Prospective Development of the International VLBI Service for Geodesy and Astrometry over the next few years

(prepared by the IVS Directing Board)

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General

The IVS is a Service of the IAG, IAU and FAGS. 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 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.

The IVS inauguration date was March 1, 1999. As IVS has no funds of its own, but is tasked by IAG and IAU for the provision of timely, highly accurate products (EOPs, TRF, CRF, etc.), IVS is dependent on the support of individual agencies. On the other hand, as IVS is dependent on the support of its collaborating institutions, the final responsibility for success is reflected back to these institutions.

Activities, results and improvements since March 1999

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 initially employed and accepted existing infrastructure, observing programs, and related data handling. During its first two years of existence, the efforts of IVS were concentrated on the installation of new components and adoption of new IVS tasks. Coordination of activities within the service took effort, resources and time to mature.

All the activities of the first two years are documented in the Annual Reports of the IVS for the years 1999 and 2000. The first General Meeting was held in February 2000 (Proceedings are available), and several technical meetings concerning analysis and technology aspects were conducted.

Under the leadership of the IVS Technology Coordinator the VLBI Standard Interface (VSI) was developed and the experts internationally agreed upon the specifications for the hardware interface. Now the work for the software specifications is proceeding with similar promise of success.

Emphasis was placed on data analysis, coordinated by the Analysis Coordinator. Today five analysis centers provide a timely, reliable, continuous solution for the entire set of five Earth

Orientation Parameters (EOPs) - two pole motion coordinates, UT1, two celestial pole coordinates. The IVS Analysis Coordinator makes a combined solution – the IVS combined solution - as timely input for the IERS and its combination with the GPS-, SLR/LLR- and DORIS solutions. It turns out that the IVS combined solution gains 20% in accuracy over the single VLBI solutions. To improve the products of the IVS, more analysis centers were motivated to contribute and are invited to participate in Pilot Projects led by the Analysis Coordinator. Their solutions were compared, discussed and improved as all analysis centers reach for high standards.

Improving the quality of the observations and the network is a major goal of the Network Coordinator. Investigations and statistics are employed to find weak points. More improvements could be achieved, some needed improvements are difficult to realize because of the large amount of funds required for maintenance and upgrades. On the international level some additional stations will soon support IVS, such as the new station TIGO, and some additional stations will become involved which are equipped with data acquisition, recording, or transmission systems developed by Canada (S2) and Japan (K4).

Scientific Rationale

For research and applications in the fields of geodesy, geokinematics, geodynamics and astronomy, as well as in space research and space application programs, highly reliable reference frames are a strong requirement. Both the CRF and the TRF are demanded, and the EOPs that are the connecting elements between the systems must be derived from observations. In order to make full use of all the results obtained in related fields and to compare results from the past with results to be obtained in the future, the consistency of the reference frames is not only of great importance, it is the strongest requirement. Descriptions of “global change” as, for example, the result of mass transport or circulation in the atmosphere, oceans and lithosphere, or as the interaction of the masses of the planets, presume that the reference systems must be realized to the state of the art. Existing space missions such as CHAMP, and upcoming missions such as GRACE and GOCE, will provide results that describe variations in the gravity field with extremely high time resolution. The high precision of new altimeter missions will result in very precise information on profiles of the Earth. Not only is the consistency of the reference frames over decades of time a demand but also the ability to describe geometric and geophysical phenomena in one common reference frame will be necessary to generate comparable results. The accuracy of information will be on the level of 10^{-8} to 10^{-9}, which at least requires a uniform reference frame precise to 10^{-9}.

A reference frame at the level of 10^{-9} cannot be achieved by only one technique. The limitation comes from observing errors, modeling errors and unknown systematic effects. A demand by IAG is the combination of results provided by various techniques so as to benefit from the different sensitivities. While satellite techniques must include the orbit integration, and employ a gravity field, VLBI directly connects the inertial reference frame, EOPs and TRF, thus eliminating one major error source.

Combination means that all techniques provide independent comparable time series, which can be combined using SINEX or, preferably, on the observation level. Combination does not mean to derive the required products by one single technique (e.g. GPS) and, if required, along with a few selected determinations of corrections from a superior technique (VLBI). This will not help to eliminate and understand systematic errors and will not support the science driven by the best time series available.

IAG has promoted the establishment of the services in order to obtain such products as time series, which finally are combinable by IERS. In the sense of IAG, the services (IVS, ILRS and IGS) must generate timely products so that a joint automatic procedure can be established to generate the final results. Investigations are required to understand discrepancies and to improve analysis procedures. Such a bootstrap technique, successfully used in the past, will help obtain a better understanding of the "changing Earth" and improve models for describing the phenomena. There is no doubt that time series obtained during the past 100 years, at the time generated on the level of state of the art, have been, and still are, of fundamental interest for research and for proving the models in related fields. As such the services are the basis for research and will drive most of the research by themselves. In its new structure IAG acknowledges the services as the basis for all its research activities by giving the services a high rank, on the same level as the Commissions. IGGOS (Integrated Global Geodetic Observing System), a candidate IAG project, points out the strong requirement for the services and the demand for the reference frame on the level of 10^{-9}.

IVS is recognized as a service of IAU, as the VLBI technique is the only technique that uniquely realizes the inertial reference frame, the EOPs, and the TRF, which are urgently required for astronomical research and for all missions in space.

It has to be emphasized that IVS is working hard towards developing the procedures to provide their products in the required form. Further steps in organization and development are needed.

Review of products and observing programs

At the 4th IVS Directing Board meeting held in September 2000 in Paris, the requirement for reviewing the products and the related observing programs was discussed with the view that IVS must meet its service requirements and improve its products. Because such a review requires overall expertise, a broad discussion and acceptance within the entire community, a Working Group (WG2) for Product Specification and Observing Programs was established at the 5th Directing Board Meeting in February 2001. (The Minutes of all meetings are published and made available on the IVS web site.) The assignment of WG2 was to

- review the usefulness and appropriateness of the current definition of IVS products and suggest modifications,
- recommend guidelines for accuracy, timeliness, and redundancy of products,
- review the quality and appropriateness of existing observing programs with respect to the desired products,
- suggest a realistic set of observing programs which should result in achieving the desired products, taking into account existing agency programs,
- set goals for improvements in IVS products and suggest how these may possibly be achieved in the future,
- present a written report to the IVS Directing Board at its next meeting.

To establish a broad basis for discussion and to secure acceptance in the community, the members were chosen from among experts in the field of geodetic/astrometric VLBI. Led by Professor Harald Schuh (hschuh@luna.tuwien.ac.at) as chair, the following experts are the members of the Working Group:

- Patrick Charlot (charlot@observ.u-bordeaux.fr),
- Hayo Hase (hase@wettzell.ifag.de),

- Ed Himwich (weh@ivscc.gsfc.nasa.gov),
- Kerry Kingham (kak@cygx3.usno.navy.mil),
- Calvin Klatt (klatt@geod.emr.ca),
- Chopo Ma (ma@leo.gsfc.nasa.gov),
- Zinovy Malkin (malkin@quasar.ipa.nw.ru),
- Arthur Niell (aen@haystack.mit.edu),
- Axel Nothnagel (nothnagel@uni-bonn.de),
- Wolfgang Schlüter (schlueter@wettzell.ifag.de),
- Kazuhiro Takashima (takasima@leo.gsfc.nasa.gov),
- Nancy Vandenberg (nrv@gemini.gsfc.nasa.gov).

A draft report of the WG2 was presented at the 6th IVS Directing Board meeting held in September 2001. A general consensus of approval was obtained at the meeting, and after some updates were made the board reviewed the final version and accept it for publication. The report will be the basis for continuous improvements and for related research within IVS over the next few years. The results of the report will help IVS meet the objectives and future requirements set up by the IAG and IAU for research in the geosciences and astronomy. The following sections are based on the WG2 report, which is available under http://ivscc.gsfc.nasa.gov/WG/wg2.

Summary of current products and prospective improvements in the next few years

IVS is required to deliver products according to its ToR. Some products are uniquely provided by VLBI: UT1, CRF, and celestial pole; other products are available from more than one technique: Polar Motion, EOP, TRF, and certain geodynamical and physical parameters. 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 current situation with IVS products is described in detailed tables in the WG2 report. In summary, the products and their current accuracies are:

EOP UT1	24 hr sessions	UT1: 5 μs
	1 hr sessions	UT1: 15 μs
EOP pole	24-hr sessions	Xp:200 μas Yp:100μas
TRF	single solution	positions: 5 to 20 mm
	global solutions	positions: 1 to 4 mm; velocities: 0.1 to 1 mm/yr
CRF	source positions	0.25 mas
Celestial pole (precession/nutation)		0.1 ... 0.4 mas

As of late 2001, IVS products are generated from ~3 days/week observing with 6-station networks. The time delay ranges from 10 days to 6 months, with an overall average value of 60 days. Over the next four years, the goals of IVS with respect to its products are the following (specific goals for each product are listed in the WG2 report tables):

- improve the accuracies of all EOP and TRF products by a factor of 2 to 4 and improve the sky distribution of the CRF,
- decrease the average time delay from 60 to 30 days, and designate 2 days per week as rapid turnaround sessions with a maximum delay of 3-4 days, starting 2002,
- increase the frequency of observing sessions from 3 to ~7 days per week,
- deliver all products on a regular, timely schedule.

It is certainly feasible to achieve these challenging goals for IVS products, if the proposed observing programs are carried out and if required improvements are realized.

Evolving observing programs

To meet its product goals IVS has designed an observing program which will be coordinated with the international community beginning with the 2002 observing year. The proposed observing program includes the following sessions:

- EOP: Two rapid turnaround sessions each week, initially with 6 stations, increasing to 8 when station and recording media resources are available. These networks will be designed to have comparable Xp and Yp results. One-baseline 1-hr INTENSIVE sessions four times per week, with at least one parallel session.
- TRF: Monthly TRF sessions with 8 stations including a core network of 4 to 5 stations and using all other stations three to four times per year. The number of stations may be increased if the correlator can support the increase data load.
- CRF: Bi-monthly RDV sessions using the VLBA and 10 geodetic stations, plus quarterly astrometric sessions to observe mostly southern sky sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Annual, or semi-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 K4 technology will have the same accuracy and timeliness goals as those using Mk4 or Mk5.

The observing programs and product delivery can only be accomplished by making some changes and improvements in IVS observing program resources (station days, correlator time, and magnetic media), by improving and strengthening analysis procedures, and by pursuing a vigorous technology development program.

Requirements to IVS components

The WG2 report contains many recommendations for different aspects of IVS, its products, and its programs. What follows is a summary of the most important ideas.

Program resources: The number of required station observing days increases by about 30% over the next two years and by 2005 the top dozen geodetic stations will need to be observing up to 4 days per week. Increased station reliability and unattended operations can improve temporal coverage by VLBI and also allow substantial savings in operating costs. Higher data rate sessions can yield more accurate results, and therefore all geodetic stations must be upgraded to Mk4 or Mk5 capability as soon as possible. More stations need to be equipped with S2 and K4 systems so that global geodetic networks can be designed using these systems. The present level of support at the three Mk4 correlators must be sustained to meet the IVS product goals, and support is needed from the S2 and K4 correlators. The efficiency of the correlators needs to approach a processing factor of unity, i.e. one day processing for one day observing. All correlators must commit to handling the IVS data with priority processing for meeting timely product delivery requirements. Additional recording media

capacity, equivalent to ~100 Mk4 tapes, will be needed to support the higher data rate observing that is necessary for increased accuracy. Alternatively, additional media capacity can be realized by using rapid shipping modes to shorten the tape cycle time.

Analysis: More analysis centers and those using different software packages should participate in the analysis that is required for robust IVS products. The increased amount of VLBI data to be produced under the new observing program will require analysis centers to handle a larger load. Partially automated analysis procedures will help improve the timeliness of product delivery. New IVS products such as EOP rates, a combined TRF solution, and geodynamical parameters should be developed because they can contribute to scientific investigations.

Technology upgrades and improvements: The Mk5 system under development should be deployed as soon as feasible because not only will it enable higher data rate recording but it will also improve station and correlator reliability and efficiency. In addition, new methods for data transmission, including electronic media, should be strongly pursued because higher data rates, automated observing and processing methods will lead to increased accuracy, reliability, timeliness, and efficient use of resources.

Summary

IVS has the capacity to meet the requirements set up by IAG and IAU in the realization of the reference frames and related products. In general, precise time series of the products, with sufficient accuracy (bias free), density, and timeliness must be generated. IVS as a Technique Center of IERS must guarantee the realization of precise celestial and terrestrial reference frames that are consistent over decades.

To meet this guarantee, improvements are required in the availability and reliability of the network stations. Automation for unattended observing will help to overcome the weekend gaps. More capacity is required in data transmission media, which will be solved by the development of a modern disc based recording system (Mk5) and by the ability to transfer data via the Internet (e-VLBI). These new systems will reduce the time delay and dramatically reduce expenses currently needed for tapes and tape drives. The global network configuration has to be improved, especially in the southern hemisphere, and more observing time is required. Encouraging additional related institutions and including the S2 and K4 technologies will also improve the situation. High priority has to be placed on rapid turnaround sessions at the correlator. To avoid backlogs the throughput at the correlators has to be improved. More analysis centers with different software are required to improve the analysis and to increase the robustness of the products.

IVS's primary duty is to provide the best possible results through optimized and efficient coordination of all the resources available. The new product specifications and the new related observing programs should give the basis for cooperation and for contributions by collaborating institutions. Nevertheless, the current IVS situation is highly dependent on only a few institutions and requires the strong, continued support and contributions of those key players.