

# **International VLBI Service for Geodesy and Astrometry (IVS)**

## **— Status Report 2003-2005 —**

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### **Abstract**

This report reviews the activities and the progress made in the time span from 2003 to 2005. It summarizes and qualifies the products generated continuously by IVS. The efforts for improving the TRF, CRF, and EOP are shortly described. Special emphasis is put on the future vision for a next generation VLBI system.

### **1. General remarks and the key role of geodetic VLBI**

The Very Long Baseline Interferometry (VLBI) technique has been employed in geodesy for nearly 40 years. Covering intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art and providing the quasar positions as the best approach to an inertial reference frame, VLBI significantly contributed to the tremendous progress made in geodesy over the last decades. VLBI was a primary tool for understanding the global phenomena changing the “solid” Earth. Today VLBI routinely monitors Earth rotation and its variations and also crustal movements in order to maintain global reference frames, coordinated within the International VLBI Service for Geodesy and Astrometry (IVS) – a Service of the IAG and IAU. Science and applications set the requirements for the realization and maintenance of global reference frames at VLBI’s technical limitations. VLBI, as the unique technique for providing a celestial reference frame and for deriving the full set of Earth rotation parameters, plays the fundamental role of generating the basis for many applications and research in the geosciences.

VLBI today is the key technique for monitoring and realizing global reference frames. The importance of global reference frames has increased as space and satellite technologies, e.g. satellite navigation systems, are employed for many applications in research, in particular in geosciences and in all kinds of surveying and navigation. For the description of satellite orbits a “quasi” inertial system is required, which does not rotate with the Earth – a celestial reference frame (CRF). Such a system is realized by positions of radio sources and is internationally available as the International Celestial Reference Frame (ICRF). Point positioning on the surface of the earth needs an Earth fixed system – a terrestrial system (TRF). The terrestrial reference frame is realized through stations for which the positions and velocities are determined and known. The most recent realization (the adopted international realization) is the ITRF2000. Both TRF and CRF systems are needed and the relation between both must be known to the highest accuracy possible, in order to meet the broad spectrum of applications. The relation between the CRF and TRF is described by the Earth Orientation Parameters, which fix the Earth rotation axis with respect to the CRF ( $d\epsilon$ ,  $d\phi$ ) and by the polar motion parameters  $x_p$  and  $y_p$  which fix the Earth’s crust. The rotation is described by the parameter DUT1 as the difference between the time scale provided by the Earth rotation itself (Universal Time, UT1) and the time

scale generated by atomic clocks (Universal Time Coordinated, UTC).

As all the parameters are changing with time and no model is precise enough for prediction, the parameters have to be derived continuously from observations. Among the geodetic space techniques (Satellite/Lunar Laser Ranging and GPS etc.), VLBI plays a unique role, as it is the only technique which is capable of realizing and maintaining the CRF, of providing the complete set of Earth orientation parameters and in particular of observing DUT1. Due to superior accuracy in the determination of long baselines VLBI dominates in the determination of the ITRF scale. Because sub-daily variations in Earth rotation occur, it is important to observe regularly with adequate resolution in time and accuracy. Regular and more dense observations will become a demand with the request for mm-precise reference frames, consistent for decades, that is set by the IAG within its project Global Geodetic Observing System (GGOS).

## **2. International VLBI Service for Geodesy and Astrometry**

The International VLBI Service for Geodesy and Astrometry (IVS) is a Service of the International Association of Geodesy (IAG) and of the International Astronomical Union (IAU) and a member of the Council of Astronomical and Geophysical Data Analysis Services (CAGS). The charter and the basis for international collaboration is given by the Terms of Reference (ToR) accepted by IAG and IAU and by the proposals provided by individual agencies in response to the call for participation.

IVS is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components. The goals are

- to provide a service to support geodetic, geophysical and astrometric research and operational activities;
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique;
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

As IVS has no funds of its own, but is tasked by IAG and IAU for the provision of timely, highly accurate products (Earth Orientation Parameters (EOPs), Terrestrial Reference Frame (TRF), Celestial Reference Frame (CRF), etc.), IVS is dependent on the support of individual agencies. Figure 1 shows the global distribution of the IVS components.

In order to maintain the strong requirement for consistency, which is the basis for realizing and maintaining global reference frames such as the CRF and TRF, IVS coordinates the VLBI infrastructure from the network stations to the analysis centers. Currently the IVS consists of

- 30 Network Stations, acquiring VLBI data;
- 3 Operations Centers, coordinating the activities of a network of Network Stations;
- 6 Correlators, processing the acquired data;
- 6 Data Centers, distributing the products to users, providing storage, and archiving functions;
- 21 Analysis Centers, analyzing the data, processing the results and products;
- 7 Technology Development Centers, developing new VLBI technology;
- 1 Coordinating Center, coordinating the daily and long term activities.

In total, there are 74 Permanent Components, representing 37 institutions in 17 countries with ~250 Associate Members.

Activities of the past two years are documented in the Annual Reports of the IVS for the years 2003 and 2004 [Vandenberg and Baver, 2004; Behrend and Baver, 2005]. The third General Meeting was held in Ottawa, Canada in February 2004 and several technical meetings concerning analysis and technology aspects

were conducted. Proceedings of the General Meeting are available [Vandenberg and Baver, 2004].

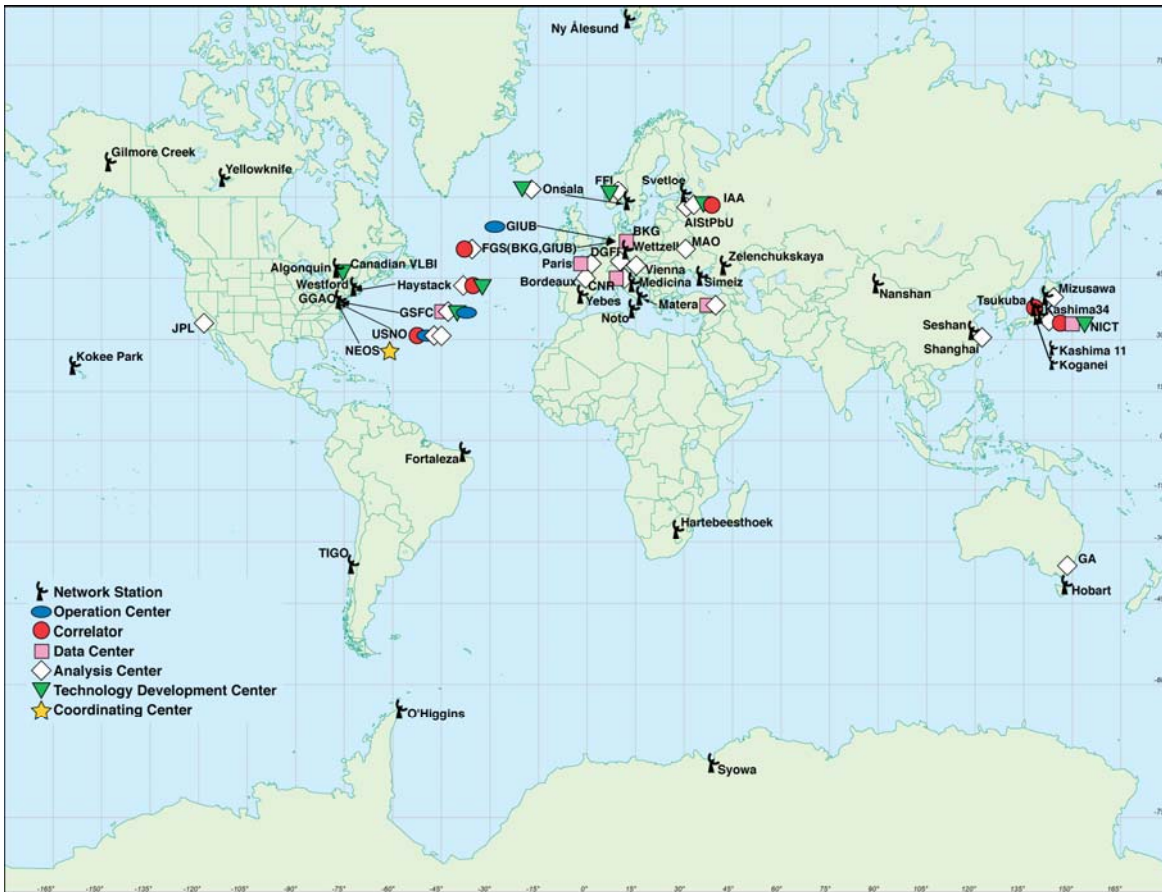


Figure 1: IVS components and their global distribution

### 3. IVS Products and Goals

In 2001 the IVS Working Group 2 (WG2) reviewed the IVS products and the corresponding observing programs in terms of meeting the service requirements. The WG2 report [Schuh et al., 2002] proposed a development of the products and the observing programs up to the year 2005. Even if, due to the limited resources, the proposed goals cannot be achieved in the expected period, the general view remains valid for years to come. The IVS products are summarized in Table 1. The demands on a next generation VLBI system need to be based on the requirements imposed on the products IVS has to provide. With respect to accuracy and latency, IAG's project GGOS will drive the future demands. The categories summarized in Table 1 have different requirements and conditions in terms of operation and timeliness. Some of the products, such as the EOP or TRF (partly), have to be provided operationally and in near-real time. Other products, in particular scientific products for CRF and TRF (partly), necessitate individual studies. Here the accuracy is of primary interest, whereas timeliness is not. The various requirements will be reflected in the specifications for the IVS components and in the demands for the observing programs and the data handling. Combinations of VLBI, GNSS (Global Navigation Satellite Systems), and SLR products will significantly improve the overall accuracy of all products. Systematic errors will be detected if time series of comparable precision are made available by all techniques. For the combination of all techniques to be useful, a reasonably timely delivery of products will be required. By making use of the technical potential of the Internet, timely solutions will become more economical.

Table 1: IVS products and goals for the coming years in terms of accuracy, frequency of solutions, resolution

and timeliness

Category	Products	Accuracy	Frequency of solutions	Resolution	Timeliness
<b>CRF</b>	$\alpha, \delta$	0.25 mas for as many sources	yearly		1 month
	$\alpha, \delta$ time series	0.5 mas	monthly	1 month	1 month
	source structure		monthly	1 month	3 months
	flux density		7 days/week	1 hour	near real time
<b>TRF</b>	x,y,z time series (1 solution/session)	2...5 mm	7 days/week	1 day	1 day
	episodic events	2...5 mm	7 days/week	< 1 day	near real time
	annual solution coordinates velocities	1...2 mm 0.1...0.3 mm/y	yearly	-	1 month
<b>EOP</b>	DUT1	5 $\mu$ s	7 days/week continuous	10 min	near real time
	D $\phi$ , d $\epsilon$	25...50 $\mu$ as	7 days/week	1 day	near real time
	x <sub>p</sub> , y <sub>p</sub>	25...50 $\mu$ as	7 days/week	10 min	near real time
	dx <sub>p</sub> /dt, y <sub>p</sub> /dt	8...10 $\mu$ as/day	7 days/week	10 min	-
<b>Geodynamic parameters</b>	solid Earth tides h,l	0.1%	1 year	1 year	1 month
	ocean loading A, $\phi$	1%	1 year	1 year	1 month
	Atmosphere loading	10%	1 year	1 year	1 month
<b>Physical parameters</b>	tropospheric parameters				near real time
	zenith delay	1...2 mm	7 days/week	10 min	
	gradients	0.3...0.5 mm	7 days/week	2 hours	
	ionospheric mapping	0.5 TEC units	7 days/week	1 hour	near real time
	light deflection parameter	0.1%	1 year	all sessions used	1 month

The observing program for 2003–2005 included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 7 stations, some with 6 or 8 stations depending on station availability. These networks were designed with the goal of having comparable x<sub>p</sub> and y<sub>p</sub> results. Data bases are available no later than 15 days after each session. Daily 1-hour UT1 Intensive measurements on five days (Monday through Friday) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA) and on weekend days (Saturday and Sunday) on the baseline Wettzell (Germany) to Tsukuba (Japan). The daily sessions are recorded using Mark 5 (Wettzell-Kokee) and K5 (Wettzell-Tsukuba) technology. Comparisons of the two series showed good agreement with the IERS C04 series.
- TRF: Monthly (2003, 2004) and bi-monthly (2005) TRF sessions with 16 stations using all stations at least two times per year. The increase from 8 stations in the observing years 2002/2003 to 16 stations in 2004/2005 is largely due to the deployment of the Mark 5 technology, which sped up the correlator processing time significantly. The limiting factor has shifted from correlator to station availability.
- CRF: Bi-monthly RDV sessions using the Very Long Baseline Array (VLBA) and 10 geodetic stations, plus astrometric sessions to observe mostly southern sky sources where the sessions were increased from 8 in 2003, over 10 in 2004, to 16 in 2005.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Bi-annual, or annual if resources are available, 14-day continuous sessions to demonstrate the best

results that VLBI can offer, aiming for the highest sustained accuracy.

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. Sessions in the observing program that are recorded and correlated using S2 or K5 technology will have the same accuracy and timeliness goals as those using Mark 5. On average, a total of more than 1000 station days per year were used in about 180 geodetic sessions during the year increasing the average days per week which are covered by VLBI network sessions to 3.5.

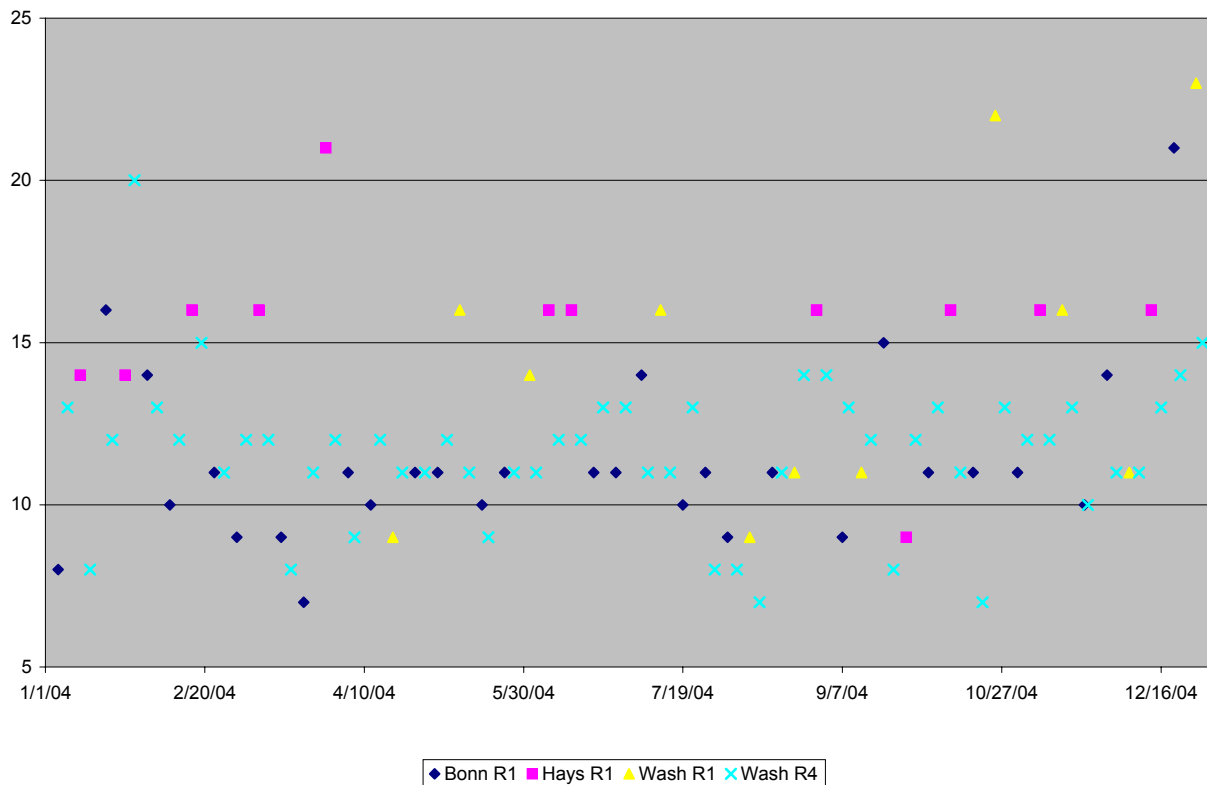


Figure 2: Delay (in days) between the observation and the availability of the results of the rapid turnaround sessions IVS R1 and IVS R4 as performed in the observation year 2004

The objective of the rapid turnaround observation sessions is to minimize the delay between the observations and the availability of the results. As shown in Figure 2 the delay from the observation to the results is better than two weeks (12 days average) for the chosen observation year 2004. The current observation year (2005) has followed through with the same performance. Though the WG2 goal of only 4 days has not been achieved, a clear improvement was made as compared to the year 2002 where the average was 15 days. In addition, now several sessions have single digit time delay values, which was not the case two years earlier. The limiting factor is still the data transmission that is mostly done via physically shipping the digital recording disks from the stations to the correlator. A significant improvement will occur when the e-VLBI capability of the Mark 5 digital recording system can be fully exploited. Currently, only very few stations have high speed Internet connections for fast data transmission.

Many hardware components for VLBI (such as radio telescopes) supporting IVS were constructed three to four decades ago; some are badly worn and inefficient in operation and in urgent need of an upgrade or replacement. The increase of radio interference, particularly at S-band (2.0-2.4 GHz), caused by modern wireless technology (cell phones and satellite radio, among others) severely degrades the quality of many current observations and will force a move to higher frequencies. Additionally, the increasing demand for higher-quality global reference frames requires better global coverage. All these factors led the IVS to

establish a Working Group, WG3, at the 10<sup>th</sup> Directing Board Meeting in September 2003 with the objective to develop future visions.

Work has begun that should ultimately lead to a redetermination of the ICRF. In February 2004 the IVS began a program to systematically monitor 307 sources. These include the non geodetic ICRF defining sources as well as astrometric sources identified by Martine Feissel-Vernier as stable or potentially stable based on analysis of position time series. The goal of this monitoring program is to observe each source at least twice a year using a small part of the time of the geodetic networks. A database was developed to track when these sources are observed and the number of successful observations. The procedure for including these sources in schedules is largely automatic. At present only the R1 and RDV sessions are used, but it is anticipated that other geodetic observing programs will be included in the future.

In terms of increasing the number of observations of poorly observed sources, the monitoring program has been a success. Prior to the start of the program approximately 160 sources had not been successfully observed in the preceding twelve months. Now all sources have been observed successfully. Prior to the program only 70 of the sources had been observed at least twice in the same period. This has been reduced to a very few sources. The data gathered by the source monitoring program should permit the selection of better defining sources for a redetermined ICRF.

In parallel to improving the astrometric data set work started to coordinate the IVS analysis centers for the ICRF redetermination. The first step in February 2005 was the generation of source catalogues in a configuration similar to the 1995 ICRF analysis, i.e., source positions as global parameters and station positions are arc parameters. The analysis centers participating in this effort are:

- U. S. Naval Observatory, U.S.A.
- Jet Propulsion Laboratory, U.S.A.
- Geoscience Australia, Australia
- Deutsches Geodätisches Forschungsinstitut, Germany
- Institute of Applied Astronomy, Russia
- Main Astronomical Observatory, Ukraine
- Bundesamt für Kartographie und Geodäsie, Germany
- Shanghai Observatory, China
- Space Geodesy Center Matera, Italy
- Goddard Space Flight Center, U.S.A.

The catalogues will be compared by the analysis centers at JPL, Paris Observatory, USNO and IAA. Over the next several years it is anticipated that many test catalogues will be made, compared, and analyzed to identify systematic errors, to try methods for treating source position instabilities, to determine the real size of position errors, and to decide on the analysis configuration for the final result. One goal will be the consistent estimate of VLBI CRF, TRF and EOP. Another area of work will be the generation of position time series and analysis of these series to decide on the defining sources of the redetermined ICRF.

The IVS also contributes to the effort to determine a combined TRF solution which will eventually become the ITRF2004. IVS provided a consistent set of combined TRF, EOP and CRF estimates based on solutions from five analysis centers. This set will be combined at the IERS with the solutions of the other geodetic space techniques. Since the ITRF2000 was based on data up to the end of the year 2000, the quality of this TRF deteriorated in the subsequent years. In order to provide a TRF for operational VLBI determinations of EOP and atmospheric water vapor content, a new conventional VLBI TRF (VTRF2005) was compiled from a combination of five VLBI TRF realizations. The complete list of VTRF2005 coordinates at epoch 1997.0 and their velocities can be found at <http://vlbi.geod.uni-bonn.de/IVS-AC>.

Data of the 15-day Continuous VLBI Campaign 2002 (CONT02) were used to perform combination studies with other techniques. Thaller et al. (2005) investigated, among other things, the effect of combining estimates for UT1-UTC (DUT1). VLBI is the only technique to fully determine DUT1, as the satellite

techniques GPS and SLR only yield the rate terms. Figure 3 shows hourly UT1-UTC values estimated by VLBI and GPS w.r.t. the official C04-series and the IERS2000 sub-daily model. Despite the large drift in the GPS estimates, the combined solution aligns very well with the VLBI-only solution. The combined solution appears to be an improvement over the VLBI solution as the RMS of the remaining differences to C04/IERS2000 reduces from 0.015 ms for VLBI to 0.011 ms for the combined solution demonstrating the advantage of an inter-technique combination.

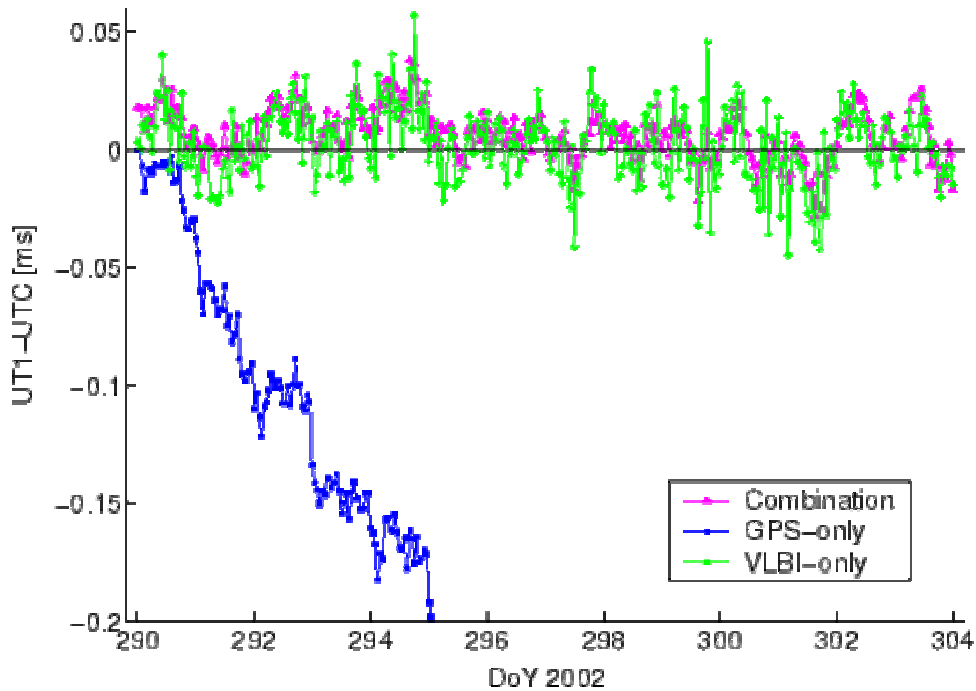


Figure 3: Hourly UT1-UTC estimates w.r.t. C04/IERS2000 derived from VLBI, GPS, and a combined solution.

#### 4. Next Generation VLBI System

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.

##### 4.1 Future Requirements for VLBI

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 [Schuh et al., 2002], on the requirements of the Global Geodetic Observing System (GGOS) project of the International Association of Geodesy, and on the science driven

geodetic goals outlined in the NASA Solid Earth Science Working Group Report (SESWG, <http://solidearth.jpl.nasa.gov/seswg.html>). 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.

## 4.2 Strategies and Recommendations

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.

### 4.3 Next Steps

The above recommendations describe a system that can begin to become reality very soon. The IVS WG3 report (Niell et al., 2005) 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.

A report of the WG3 was presented in September 2005. The IVS Directing Board reviewed the final version and accepted it for publication. It is available under <http://ivscc.gsfc.nasa.gov/wg/wg3> and will be published in the Annual Report 2005.

At the 14<sup>th</sup> Directing Board meeting held in September 2005 in Washington, DC, a Committee was formed, VLBI2010 Committee, whose primary function is to promote and guide research into the improvement of the “technique” of geodetic VLBI. The committee will take an integrated view of VLBI and will evaluate the effectiveness of proposed system changes based on the degree to which they improve IVS’ final products. In addition, the committee will take responsibility for encouraging the implementation of the WG3 recommendations.

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