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ORIGINAL ARTICLE

The International VLBI Service for Geodesy and Astrometry (IVS): current capabilities and future prospects

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Abstract Very Long Baseline Interferometry (VLBI) plays a unique and fundamental role in the maintenance of the global (terrestrial and celestial) reference frames, which are required for precise positioning in many research areas such as the understanding and monitoring of global changes, and for space missions. The International VLBI Service for Geodesy and Astrometry (IVS) coordinates the global VLBI components and resources on an international basis. The service is tasked by the International Association of Geodesy (IAG) and International Astronomical Union (IAU) to provide products for the realization of the Celestial Reference Frame (CRF) through the positions of quasars, to deliver products for the maintenance of the terrestrial reference frame (TRF), such as station positions and their changes with time, and to generate products describing the rotation and orientation of the Earth. In particular, VLBI uniquely provides direct observations of nutation parameters and of the time difference UT1-UTC. This paper summarizes the evolution and current status of the IVS. It points out the activities to improve further on the product quality to meet future service requirements.

Keywords International VLBI Service for Geodesy and Astrometry (IVS) · Very Long Baseline Interferometry (VLBI) · Earth orientation parameters (EOP) · Terrestrial reference frame (TRF) · Celestial reference frame (CRF)

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1 Introduction

The Very Long Baseline Interferometry (VLBI) technique has now been employed in geodesy for nearly 40 years. During this time, most of the scientific and operational activities had been organized through national or bi-lateral agreements, sometimes on an ad hoc basis. Today, the global VLBI resources are coordinated by the International VLBI Service for Geodesy and Astrometry (IVS) to routinely monitor Earth rotation and its variations as well as crustal motion in order to maintain the global (terrestrial and celestial) reference frames (cf. Vennebusch et al. 2006).

According to its terms of reference (Schlüter 1999), the IVS is an international collaboration of organizations that operate or support VLBI components for geodetic and astrometric applications. Specific 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.

The international collaboration, in accordance with the IVS terms of reference, is based on a standing call for participation that was first issued in 1998 (Schlüter 1999).

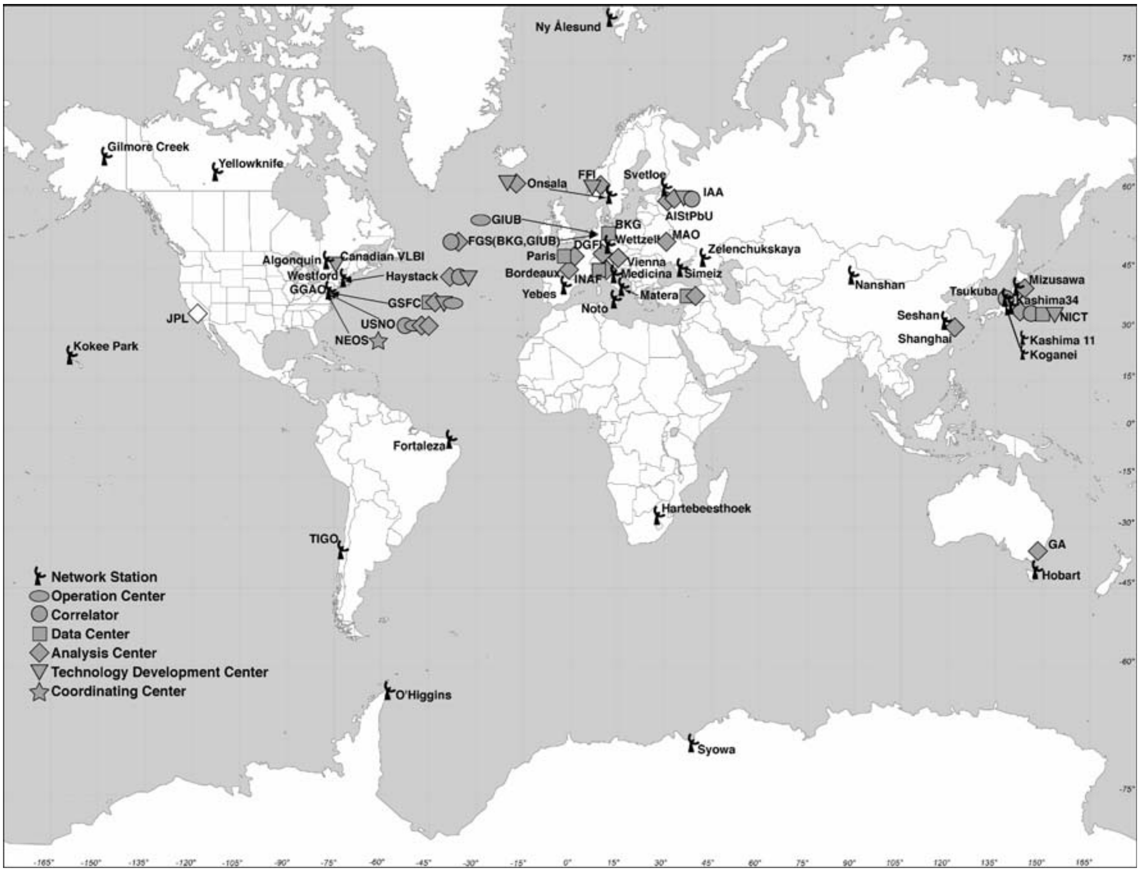

Fig. 1 Global distribution of IVS components

Any institution that is prepared to participate in IVS activities may join at any time following the rules of the call. Formally, the IVS was inaugurated in February 1999 and the Directing Board held its first meeting at the Fundamental Station Wettzell, Germany in the same month. Later on, the IVS was approved as a service of the International Association of Geodesy (IAG), of the International Astronomical Union (IAU) and of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

Owing to its observational properties, geodetic VLBI is the only technique that can link the terrestrial reference frame (TRF) and the quasi-inertial reference frame materialized through positions of far-distant celestial objects. Only VLBI allows maintenance of consistency between these reference frames and the rotational parameters of the Earth. Through constant improvements in the quality of the observations and their analyses, geodetic VLBI results have steadily been improved. For this reason, geodetic VLBI has contributed significantly to the tremendous progress made in geodesy over the last four decades by measuring site positions and lengths of intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art, and providing precise quasar positions as the best approach to an inertial reference frame. VLBI has been a primary tool for understanding global phenomena changing the “solid” Earth (e.g., National Aeronautics and Space Administration 2002).

As a consequence, the main task of the IVS is the coordination of the globally distributed VLBI components (see below) to guarantee the provision of the products and parameters that realize the celestial reference frame (CRF) and the TRF, as well as monitor the Earth’s angular velocity and orientation of the rotation axis in both reference frames through Earth orientation parameters (EOPs). Since VLBI is a key technique for these monitoring efforts, the IVS will play an important role in the realization of the recently established Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) (Pearlman et al. 2006).

2 Current status of geodetic VLBI coordinated by IVS

The organizational structure of the IVS is separated in groups of components (Fig. 1). As of late 2006, the IVS consists of

- One coordinating center (CC) to coordinate the daily and long-term activities (Goddard Space Flight Center, Greenbelt, USA).
- Thirty network stations for the acquisition of VLBI data (Fig. 1).
- Three operations centers to coordinate the observations of the Network Stations (Institute for Geodesy and Geoinformation of the University of Bonn, Germany; Goddard Space Flight Center, Greenbelt, USA; US Naval Observatory, Washington, USA).
- Six correlators for processing the raw VLBI data (Max-Planck-Institute for Radio Astronomy, Bonn, Germany; Massachusetts Institute of Technology Haystack Observatory, Westford, USA; Institute of Applied Astronomy, Saint Petersburg, Russia; National Institute of Information and Communications Technology (NICT), Kashima, Japan; Geographical Survey Institute, Tsukuba, Japan; and US Naval Observatory, Washington, USA).
- Six data centers to distribute the products to users, provide storage and archiving functions (Bundesamt für Kartographie und Geodäsie, Leipzig, Germany; NASA Crustal Dynamics Data Information System, Greenbelt, USA; Geodetic Data Archive Facility, Matera, Italy; National Institute for Astrophysics, Bologna, Italy; NICT, Kashima, Japan; and Paris Observatory, Paris, France).
- Twenty-one analysis centers (ACs), analyzing the data, generating results and products.
- Seven technology development centers for developing new VLBI technology.

In total, the IVS consists of 74 permanent components, representing 37 institutions in 17 countries with ~250 associate members. It coordinates the activities of all VLBI components for geodetic and astrometric applications based on their proposals. The contributions are dependent on the individual capabilities of the institutions, meaning that each institution provides as much as its resources allow.

2.1 Coordinating center

The IVS CC at NASA's Goddard Spacer Flight Center (GSFC) is responsible for the coordination of both the day-to-day and the long-term activities of the IVS, consistent with the directives and policies established by the Directing Board.

Primary functions of the CC include the preparation of the master observing plan for each calendar year, the organization of workshops and meetings, the production and publication of reports and communications, and the maintenance of the IVS information system (e.g. website and mailing lists). Annual reports and meeting proceedings have been published by the CC documenting the status and the progress being made (Vandenberg 1999; Vandenberg and Baver 2000, 2001, 2002a,b, 2003, 2004a,b; Behrend and Baver 2005, 2006a,b). A wealth of information on the IVS and its activities is being made available online at http://ivscc.gsfc.nasa.gov.

2.2 Network stations

Figure 1 shows the locations of the antenna sites in the 17 countries that support geodetic and astrometric VLBI within the IVS. One-third of the antennas are dedicated to geodetic/astrometric observing, whereas the others are dual use (i.e., both geodesy and radio astronomy). The IVS aims at increasing the number of network stations in the Southern Hemisphere.

The network stations participate in observing sessions between several times a week and several times a year depending on their allocations of observing time for geodesy and astrometry. Standard single observing sessions last 24 h [solar] and usually involve six to eight stations operating simultaneously. Some stations carry a high load of observations and are included in most of the observing sessions, while other stations can only contribute to dedicated campaigns (see Sect. 4). Daily one-hour sessions for the determination of UT1-UTC are carried out on the baselines Kokee Park (Hawaii) and Wettzell (Germany) (Monday–Friday) and Wettzell—Tsukuba (Japan) (Saturday–Sunday).

Stations like Wettzell (Germany) and Kokee Park (USA) are regularly involved in the entire observing program. Other stations, such as O'Higgins or Syowa (both in Antarctica), contribute only campaign-wise, due to their very remote location and the logistical difficulties related to transporting personnel and recording media. Many stations are operating with aging instrumentation with hardware from the late 1960s; a problem of importance is radio frequency interference through television and mobile phone repeaters, which disturbs the faint radio signals of the quasars.

Most of the antennas are not primarily designed for geodetic and astrometric VLBI. Deformations of the telescope structures (e.g., thermal expansion (cf. Wresnik et al. 2006) and gravity sag) will lead to variations of the reference point, which is usually assumed as an invariant point of the telescope (cf. Dawson et al. 2006). Systematic errors due to such deformations will have to be considered for VLBI to make a better contribution to geodesy.

The raw VBLI data are recorded onto transportable disk systems and then shipped to the correlators. The storage requirement for a typical 24 h observing session amounts to around 1 TerraByte. The transportation of the data to the correlator is one of the major reasons for the time delay of the products. For this reason, access to high-speed data links for data transfer is now already realized for a few stations and is being investigated for some other sites. Here, the so-called "last-mile problem" (i.e., connection of the antenna site to the backbone of a high-speed network) is causing some difficulties due to the remoteness of VLBI antennas, but a steady improvement is imminent.

Time and frequency information is provided by Hydrogen masers for precise frequency generation and by employing Global Positioning System (GPS) time-transfer receivers to compare the local timescale to a global time scale, such as Universal Time Coordinated UTC(GPS). The current stability of the H-masers supports the accuracy of the observable to 20 to 30 picoseconds (ps); the comparison via GPS is good to approximately 100 ns.

Within the IVS, various data recording techniques, such as Mark IV and Mark 5 (developed at Haystack Observatory, USA), K4 and K5 (developed at NICT, Kashima, Japan), and S2 (developed in Canada), are being used in separate networks. This is still necessary due to compatibility reasons, although examples of cross-operations using copying techniques are already being realized. The development and general worldwide acceptance of the VLBI Standard Interface (VSI) will be the basis to overcome such limitations in the future.

2.3 Operation centers and correlators

Three IVS Operation Centers coordinate the routine operations of the network stations and prepare the detailed observation schedules. The schedules are posted to a Data Center with sufficient lead time (a week or more) before the start of a session. Most of the observing sessions are correlated with the Mark IV/Mark 5 correlators at the US Naval Observatory (Washington, USA), at the Max Planck Institute for Radio Astronomy (Bonn, Germany), and at Haystack Observatory (Westford, USA).

Some sessions are correlated with the K4/K5 correlators in Kashima and Tsukuba, Japan, and some with the S2 correlator in Penticton, Canada. A big step forward was made by the development of the disk-based recording systems Mark 5 and K5. Here, too, the VLBI Standard Interface (VSI) will make it possible to overcome the limitations of different data formats and recording philosophies.

Existing correlators for geodetic and astrometric applications have the capability to correlate between 3 and 16 stations in a single pass, depending on the number of available playback units. Sessions with more stations than playback units are correlated in multiple passes. Since access to high-speed data links has not been realized routinely, the time delay from observation to product delivery is dominated by the shipment of the disk media. For the two weekly rapid-turnaround sessions (IVS-R1 and IVS-R4, see Sect. 4), the time delay for product delivery is about 10 days on average. Other session types have delays from several weeks up to a month.

High-speed links at Haystack Observatory have enabled routine e-transfer of observation data from Tsukuba and Kashima, and further stations will follow soon. First experiences are being gathered with a software correlator at the Geographical Survey Institute (GSI) in Tsukuba, Japan, for the baseline Wettzell–Tsukuba. Software correlators, which use general-purpose computers (e.g., commodity PCs) instead of custom-built electronic hardware, are likely to become important for providing IVS products in real time.

2.4 Data and analysis centers

Six ACs regularly analyze the VLBI data in a rapid turnaround mode and submit their results to the Data Centers, employing different software programs such as CALC/SOLVE (Ma et al. 1990), OCCAM (Titov et al. 2004) and SteelBreeze (Bolotin 2000). Associate Analysis Centers regularly submit specialized products, such as tropospheric and ionospheric parameters, using complete series or subsets of VLBI observing sessions and perform special investigations and research. The results derived from the same dataset obtained by different ACs show discrepancies on the order of 80–100 mas in the daily EOP results.

The results of six ACs are combined by the IVS Analysis Coordinator to obtain the official IVS solutions (Nothnagel and Steinforth 2002). To improve the product reliability, more ACs and more software packages need to be involved in the procedure. The routine analysis process requires more automation for near-real-time provision of products.

The six Data Centers are repositories for all types of VLBI data like observing schedules, station log files, and data products. The three primary Data Centers mirror each other to make the distribution and maintenance of data and products more efficient and reliable.

2.5 Technology developing centers

Hardware technology developments within IVS are mainly carried out by the Haystack Observatory and NICT, in collaboration with related groups. The

Table 1 Summary of current IVS main products: status and goal specifications

Products	Specification	Status 2002	Status 2006	Goals (2010)
Polar motion x_p, y_p	Accuracy	$x_p \sim 100$ µas, $y_p \sim 200$ µas	x_p, y_p: 50–80 µas	25 µas
	Product delivery	weeks–4 months	8–12 days	1 day
	Resolution	1 day	1 day	10 min–1 h
	Frequency of solution	3 days/week		7 days/week
UT1-UTC (DUT1)	Accuracy	5–20 µs	3 µs	2 µs
	Product delivery	1 week	3–4 days	1 day
	Resolution	1 day	1 day	10 min
Celestial pole $\delta\varepsilon; \delta\psi$	Accuracy	100–400 µas	50 µas	25 µas
	Product delivery	weeks–4 months	8–12 days	1 day
	Resolution	1 day	1 day	
	Frequency of solution	~3 days/week		7 days/week
TRF (x, y, z)	Accuracy	5–20 mm	5 mm	2 mm
CRF $(\alpha; \delta)$	Accuracy	0.25–3 mas	0.25 mas (for more frequency bands)	0.25 mas (for more frequency bands)
	Frequency of solution	1 year	1 year	
	Product delivery	3–6 months	3 months	1 month

development of digital data recorders, the developments in e-VLBI (electronic VLBI using high-speed networks), and the progress in the VLBI Standard Interface (VSI) should be noted as significant steps forward as realized in the last 2 years.

VSI provides a standardized specification for VLBI data formats and protocols that is compatible between both homogeneous and heterogeneous VLBI data systems (Whitney 2006). These developments will play a key role in the evolution of the IVS as it will allow full interoperability between various VLBI systems, while still allowing separate development avenues.

3 Current and future products

When IVS started in early 1999, the continuity requirement for maintaining the TRF and CRF required the continuation of the existing observing programs set up by the US Naval Observatory for the National Earth Orientation Service (NEOS), or by NASA for the Continuous Observations of the Rotation of the Earth (CORE). In 2001, a working group (WG2) was established to review the products and the existing observing programs.

The IVS products can be defined in terms of their accuracy, reliability, frequency of observing sessions, temporal resolution of the estimated parameters, time delay from observing to final product, and frequency of solutions. The situation before 2002 and the goals for the follow-on years with IVS products are described in detail in the WG2 report (Schuh et al. 2002). It was the basis for improving products and evolving observing programs to meet service requirements. The main IVS products, their current accuracies and the goals are summarized in Table 1. The VLBI technique allows us to provide additional products and IVS intends to set up the extended products summarized in Table 2.

Until the end of 2001, IVS products were generated from ~3 days/week observing with six station networks. The time delay from observing to product delivery ranged from 1 week up to 4 months, with an overall average value of 60 days. From 2002 to date, many of the goals outlined in the WG2 report have been achieved:

- all products are delivered on a regular, timely schedule,
- the accuracies of all EOP and TRF products have improved by a factor of 2 to 4,
- the average time delay has decreased from 60 to 30 days, and 2 days per week rapid turnaround sessions (IVS-R1 and IVS-R4) are observed with an average time delay of 10 days.

The more ambitious goals are still being worked on:

- increase the frequency of observing sessions from ~3 to ~7 days per week,
- improve the sky distribution of the CRF,
- reduce the time delay to 3–4 days, and eventually to 1 day.

4 Current observing program

4.1 Overview of observing sessions

To meet its product goals, beginning with the 2002 observing year and continuing until today, IVS designed an observing program coordinated with the international

Table 2 Overview of future IVS products

Earth orientation parameter additions	• dUT1/dt (length of day) • dx_p /dt; dy_p /dt (pole rates)
Terrestrial reference frame (TRF)	• x-, y-, z- time series[a] • Episodic events • Annual solutions • Nonlinear changes
Celestial reference frame (CRF)	• Source structure • Flux density
Geodynamical parameter	• Solid Earth tides (Love numbers h, l) • Ocean loading (amplitudes and phases A_i, f_i) • Atmospheric loading (site-dependent coefficients)
Physical parameter	• Tropospheric parameters[b] • Ionospheric parameters • Light deflection parameter

[a] A Pilot Project to provide baseline length information over time is underway
[b] Total and wet zenith delays are provided on an operational basis for the R1 and R4 sessions

community. Since 2002, the observing program has included the following sessions:

- EOP: Two rapid turnaround sessions each week (IVS-R1 and IVS-R4), initially with six stations, increasing to seven or eight. These networks were designed with the goal of having comparable polar motion results (x_p and y_p). One-baseline, 1 hour intensive sessions four times per week, increasing to seven times per week in 2004.
- TRF: Monthly TRF sessions with eight stations including a core network of four to five stations and using all other stations three to four times per year. In mid 2005, this changed to 16 stations observed six times per year.
- CRF: Every 3–4 weeks, dedicated CRF sessions to provide astrometric observations that are useful in improving the current CRF and in extending the CRF by observing "new" sources. Bi-monthly RDV (R&D with the VLBA) sessions using the ten stations of the Very Long Baseline Array (VLBA) and ten geodetic stations, providing state-of-the-art astrometry as well as information for mapping CRF sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Tri-annual 14-day continuous sessions (like the CONT02 and CONT05 campaigns) to generate continuous data sets for various types of studies and to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy.

Although certain sessions have primary goals, such as CRF, most of the sessions are scheduled so that they simultaneously contribute to all geodetic and astrometric products. The observing program and product delivery was accomplished by making some changes and improvements in IVS observing program resources (station days, correlator time, and storage media), by improving and strengthening analysis procedures, and by a vigorous technology development program.

4.2 Experiences with the observing program

Compared to 2001, the number of station observing days increased by about 10% in 2002 with an additional 12% devoted to the CONT02 campaign. Not counting CONT02, the number of observing days increased by another 12% in 2003, in 2004 and also in 2005. In 2005, the CONT05 was performed (MacMillan et al. 2006), in order to provide the best dataset VLBI ever had. The International GNSS Service (IGS) and the International Laser Ranging Service (ILRS) enhanced their observation during this campaign, which promised best results in the combination of the techniques.

The required observing days will continuously increase such that by 2007 the top 12 geodetic stations will need to observe up to 4 days per week—an ambitious goal. Increased station reliability and unattended operations can improve temporal coverage of Earth rotation monitoring by VLBI and also allow substantial savings in operating costs. Higher data-rate sessions can yield more accurate results, and therefore nearly all geodetic stations have been upgraded to Mark 5 or K5 technology; by the end of 2006 all stations will have upgraded.

As of the end of 2003, the correlators and most of the observing stations were equipped with Mark 5 digital recording systems. All correlators were committed to handling the IVS data processing with priority for meeting timely product delivery requirements. High-capacity disks (120–250 GB) were purchased and organized in a common pool to replace magnetic tapes and to obtain additional recording capacity.

The progress in communication technologies supported the breakthrough for e-VLBI. Some stations are already connected to fast Internet links (1 Gbit/s) and regular applications for e-VLBI (real-time or near-real-time) have been established. The 1 hour intensive observation sessions are routinely transferred electronically to a Mark IV/5 or K5 correlator. The increased amount of VLBI data to be produced under the new observing program required ACs to handle a larger load. Partially automated analysis procedures help to improve the timeliness of product delivery.

As an official IVS product, a complete set of EOPs is regularly submitted to the International Earth Rotation and Reference Systems Service (IERS). The set is obtained as a combination of the individual solutions of six IVS Analysis Centers (Nothnagel and Steinforth 2002). Until the end of 2001, the parameters were derived from the NEOS observations, while since January 2002 the IVS-R1 and IVS-R4 have been used implementing the WG2 recommendations. The objective of the rapid turnaround observation sessions is to minimize the delay between the observations and the availability of the results. The delay between the observations and the results is better than two weeks since April 2002 (see Table 1). This should be regarded as significant and real progress, even though the WG2 goal of only 4 days has not yet been achieved.

Improvements for data transmission and a higher throughput at the correlators were achieved, following the implementation of the newly developed Mark 5 digital data recording system, which has e-VLBI capabilities, permitting data transmission via high-speed Internet links. The determination of DUT1 from the now daily 1 hour observations known as "Intensives" have been carried out from 1983 to 1994 on the baseline Wettzell–Westford, from 1994 to 2000 on the baseline Wettzell–Greenbank and since 2000 on the baseline Wettzell–Kokee Park. These weekday Intensives now employ the Mark 5 recording system. In 2002, a time-series on the baseline Wettzell–Tsukuba has been started. These weekend Intensives use the Japanese K5 system. The regular application of fast Internet links for the Intensives facilitates the rapid provision of DUT1, which is now accomplished in 3–4 days.

The VLBI observations from the IVS-R1 and IVS-R4 allow the determination of tropospheric parameters, in particular the wet zenith path delay. Since July 2003, the zenith wet path delay is an official IVS product. The Vienna University of Technology is combining the solutions of up to nine ACs to produce total and wet zenith path delays from the weekly rapid turnaround sessions IVS-R1 and IVS-R4 (Schuh et al. 2004).

5 The future VLBI system

A strategic paper "VLBI2010" for geodetic VLBI has been released in September 2005 for the coordination of developments in the next decades (Niell et al. 2006). The IVS Working Group 3 (WG3) was tasked 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. The proposals are based on the recommendations for future IVS products detailed in the IVS Working Group 2 Report (Schuh et al. 2002), on the requirements of IAG's GGOS (Pearlman et al. 2006), and on the science-driven geodetic goals outlined in the NASA Solid Earth Science Working Group Report (National Aeronautics and Space Administration 2002).

The criteria are

- one-millimeter measurement accuracy on global baselines,
- continuous measurements for time-series of station positions and EOPs,
- turnaround time to initial geodetic results of less than 24 h.

The WG3 sought approaches for the design of the new observing 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.

The WG3 report identifies specific steps that need to be taken next in order to develop, deploy, and bring the new 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.

Results of these studies and projects should be well communicated within the community. The IVS Directing Board established the VLBI2010 Committee (V2C), which is tasked to coordinate the required steps. In addition to the regular meetings of the V2C, the progress of the VLBI2010 efforts is discussed at general VLBI meetings, dedicated workshops and online fora.

It is our belief that the envisioned new VLBI system 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.

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