

IVS High Accurate Products for the Maintenance of the Global Reference Frames as Contribution to GGOS

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Abstract. VLBI provides highly accurate and unique products for the realization and maintenance of the celestial and terrestrial reference frames, ICRF and ITRF, as well as for the Earth Orientation Parameters. In 2001 the products were reviewed with respect to obtaining highest accuracy and to improving the observing sessions in order to make best use of the resources which are made available by the IVS member institutions. Since 2002 improved observing sessions were coordinated by the IVS aiming at fast turn-around products for EOP and better products for TRF and CRF. The number of observations increased by more than 30% from 2002 to 2004. New products, e. g. the troposphere zenith path delay, are now being generated. Concerns about the aging technology, which has been used for the past three decades, and about radio interference problems that decrease the number of useable observations, led to the establishment of IVS Working Group 3. The working group 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. The results are summarized in a vision paper, VLBI2010 (Niell et al., 2005), which is recommended for coordination of new developments in VLBI and for plans to invest in new components by member institutions. This paper reviews IVS activities of recent years and gives a perspective about new developments for meeting future requirements, which are set up by GGOS.

Keywords. International VLBI Service, global reference frame, VLBI, IVS, GGOS

1 Introduction

High-precision global reference frames are needed for precise positioning in geodesy, for navigation on the Earth and in space, for Earth and space research, and for applications in precision surveying. This is particularly true if satellite-based navigation systems such as GPS and GLONASS (or the future GALILEO) are employed. An inertial reference frame that is fixed in space is needed for orbit determination of space vehicles, of the moon and the planets, and for the description of the positions of stars and extragalactic sources. An Earth-fixed reference frame, i.e. a frame rotating with the Earth, is required for point positioning on the Earth. These two reference frames are connected through the dynamic motions of the Earth in space, including rotation, polar motion, nutation, and precession.

The inertial frame is defined by quasars – radio sources which are billions of light years away – and realized through the description of their positions through a pair of coordinates, known as right ascension (α) and declination (δ) in the defined Celestial Reference Frame (CRF). The Earth-fixed frame is defined by a set of stations that are located on the Earth's surface and are globally distributed. The stations' positions are described through coordinates (latitude, longitude, and height, or

geocentric x , y , and z) at a given epoch (e.g. 2000.0), and their change with time is given by their velocity (dx/dt , dy/dt , dz/dt) in a defined Terrestrial Reference Frame (TRF). For the transformation from CRF to TRF, and vice versa, the dynamic orientation of the Earth in space must be known. A set of five parameters, named Earth Orientation Parameters (EOP), describe the orientation of the Earth. In combination with precession and nutation models, two parameters ($d\psi$, $d\epsilon$) fix the instantaneous rotation axis in the CRF, two parameters (x_p , y_p) fix the instantaneous axis with respect to TRF, and one parameter describes the speed of rotation (DUT1). DUT1 is the difference of the Universal Time, UT1, based on the angle of rotation of the Earth at any given instant, and the Universal Time Coordinated, UTC, which is generated by stable atomic clocks. Due to the continuous changes in the Earth system (atmosphere, ocean, biosphere, lithosphere, mantle, and core), and in particular due to the variation of the mass distribution within the Earth system, all EOP parameters are subject to continuous changes. Since no models currently exist to describe these changes with sufficient precision, continuous observations are needed to accurately measure the EOP parameters.

Very Long Baseline Interferometry (VLBI) plays a fundamental role in the process of the realization and maintenance of the global reference frames and in the determination of the EOP:

- Only VLBI allows the observation of quasars, which realize the CRF.
- Only VLBI can provide the complete set of EOP and is unique for the determination of DUT1.
- VLBI provides most precisely the length of intercontinental baselines, which strongly support the realization and maintenance of TRF.

The International Association of Geodesy (IAG) is currently establishing the project GGOS (Drewes and Reigber, 2004), which aims to realize a global reference frame with a precision of 10^{-9} , consistent for decades, which demands a strong support by national and international agencies coordinated through the International Services of the IAG. The International VLBI Service for Geodesy and Astrometry (IVS), as one of the IAG services, is tasked to coordinate VLBI components operated and provided by its member organizations and to generate the required EOP parameters precisely and in a timely manner. In 2001, a review of the existing products and observing programs was carried out by IVS Working Group 2 (Schuh et al.,

2002), which clearly defined the necessary IVS products and prescribed an IVS observing program optimized to make best use of the available resources to create these products.

Many hardware components for VLBI (such as radiotelescopes) 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 create the report called ‘VLBI2010’ which specifies guidelines for the future evolution of VLBI, for the refinement of its components, and for the replacement of old components and the development of new components (Niell et al., 2005).

2 VLBI 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 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 2.1. 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, the upcoming IAG project GGOS will drive the future demands. The categories summarized in Table 2.1 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 avail-

able 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, e-VLBI will be realized in general and timely solutions will become more economical.

Table 2.1. IVS products and the demands on a next generation VLBI system

Category	Product	Accuracy	Freq. of sol	Resolution	Timeliness
CRF	α, δ	0.25 mas	yearly		1 mo
	α, δ -TS	0.5 mas	1/mo	1 mo	1 mo
	sou struc		1/mo	1 mo	3 mo
	flux dens		7 d/w	1 hr	NRT
TRF	x, y, z -TS	2...5 mm	7 d/w	1 d	1 d
	episo event	2...5 mm	7 d/w	<1 d	NRT
	annual soln		yearly	-	1 mo
	coordinates	1...2 mm			
	velocities	0.1...0.3mm/y			
EOP	DUT1	5 μ s	7 d/w	10 min	NRT
	d ϕ , d ϵ	25...50 μ as	7 d/w	1 d	NRT
	x_p, y_p	25...50 μ as	7 d/w	10 min	NRT
	dx $_p$ /dt				
	dy $_p$ /dt	8...10 μ as/d	7 d/w	10 min	-
GDP	solid Earth tides	0.1%	1 y	1 y	1 mo
	ocean load	1%	1 y	1 y	1 mo
	atmos load	10%	1 y	1 y	1 mo
PP	trop param				NRT
	zen delay	1...2 mm	7 d/w	10 min	
	gradients	0.3...0.5 mm	7 d/w	2 h	
	iono map	0.5 TECU	7 d/w	1 h	NRT
	light defl param	0.1%	1 y	session all	1 mo

GDP, geodynamical parameters; *PP*, physical parameters; *NRT*, near-real time; *TS*, time series; *episo*, episodic

3 Current Status of Geodetic VLBI Coordinated by IVS

Figure 3.1 shows the distribution of the IVS components. As of 2004, 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.

IVS coordinates the activities of all VLBI components for geodetic and astrometric use based on the proposals made by the institutions in reply to a call for participation. The contributions are dependent on the individual possibilities of the institutions, meaning that each institution provides as much as their resources allow.

3.1 Network Stations

From Figure 3.1 it is apparent that most of the components are located on the northern hemisphere. The distribution of components is clearly not distributed homogeneously. The non-homogeneity is enhanced further by the fact that the network stations contribute differently to the amount of observations. 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. Stations like Wettzell and Kokee Park are regularly involved in the entire observing program. Other stations, such as O'Higgins or Showa, contribute only campaign-wise, due to their very remote location. The number of technical failures is increasing due to worn-out instrumentation or due to RFI (radio frequency interference).

The various data recording techniques, such as Mark IV and Mark 5 (developed at Haystack Observatory for NASA), K4 and K5 (developed at NICT, Kashima, Japan), and S2 (developed in Canada), lead to additional constraints for the combination of network stations in common observing sessions, because the correlators are dedicated to one recording system only. The development of the VLBI Standard Interface (VSI) will help to overcome such a limitation in the near future.

Most of the antennas are not primarily designed for geodetic and astrometric VLBI. Deformations of the telescope structures will lead to variations of the reference point, which is usually assumed as an invariant point of the telescope. Systematic errors due to such deformations will have to be considered. The transportation of the data to the correlator is one of the major reasons for the latency of the products. Access to high speed data links for data

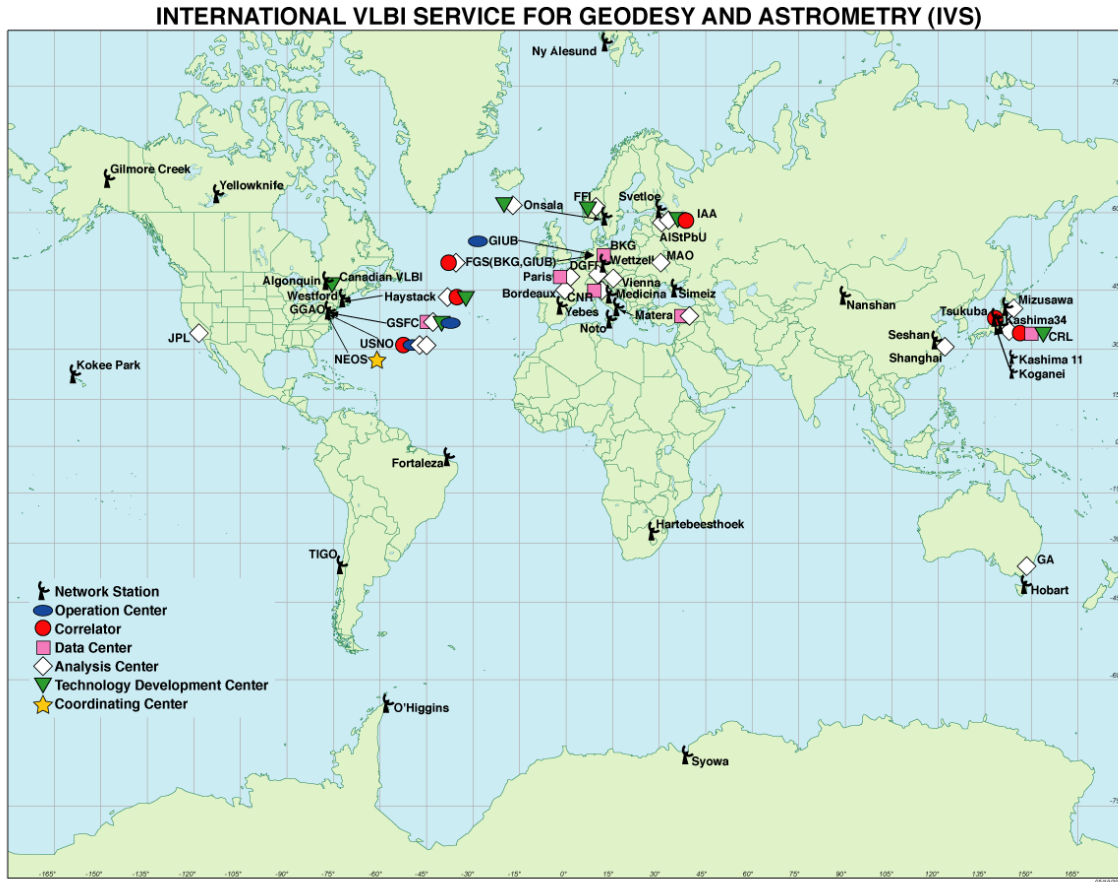


Fig. 3.1. Global distribution of IVS components

transfer is highly welcome. Nevertheless, high speed Internet access is currently not available at many stations due to the last mile problem and the high costs. Time and frequency information is provided by H-Masers for precise frequency generation and by employing GPS time transfer receivers to compare the local timescale to a global time scale, such as UTC(GPS). The current stability of the masers supports the accuracy of the observable to 20 to 30 ps; the comparison via GPS is good to approximately 100 ns.

3.2 Operations Centers

A master schedule is prepared for each calendar year by the IVS Coordinating Center. There are three Operations Centers, which coordinate the network stations for dedicated observing programs by preparing the detailed observation schedules. The schedule is set up before the session starts. As a means of gaining more flexibility in the event of a station failure, and for making best use of the sta-

tion resources, dynamical scheduling offers the promise of great improvement.

Quasar positions are provided by the ICRF. The positions are available only for S- and X-band observations. Observations employing other frequency bands than S/X will require the determination of quasar positions in the respective frequency band, including long-term monitoring to ensure the required stability.

3.3 Correlators

Most of the observing sessions are correlated with the Mk4 correlators at the US Naval Observatory, the Max-Planck-Institut für Radioastronomie, and Haystack Observatory. Some experiments are correlated with the K4 and K5 correlators in Kashima and Tsukuba, Japan, and some with the S2 correlator in Penticton, Canada. A real step forward was made by the development of the disk based recording systems Mark 5 and K5. The VLBI Standard Interface (VSI) will help to overcome the dif-

ferent formats and recording philosophies. The Mk4 correlators have the capability to correlate up to 16 stations, but due to the limited available number of recording systems and station units, the capacity is limited to 8 or 9 stations for one correlator run. Since access to high speed data links has not been realized, the latency from observation to product delivery is dominated by the shipment of data carriers. First experiences are being gathered with a software correlator at the Geographical Survey Institute in Tsukuba, Japan, for the baseline Wettzell–Tsukuba. Software correlators are likely to become important for providing products in real time.

3.4 Data and Analysis Centers

There are 21 Analysis Centers but only five or six Analysis Centers are handling the regular data flow, employing software programs such as CALC/SOLVE, OCCAM and SteelBreeze. Many of the Analysis Centers are doing special investigations and research. The results derived from the same data set obtained by different Analysis Centers show biases on the order of the internal precision. Studies to reduce the differences are under way. The results of the various Analysis Centers are combined to obtain the IVS solutions. To improve the product reliability more Analysis Centers and more software packages need to be involved in the procedure, in particular supporting the internal IVS combination routines. The routine analysis process requires more automation for near-real time provision of products.

3.5 Technology Developing Centers

Technology developments for IVS are mainly carried out by the Haystack Observatory and by NICT in collaboration with related groups. The development of digital data recorders, the developments in e-VLBI, and the progress in the VLBI Standard Interface should be noted as significant steps forward in the last two years. These developments will play a key role in the evolution of the IVS.

4 Future Demands on IVS Products, and Required Steps of Improvement

Future demands on IVS products are placed by the requirements set up by users of highly precise global reference frames and by the scientific community as well. The IAG has established the project GGOS, which will result in the provision of a precise global reference system, consistent for decades. Several groups expressed their willingness on the

international floor to contribute strongly to global and to regional projects. Close to real time products, time series derived in post-processing mode to achieve highest quality, and products acquired from special observing campaigns are provided, as summarized in the Table 4.1.

Table 4.1. General future demands to IVS products

Products	mode of generation	product availability	Processing	overall requirements
EOP	CONTOBS, TS w/ highest resolution	close to RT for operational maintenance	POST for best accuracy	COMB
TRF	CONTOBS for episodic events ^a	close to RT for episodic events	POST for best accuracy	COMB
CRF	campaign-wise ^b		POST	
PP	by-product of EOP, TRF and CRF campaigns	NRT	POST	COMB
SV	on demand		POST	

PP, physical parameters; SV, space vehicles; CONTOBS, continuous observation over a short time interval; TS, time series; RT, real time; NRT, near-real time; POST, post-processing; COMB, combination with other techniques

^a In combination with the observing sessions, time series for precise position monitoring.

^b In combination with source monitoring observing sessions.

The first attempt to optimize the overall resources resulted from the WG2 report. Nevertheless, to meet the upcoming service requirements and to guarantee the products provision for the maintenance of global reference frames, much more effort is required. Urgent steps of improvement are:

- to overcome the unbalanced network configuration,
- to increase the observing capabilities,
- to reduce technical failures of old components (antennas),
- to avoid frequency interferences,
- to obtain compatibility in technology, in particular in data recording,
- to develop dynamical scheduling to make best use of observation resources,
- to speed up the data transmission to the correlators,
- to reduce the latency between observations and product provision,

- to reduce the systematic errors of the instrumentation,
- to reduce systematic errors caused by the analytical and numerical models,
- to increase the automation in the data handling process from the correlator to the final analysis, and
- to support the combination with the other techniques.

The observable in VLBI is the time delay τ , which is currently acquired with an accuracy of approximately 30 ps. To increase the overall accuracy in VLBI towards the demands of GGOS, which is approximately mm-accuracy in station position, the time delay τ has to be derived with an accuracy of 4 ps. Such an increase in accuracy may require time and frequency stability that is almost one order of magnitude more precise than is possible with the systems currently employed. Because of the correlations among the station height, the atmospheric refraction, and the time scale, new and better ways of correcting for the clocks and atmospheres will be needed. For example, the inclusion of water vapour radiometers will have also to be considered. As currently the precise positions of the quasars have been obtained only through S- and X-band observations, the catalogue needs to be extended to the other frequency bands that will be observed in the future. Moreover, variations in source positions and in the strengths of the sources need long term, continuous monitoring. The capac-

ity to link dedicated satellites to the CRF by means of VLBI observations should be considered. Such features will become important for observing very remote space missions or for connecting navigation satellites to the CRF. For planning the future of the VLBI system, the long term continuity of VLBI must be taken into consideration. The changes that are needed must be accomplished through well-organized transition plans, and the realization will need approval of all contributing institutions.

References

- Drewes, H., C. Reigber (2004) The IAG Project “Integrated Global Geodetic Observing System (IGGOS)” Setup of the initial Phase, in *International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings*, edited by N. Vandenberg and K. Baver, NASA/CP-2004-212255, pp.186-190. (<http://ivscc.gsfc.nasa.gov/publications/gm2004/drewes>)
- Niell, A., A. Whitney, W. Petrachenko, W. Schlüter, N. Vandenberg, H. Hase, Y. Koyama, C. Ma, H. Schuh, G. Tuccari (2005) VLBI2010: Current and Future Requirements for Geodetic VLBI Systems, IVS WG3 Report, <http://ivscc.gsfc.nasa.gov/about/wg/wg3>.
- Schuh, H, P. Charlot, C. Klatt, H. Hase, E. Himwich, K. Kingham, C. Ma, Z. Malkin, A. Niell, A. Nothnagel, W. Schlüter, K. Takashima, N. Vandenberg (2002) IVS Working Group 2 for Product Specification and Observing Programs, in *International VLBI Service for Geodesy and Astrometry 2001 Annual Report*, edited by N. Vandenberg and K. Baver, NASA/TP-2002-210001, pp. 13-45. (<http://ivscc.gsfc.nasa.gov/about/wg/wg2>).