of bits collected during a scan.

Approximately 100 sources are currently used for standard geodetic observing. As discussed in [25], this number of sources is available if a minimum correlated flux density of ~0.5 Jy is chosen. According to Figure 1, an interferometer of 10 m diameter antennas will achieve the requisite SNR with a ~60 Gb observation (2 Gbps for 30 secs, for example). On the other hand, the minimum correlated flux density drops to a level of a few tenths of a Jy for the larger number of sources desired to maintain the CRF. In this case Figure 1 indicates that a 10 m antenna with a ~300 Gb scan, or a 12 m antenna with a 240 Gb scan, is necessary to achieve the desired minimum SNR at a correlated flux-density level of ~0.2 Jy. Of course, if larger antennas are used as part of the network, even weaker sources can be observed, though slower moving antennas can severely constrain the rate at which observations can be taken. In order that the network of new small-antenna stations can stand alone for EOP, TRF, and CRF observations, a 12 m diameter antenna appears to be the best choice for the new observing system, though a 10 m antenna could be considered.

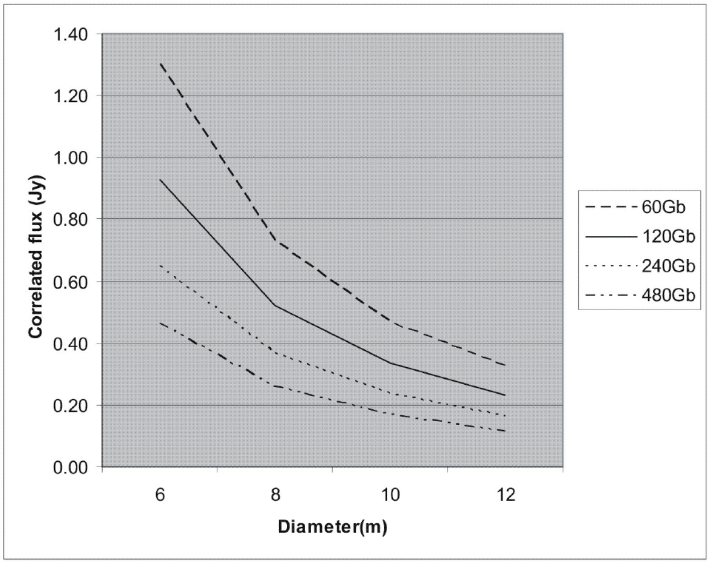

Figure 1. Antenna diameter required to reach an SNR of 24 as a function of correlated flux density for various per-antenna scan-data volumes (for example, 120 Gb is equivalent to a scan of 1 Gbps for 120 sec, 2 Gbps for 60 sec, etc); antennas in the VLBI network are assumed to be identical with T_{SYS}=45K, efficiency=60%.

Other important mechanical criteria must also be met in order to support the goal of 1 mm accuracy:

- **High slew rates.** In order to reach the goals of significantly increased observation density, the antennas need to support a slew speed of at least 5 deg/sec in both azimuth and elevation. This will allow the antenna to move between most points in the sky in less than ~30 seconds (only excluding near-360° azimuth slews that are sometimes required to manage cable wrap limits) and maintain a 50% observing duty cycle for 30-second observations that are typically the minimum scheduled length for individual geodetic observations.
- **Rugged and stiff mount.** Mount ruggedness and stiffness are of primary concern for the antenna. The reference point of the antenna should be stable to ~0.1 mm, including observing under windy conditions. The mechanical quality must guarantee long periods of trouble-free operation under rapid high duty-cycle observations; mechanical changes and repairs always run the risk of movement of the antenna reference point with respect to local geodetic markers, requiring re-calibration and re-alignment.

3.1.2. Radio Frequency Range, Feed and Receiver

Modern antenna, feed, and receiver systems have been built that span much broader frequency ranges than legacy VLBI systems. For example, the ATA antenna/feed/receiver system spans ~1–11 GHz [1]. For geodetic VLBI, a continuous spanned bandwidth from ~1 GHz to ~14 GHz appears to be a desirable target for several reasons:

- covers existing S and X bands for backwards compatibility

- allows group-delay determination over a much broader RF band than current practice
- provides options for choosing RF observing channels free of interference

As an additional benefit, if the lower bound of ∼1 GHz can be reached, Global Navigation Satellite System (GNSS) satellites can be observed by VLBI so that the GNSS-based reference frame can be directly related to the VLBI reference frame.

The most critical component in realizing this broad frequency range is the feed system, though this scale of frequency range has already been demonstrated by the ATA feed and receiver system (∼0.5–11 GHz) [1] and should be scaleable to our desired frequency range. Circular polarization is preferred; however, in order to achieve this broad continuous frequency range, it may be necessary that the feed be of a dual-linear polarization design. Dual-linear polarization could increase the correlation load if all cross-polarization products are formed, but dual linear or circular polarization will have the important benefit of virtually eliminating the potentially large systematic instrumental delay errors caused by cross-polarization leakage.

A low-noise receiver system to achieve an average T_{SYS} of ∼45K across the observing band is within the range of existing technology, a similar system already having been demonstrated by the ATA [1].

A dual-band X/Ka (Ka∼32 GHz) frequency system, analogous to the current S/X system, was considered as a possible alternative and is attractive because it would be compatible with frequency ranges being implemented in new NASA tracking systems. Furthermore, such coverage would extend the Celestial Reference Frame to the higher frequencies. However, the lower frequency range of ∼1–14 GHz has the advantages of less stringent antenna requirements, less expensive and more sensitive receivers, stronger source flux densities, less degradation due to atmospheric effects, and, most importantly, compatibility with the current S/X system. The combination of these factors tips the scales in favor of the lower frequency range, at least for the initial implementation.

3.1.3. Backend System

The received signal will be digitized by the backend system as early as possible in the signal chain, and all further processing of the signals will be entirely digital. In the present design concept, the ∼13 GHz bandwidth of the receiver output will be processed by a bank of perhaps 4 identical digital processors, each of which may flexibly select any 1–2 GHz bandwidth slice from each of the receivers (two receivers in the case of a dual-polarization system) and process the bandwidth slice for presentation to the data-recording/data-transfer system. In this way, 4 to 8 GHz of observed bandwidth (in each polarization) of the ∼13 GHz available from the receiver(s) can be acquired, allowing the maximum system data rate to eventually expand to as much as 32 to 64 Gbps as data recording and transmission systems become more capable (64 Gbps corresponds to 8 GHz of bandwidth observed in each of two polarizations and sampled at 2 bits/sample).

Dual-polarization observing will require a separate frontend and backend system for each polarization, though resources such as LO systems can be shared. However, observing in dual-polarization mode will not increase the total observing bit rate required to reach the desired signal-to-noise ratio.

3.1.4. Frequency Standard

Analysis of frequency-standard requirements to reach the goal of 1 mm accuracy indicates that, with a single antenna at each site and with current observing strategies, frequency-standard performance must reach a stability level of a few parts in 1016 for averaging times longer than about 1 hour (see Figure 2). This level of performance is not reached by H-masers currently deployed, which tend to have stability of at best a few parts in 1015 for averaging times of ∼1–24 hours. Although increasing the observation density and/or making other changes in observing strategy, as recommended in Section 2, may somewhat relax demands on H-maser stability, further study is needed to fully understand the possible tradeoffs and the impact on both accuracy and cost ([9], [10]).

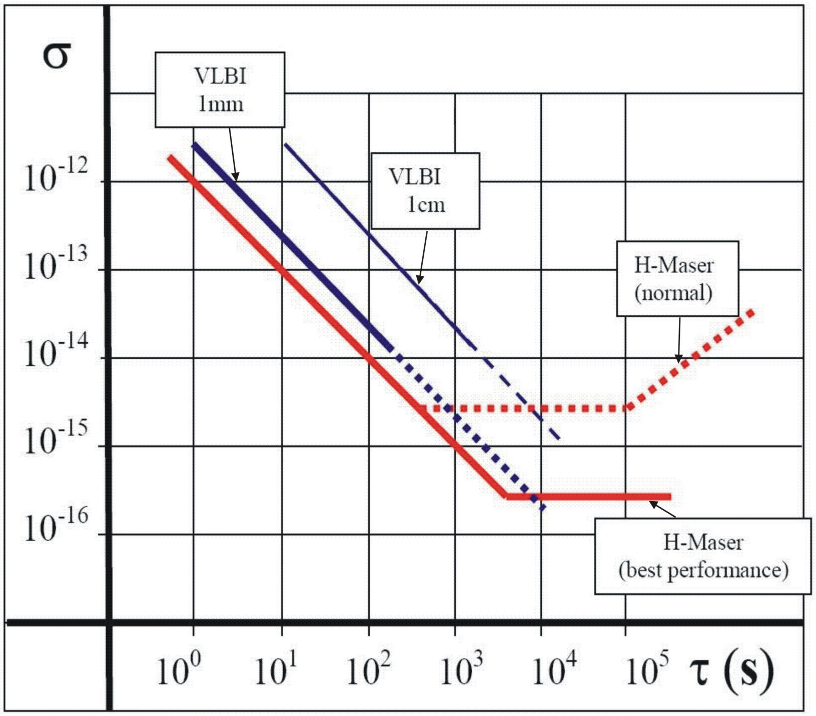

Figure 2. VLBI requirements versus H-maser stability.

Attention should also be paid to promising new experimental oscillator types and to a possible alternate approach whereby a 2-way satellite link may be used to frequency lock widely separated reference oscillators, though it is too early to determine whether any of these approaches will be sufficiently robust and/or cost effective for use in a global VLBI array.

3.1.5. Upgrade Existing Stations Where Possible

As indicated in Section 2, it is planned to integrate as many as possible of the existing antennas into the next-generation geodetic array, both for continuity of the TRF and for the enhancement and maintenance of the CRF. These stations will need to upgrade their systems as much possible to be compatible with RF and backend specifications discussed above, though full compatibility with the RF bandwidth may not be possible in some cases. The largest technical hurdle to full RF compatibility is likely to be the antenna feed, particularly in cases where the f/D ratio of the existing antennas is different than that of the new small-antenna systems. A detailed study of existing antennas will be required to determine the full extent of the compatibility that can be achieved in this regard. In any case, existing stations should update all other subsystems to meet the specification of the next-generation small-antenna system.

3.2. Transfer Data with Combination of High-Speed Networks and High-Data-Rate Disk Systems

The rapid advance of both magnetic-disk technology and global high-speed network technology will be utilized in the next-generation system. A more complete discussion of this subject and the impacts on observing is included in sub-group reports on data-acquisition and transport [28] and on observing strategies [25]. A few important points are summarized here:

- An array of antennas directly connected to the correlator via high-speed network provides the possibility for real-time or near-real-time processing to produce geodetic results in a matter of hours, which is particularly important to the rapid turnaround of EOP results.
- Modern magnetic-disk-based recording systems will allow economical recording at rates to several Gbps. With ever expanding disk capacities, stations will be able to operate unattended for periods of a day or more at a time, needing attention only for disk-module changes, and thus enabling continuous observations even for sites not connected via high-speed fiber.
- The existing global grid of research and education networks spans all the continents except Antarctica at minimum rates of 10 Gbps, and continues to rapidly improve in speed. This global grid may, with suitable agreements, be available for transmitting geodetic VLBI data.
- High-speed network connections to antenna sites must be implemented for at least a substantial subset of the sites. In many cases, sites are within a few km of a potential connection point, but some more remote sites are considerably more distant. Relatively inexpensive free-space optical links should be considered for some sites where fiber installation is otherwise too expensive or difficult.
- All data collection and transmission interfaces and formats should adhere to the set of internationally agreed VLBI Standard Interface (VSI) specifications [22].

3.3. Examine Opportunities for New Correlator Systems for Higher Data Rates

In the early stages of the operation of the next-generation system, when station data rates do not exceed ~2 Gbps, the existing set of correlators (with suitable software upgrades) will suffice. However, beyond these early stages it will be necessary to devise new correlator architectures to deal with the vast amount of data that will be collected at high rates. There are several options for such architectures [29]:

- a new large centralized correlator, perhaps modeled after the purpose-built EVLA WIDAR correlator. The WIDAR correlator is dedicated to the EVLA array and is capable of processing up to ~32 stations at bandwidths up to 8 GHz per polarization. One possible drawback of such a correlator is the extreme concentration of network bandwidth that would be required at the correlator to simultaneously bring high-rate real-time data from a large number of stations.

- a distributed correlator system based on commodity PCs, with perhaps special purpose internal hardware, to which data to be correlated are transmitted over the global high-speed network. Such a distributed system could be dedicated or might be shared with other non-VLBI users. One advantage of such a distributed system is the spreading of the communications load over a large geographic area. A correlation strategy which time-slices the data and sends each time slice to a different node (processing all baselines of that time slice) minimizes the required communications resources. Such a system will be more robust against failure than the centralized correlator if the distribution can be dynamically re-allocated.

Further study needs to be undertaken to determine the most cost-effective strategy to be adopted, and the choice may depend critically on the required timeline for development. If dual linear polarization operation proves necessary, the correlation processing load will be approximately doubled. This may impact the choice of correlator architecture.

A standardized correlator certification process should be developed that can be applied equally to all correlators to ensure that the processed results are of the highest quality, regardless of the correlation site or system.

3.4. Improve Data Analysis

While the development and deployment of a next-generation VLBI antenna and data-acquisition system is a discrete process, upgrading the software used for data analysis should proceed continually. It is clear that the goal of 1 mm measurement accuracy on global baselines requires significant improvements in existing VLBI software, particularly in the refinement of models. Known improvements should be in place and verified before the deployment of the next-generation geodetic VLBI system. With respect to the data analysis the main targets seen at this time are:

3.4.1. Troposphere

Several areas regarding tropospheric effects on VLBI results need further investigation:

- **New mapping functions:** In recent years mapping functions such as the Isobaric Mapping Functions (IMF) [14] and the Vienna Mapping Functions (VMF) [2] have been developed to make use of information on the state of the atmosphere contained in numerical weather models (NWM). The potential of NWMs with high temporal and spatial resolution and prediction capacity for the determination of mapping functions has been shown ([14], [15], [3], [20]). Additional work is needed to fully integrate NWMs into data analysis software.

- **Gradient models:** In addition to their application for the generation of a priori hydrostatic gradients, as calculated within IMF, numerical weather models should be used to investigate the azimuthal and zenithal deviations from the standard gradient models (e.g., [5], [4]).

- **Turbulence models:** The application of spatial and temporal turbulence models to describe the inhomogenous atmosphere, rather than using conventional gradient models, should be studied.

3.4.2. Loading Effects

Refinement of mass-loading models is necessary to reach the global 1 mm accuracy goal. The IERS Special Bureau for loading now provides atmospheric loading corrections on a global scale. Recent global ocean tide loading models explain more of the observed site displacement at tidal frequencies than the earlier models, though it would be desirable to also develop local ocean models for regions near some VLBI stations. Mass loading models for hydrological variables, including snow, surface liquid water and groundwater, need significant improvement. (See IERS Special Bureau for Loading description [21].)

3.4.3. Antenna Deformation

Thermal deformation of the antenna structure can be improved through direct measurement and through modeling of the structure using material expansion coefficients and measured temperatures ([16], [8], [11]); both horizontal and vertical deformations must be considered. A reference temperature must be established, preferably by agreement with other space geodetic techniques. In addition to thermal deformations, gravitational deformations of the telescope structures and their effect on the group-delay observables must be carefully considered and measured or modeled as necessary.

3.4.4. Source Structure Effects

Most of the sources observed by geodetic VLBI exhibit the standard core-jet morphology to some degree. Fey and Charlot [6] have developed a source-structure index that increases with the level of source-structure complexity, providing a simple but powerful tool for choosing low-structure sources for geodetic/astrometric observations. Nevertheless, a certain fraction of sources, particularly in the source-dense CRF observations, show significant structure. It is important to determine whether sufficiently accurate brightness temperature maps can be made of these complex sources so that corrections to the group-delay observables can be computed and applied.

3.4.5. Data Analysis Strategies

In addition to improving the models for the effects discussed above, new analysis strategies must be developed, tested, and applied.

- **Robust and reliable VLBI solutions:** In recent years, refined modeling of the many auxiliary parameters has led to an increase in the number of parameters estimated, with constraints introduced to a much greater degree. This procedure has resulted in a loss of robustness of the solution, with the consequence that the numerical results vary rather strongly depending on individual delay observables excluded from or included in the adjustment process. Robustness and reliability of VLBI solutions are key elements of the quality of VLBI results. Therefore, improved analysis strategies, together with observation scheduling, require development to reduce the influence of single observations on the results.
- **Consistency of TRF, EOP, and CRF:** An important goal for 2010 is the generation of consistent VLBI multi-purpose solutions for TRF, EOP, and CRF (VLBI complete solutions). For this, investigations must be started on the propagation of systematic effects between reference frames in VLBI complete solutions. The consistency of the VLBI products is

of particular importance with respect to their contribution to the IERS and to the new IAG project GGOS. Since the main goal of GGOS is the integration of all space geodetic techniques, regular precise surveys of the local ties at stations with more than one technique are required.

- **Intra-VLBI combinations of complete solutions:** The generation of VLBI complete solutions will offer unique opportunities for combinations of analyses by different analysis centers which are rigorous to the utmost extent. These combined solutions can be used for the combination on the next level, i.e. between the various space techniques, by the IERS and/or within GGOS.
- **Investigations of differences in analysis software packages:** Comparisons among software packages have been rather sparse in recent years. In order to understand differences and to improve the overall quality of the results, it is of great importance that intercomparisons at regular intervals become a general task of the Analysis Centers.
- **Phase solutions for all baseline lengths:** Investigations have shown that phase-delay observables can be used under very special conditions. To date, phase-delay solutions have been successful only if stations are employed which provide very stable hardware in terms of inherent phase variations. As soon as more stations update their hardware with phase-stable components, phase-delay solutions will become more practical and may be realized on a routine basis.

3.5. Automate Operations and Procedures at All Stages

Automation at all levels of operations will be required for the smooth operation of the next-generation system. This subject is discussed in more detail across several sub-group reports; here we will emphasize a few particular areas where automation is critical:

Observing

- Automated observation scheduling tailored to the purpose of each observing session (EOP, TRF, CRF, etc), taking into account the array of available stations
- Flexibility to add/subtract stations on short notice in case of unexpected failures or unavailability
- Flexibility to change observing frequencies to avoid RFI
- Logistical management of disk modules and/or automated e-VLBI data transfers
- Automated diagnostic procedures and notification of personnel when necessary

Data transfer

- Automated scheduling for shipping and management of disk modules
- Automated scheduling, as necessary, for high-speed network resources for data transfer

Correlation

- Assignment and scheduling of correlator resources
- Review of correlation results and flagging of problems

- Network transfer of correlation results to analysis center

Geodetic analysis

- Fully pipelined analysis system, including
  - Filtering and flagging of data for obvious problems
  - Creation of databases
  - Analysis for geodetic products
  - Distribution of products to final consumers
  - Maintenance of product archive

The development of these automated systems and procedures is particularly important for the timely production of EOP results, but will also significantly add to the robustness and productiveness of the system and lead to higher quality geodetic products.

4. Next Steps

In order to develop, deploy, and bring to operation the system described in Section 3, several studies and development efforts must be completed. The work can be grouped into two categories.

- **System studies and simulations** are needed to clarify issues, verify calculations, or refine estimates. Six such studies are described below. These studies, concentrated in the areas of observing strategies, network deployment, and transition planning, can be started now, and most can proceed in parallel.
- **Development projects and prototyping** are needed in the areas of the small antenna system, the correlator, backend, and data management and analysis. Some decisions about the antenna system depend on the results of the system studies and simulations. Seven such projects are described.

In this section we will address each of these efforts, with the objective of realizing a fully deployed system that meets the three major goals of 1 mm accuracy, continuous operation, and rapid results.

4.1. System Studies and Simulations

As indicated in the previous sections, several studies need to undertaken that will impact how some parts of the system are to be built and how the system is to be deployed and used. Some of these studies must take place during the early stages in the development of the new system, before any work can begin on antenna development. Others may proceed in parallel. This section describes the major studies that were suggested by the discussion of Section 3.

4.1.1. Error Budget

A complete and detailed system error budget needs to be developed. Major issues to be considered in the error budget include:

- the interaction of observation density, atmosphere estimation, and reference frequency and timing characteristics

- instrumental error effects including, for example, polarization impurity, cable and phase calibrations
- the effects of source structure on the delay observable

4.1.2. Observing Frequencies

Though the current analysis favors an RF band extending from 1 or 2 GHz to approximately 14 GHz, the dual-band system X/Ka (~8–9 GHz and ~32–36 GHz) should be further examined as a possibility. The tradeoffs between these choices must be carefully evaluated. The TRF requirements, including continuity, are likely to be satisfied both technically and economically with observations at frequencies below 15 GHz. The primary drivers to inclusion of the higher frequency band are compatibility with operations of the DSN and enhancement and maintenance of the CRF.

4.1.3. The Number and Distribution of Sites for Deployment

Studies need to be made of detailed site-placement options so as to improve the distribution of stations. Tradeoffs, such as between geographical location and infrastructure support, need to be enumerated and evaluated, and site requirements must be developed.

4.1.4. Number of Antennas per Site

Two or more antennas per site will enhance the observation density as well as allow better determination of systematic effects. The ability to define, measure, and maintain a reference point for multiple antennas at a site must be studied, as well as the tradeoff between the advantages of multiple antennas and cost.

4.1.5. New Observing Strategies

Faster antennas, and perhaps multiple antennas at a site, will require the development of new observing strategies, including optimal use of existing large antennas in conjunction with the new antennas.

4.1.6. Transition Plan and Upgrade Path

A carefully constructed and executed plan for the transition to the proposed new system is critical for maintaining continuity of the historical record of geodetic VLBI results while reaping the benefits of the new technology. A good transition plan must include a deployment schedule, plan for mixed operations and a schedule for upgrading the existing antennas.

4.2. Development Projects and Prototyping

The data-acquisition system requires the development of several new hardware components (antenna, feed, receiver, backend), as well as the augmentation of existing sub-systems (data recording/transmission, frequency standard (H-maser) and timing system, monument measurement). The final decision about an antenna system for prototype deployment will depend on results of the system studies described in Section 4.1.

4.2.1. Antenna and Mount

The designs of antennas for arrays such as the Allen Telescope Array and the NASA Deep Space Network Array give us some insight into the capabilities and costs of a small-antenna system. A preliminary report [17] describes possible development of a prototype system based on either of these designs. However, in parallel with the detailed system studies that will provide guidelines on the size of antenna needed, additional work must be done to complete the evaluation of those designs. Critical design areas are mechanical stiffness and thermal stability, durability of the mount and drive train under the continuous and demanding observing program, and the method of tying the reference point to the local reference monuments.

4.2.2. Feed and Receiver

To achieve very broadband frequency response in a reflector antenna requires ingenuity in feed design. Examples are the ATA feed/LNA construction and the low profile feeds under development at Chalmers University for the SKA. Studies are needed to determine whether these designs can be brought into alignment with our requirements. Instrumental calibration, including phase and delay calibration systems, must be integrated into the front-end design.

Detailed design studies of the small-antenna system must be completed before it will be possible to accurately estimate the costs for prototype development. This is a necessary study prior to commitment of funds.

4.2.3. Frequency and Timing Improvements

As described in Section 3, the suitability of the performance of existing hydrogen masers, and the propagation of that stability through the system, must be evaluated. If improvement is required, based on the error budget studies, an improved maser or alternative frequency standard must be found, or the delay calibration must be improved, or both. The frequency stability at all stations must be brought to the necessary level of performance.

4.2.4. Higher Data Rate System

Continued technological advances are inevitable and will permit further improvement in sensitivity and accuracy. This will involve increases in data rate, through enhancement of the recording and transmission capability and through development of new correlator architectures. Some of these projects have begun already and should be considered as part of this plan.

A higher performance, larger capacity, disk-based recording system, based on commercially available technology, should be developed in collaboration with industry. The capacity of disk storage continues to increase while the cost of disk storage per GB continues to drop, as shown in Figure 3, so that expansion of VLBI recording capability over time becomes increasingly economical. A clear path to the next generation correlator design must be compatible with the higher data rates.

4.2.5. Correlator

Though the early stages of development and testing of the new system can utilize existing correlators, a new correlator system must be developed for data rates above 2 Gbps/station. A

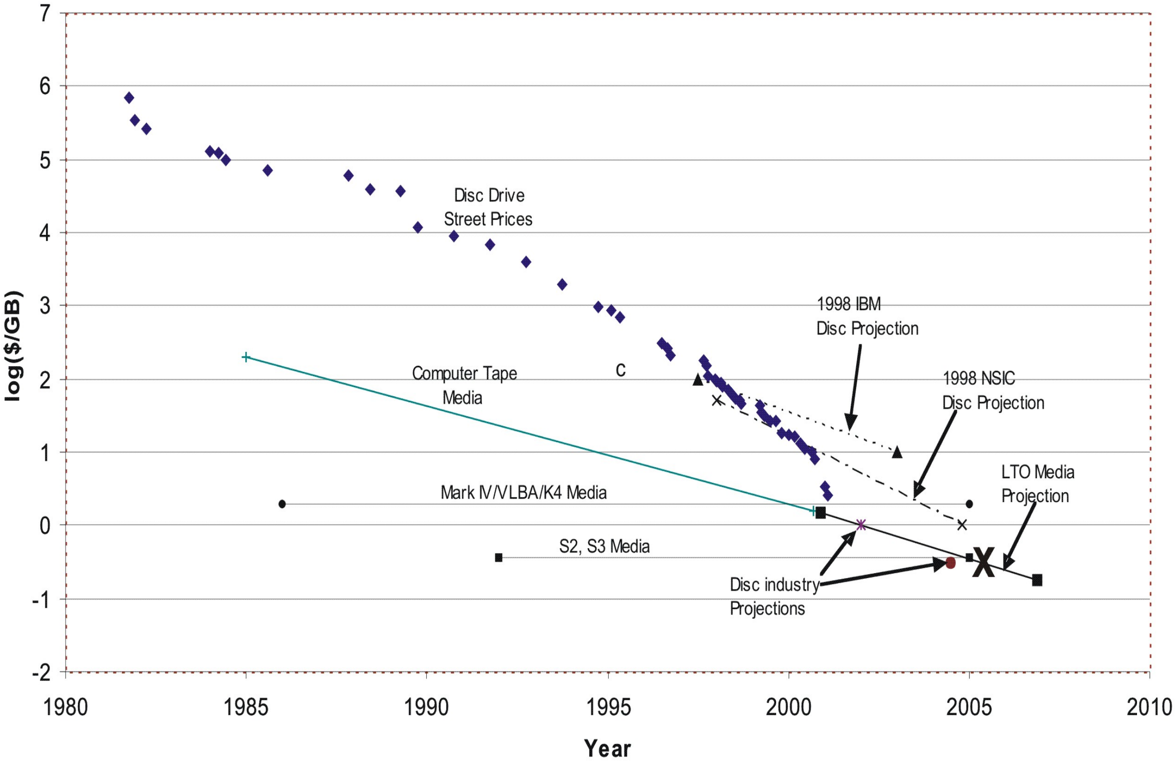

Figure 3. Disk storage price as a function of time. Large 'X' marks approximate price at mid-2005.

small prototype multi-PC correlation system has already been built in Japan [12] and could form the basis for a new large correlator system for high data rates. A distributed multi-PC system is particularly attractive for real-time observations since it avoids the network congestion issues inherent with a centralized correlator. Another possibility is a clone or near-clone of the large centralized correlator system developed for the eVLA project, which would be capable of handling the data from the proposed new geodetic VLBI system.

4.2.6. Backend

It is anticipated that the entire broadband analog output of the receiver will be transmitted via optical fiber to a remotely located backend system. Figure 4 shows a simplified block diagram of a proposed RF-to-baseband converter module currently under development. A 1 GHz slice of the RF input is selected and converted to baseband using a standard digital polyphase filter bank to generate a 4 Gbps data stream. Up to eight such modules, each selecting a different 1 GHz slice of the RF input, can be used, thus providing a sampling of 8 GHz of bandwidth. For lower portions of the RF frequency band, direct digital sampling in higher Nyquist zones may be possible, eliminating the need for analog up/down conversion before A/D conversion, thus simplifying the backend system. An alternative architecture would place individually controlled digital down-converters at desired frequencies within the IF band.

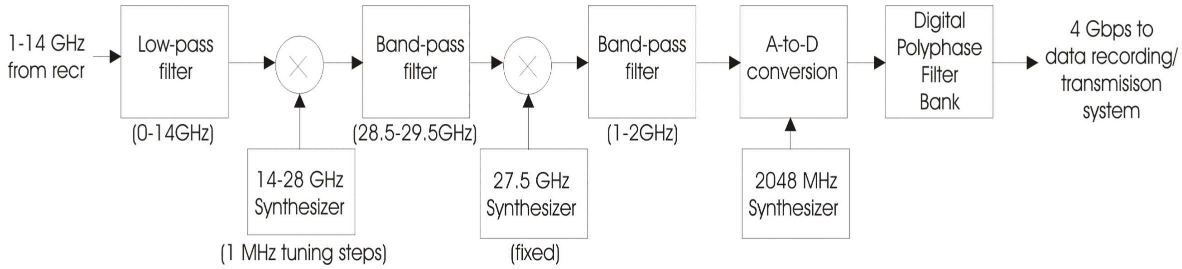

Figure 4. Simplified RF-to-baseband module block diagram.

4.2.7. Automated Data Management and Analysis Software

Automated software procedures in the entire data chain from scheduling through final analysis are required to meet the goals of the next-generation system. In addition, enhanced software is needed in some areas, such as advanced scheduling algorithms to implement new observing strategies. Such software will also be invaluable for studying and evaluating other important aspects of the system, such as the option to place multiple antennas per site. In any case, automated software procedures will also benefit current observing, and development of these tools should proceed concurrently with the existing program.

5. Summary

WG3 was formed to develop a vision for the future of geodetic VLBI. At the time, the IVS had reached a level of maturity where it was recognized that a long-term plan for the future is required to focus the activities of the organization. Three separate converging elements added urgency to this realization. First, the science case for geodesy implies that 1 mm long-term accuracy is required of VLBI measurements. This rather daunting increase in accuracy will require significant changes to the way VLBI is done, including significant improvements in models and strategies for analysis. Second, it was readily apparent that much of the hardware in use today is, for the most part, badly outdated or at least rapidly aging; furthermore, the cost of current manpower-intensive operations cannot be sustained even for existing goals such as continuous monitoring of EOP. Third, technological advances in the manufacture of antennas, digital electronics, and data storage and transmission have opened the door to cost effective solutions to these challenges. These advances, which have emerged only over the past few years, have provided both opportunities and incentive for large-scale renewal of the global geodetic VLBI system, including operations, analysis, and product generation.

Based on science and operational drivers, three performance goals have been identified:

- Accuracies of 1 mm for site position and 1 mm/year for velocity (TRF)
- Continuous measurements for EOP
- Rapid generation and distribution of the IVS products

Achieving the latter two of these goals appears comparatively straightforward. A widespread introduction of automation and continued development of e-VLBI will be the key factors required to make it happen. Although significant effort and some uncertainty are still involved, the path forward is reasonably well understood. In contrast, it is recognized that achieving the 1 mm accuracy target is unprecedented and that the path forward will require greater consideration. At the same time, the importance of achieving this target is emphasized by the realization that, although achieving this accuracy will require the integration of the complementary capabilities of all three of the space geodetic techniques, it cannot be accomplished without VLBI.

A number of strategies are proposed to improve the long-term accuracy of VLBI with an eye to achieving the 1 mm long-term accuracy target:

- Reduce the random component of the delay observable error, i.e., the per-observation measurement error, the stochastic properties of the clocks, and the unmodeled variation in the atmosphere
- Increase observation density, i.e. the number of observations per unit time
- Reduce systematic errors
- Increase the number of sites and improve their geographic distribution
- Reduce susceptibility to external radio frequency interference
- Develop new observing strategies
- Improve data analysis by refining models and revising analysis strategies

Based on the specified performance goals and the strategies listed above, four broad recommendations are made:

- Design a new observing system based on small antennas
- Transfer data with a combination of high-speed networks and high-data-rate disk systems
- Examine the opportunities for new correlator systems for higher data rates
- Automate operations and procedures at all stages

In the process of preparing this report much has been learned about the opportunities and needs for future development of geodetic VLBI, but it has become apparent that specific recommendations are often difficult to identify. Out of this effort thirteen areas have emerged that require further study, proof of concept demonstrations, or prototype development. These topics are critical for filling in the details of a coherent and rational plan for the future.

Realizing the goals of the WG3 study will produce an instrument that will provide an outstanding data record into the future for a better understanding of planet Earth. However, it is also clear that the path requires significant resources and effort. In order to be successful, it is essential that the IVS make a concerted and unified commitment to this process, and that concrete actions be taken to move forward based on the recommendations of WG3. Of immediate importance is the list of thirteen areas for further study and development described in Section 4. Most of the studies can be begun today, can be done in parallel, and, as an added benefit, will lead to improved understanding of the current system.

It is important that the IVS make a strong recommendation that some of the resources dedicated today to routine product generation and technology development be directed to address the studies and projects recommended in this report. These studies must move forward so that a detailed plan can be generated, including defensible costs and schedules. Building on the efforts of WG3, the results of these studies and projects will provide the final element required for IVS members to move forward with requests for augmented funding to implement the new vision. We believe that this vision will renew the interest of current funding resources and inspire new interest from universities, industry, and government based on the exciting possibilities for a more accurate and data-rich geodetic VLBI system.

6. Acknowledgment

The authors of this report are greatly indebted to the large group of people who contributed actively to the WG3 sub-groups and who have made suggestions and comments that have greatly enhanced the contents of this report. We also appreciate the constructive comments of Jan Kouba and Gerhard Beutler.

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