International VLBI Service for Geodesy and Astrometry (IVS)

https://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Axel Nothnagel (Germany)
Director of the Coordinating Center: Dirk Behrend (USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2015−2019. The IVS Directing Board developed a Strategic Plan for the Period 2016–2025 based on a Retreat held in October 2015. An IVS Outreach and Communications Office was created at the MIT Haystack Observatory at the end of 2018. Axel Nothnagel was re-elected as IVS Chair for a second four-year term. Two VLBI Training Schools were organized. ICRF3 became the new celestial reference frame on 01 January 2019. Work continued to make the VGOS an operational system.

Structure

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, 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; and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

They are realized through seven types of components (Network Stations, Operations Centers, Correlators, Analysis Centers, Data Centers, Technology Development Centers, and the Coordinating Center). The structure of the IVS and the interaction among the various components and external organizations is shown in Figure 1.

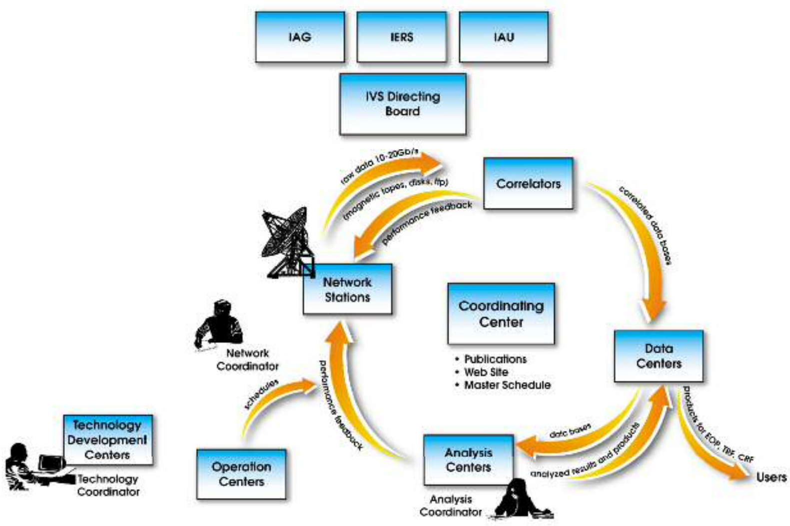

Figure 1. Organizational diagram of the IVS.

Being tasked by IAG and IAU with the provision of timely and highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Activities

Meetings and Organization

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 1 gives an overview of the IVS meetings during the report period.

Table 1. IVS meetings during the report period (2015−2019).

Time	Meeting	Location
7–8 October 2015	IVS Retreat	Penticton, BC, Canada
23–26 November 2015	4th International VLBI Technology Workshop	Auckland, New Zealand
9–12 March 2016	2nd VLBI Training School	Hartebeesthoek, South Africa
13–17 March 2016	9th IVS General Meeting	Johannesburg, South Africa
18 March 2016	17th IVS Analysis Workshop	Johannesburg, South Africa
5–6 October 2016	1st International Workshop on VLBI Observations of Near-field Targets	Bonn, Germany
12–14 October 2016	5th International VLBI Technology Workshop	Westford, MA, USA
30 April – 4 May 2017	9th IVS Technical Operations Workshop	Westford, MA, USA
17 May 2017	18th IVS Analysis Workshop	Gothenburg, Sweden
9–11 October 2017	6th International VLBI Technology Workshop	Bologna, Italy
3–7 June 2018	10th IVS General Meeting	Longyearbyen, Norway
8 June 2018	19th IVS Analysis Workshop	Longyearbyen, Norway
12–15 November 2018	7th International VLBI Technology Workshop	Krabi, Thailand
14–16 March 2019	3rd VLBI Training School	Las Palmas, Spain
20 March 2019	20th IVS Analysis Workshop	Las Palmas, Spain
5–9 May 2019	10th IVS Technical Operations Workshop	Westford, MA, USA

Noteworthy among the list of meetings are the IVS Retreat and the two VLBI Training Schools. At the retreat, the IVS Directing Board plus six invited guests discussed the current and future challenges of developing the IVS to meet the needs and take advantage of the opportunities of the next decade. In a series of SWOT analyses (Strength, Weaknesses, Opportunities, and Threats) the current state was evaluated. It was concluded that the relationships of the IVS with some of the space agencies, research institutions and surveying and mapping agencies should be improved. A business plan was discussed indicating that if the IVS were to be established from scratch it would cost an initial investment of $200 million for a network of 30 observatories plus $70 million per year operating costs for daily UT1−UTC determinations. The findings of the retreat were used as the basis for preparing the Strategic Plan of the IVS for the Period 2016–2025 (see below).

The 2nd and 3rd VLBI Training Schools were organized at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa and at the Universidad de Las Palmas de Gran Canaria in Spain, respectively. The purpose of the Schools was to help prepare the next generation of researchers to understand VLBI systems and inspire them in their future careers. Both events attracted some 50 participants from all over the world. The South African School included a large group of students from different countries in Africa with the aim to develop expertise in geodesy and especially VLBI as part of an effort to build new stations in Africa and integrate them into the global VLBI network.

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Board members are listed in Table 2.

Table 2. Members of the IVS Directing Board during the report period (2015−2019).

a) ***Current Board members (May 2019)***

Directing Board Member	Institution, Country	Functions	Recent Term
James Anderson	GFZ Potsdam	Analysis and Data Centers Representative	Feb 2019 − Feb 2023
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
Francisco Colomer	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2017 − Feb 2021
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	IERS Representative	—
Hayo Hase	BKG & AGGO, Argentina	Networks Representative	Feb 2019 − Feb 2023
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Nancy Kotary	Haystack Observatory, USA	Office for Outreach and Communications	—
Laura La Porta	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2019 − Feb 2023
Jinling Li	Shanghai Astronomical Observatory, China	At Large Member	Feb 2019 − Feb 2021
Evgeny Nosov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2019 − Feb 2021
Axel Nothnagel	IGG, University of Bonn, Germany	Analysis and Data Centers Representative, Chair	Feb 2017 − Feb 2021
Chet Ruszczyk	Haystack Observatory, USA	Technology Development Centers Representative	Feb 2019 − Feb 2023
Oleg Titov	Geoscience Australia, Australia	IAG Representative	—
Gino Tuccari	IRA/INAF, Italy	Technology Coordinator	—
Alet de Witt	Hartebeesthoek Radio Astronomy Observatory, South Africa	At Large Member	Feb 2019 − Feb 2021

b) *Previous Board members in 2015−2019*			
Alessandra Bertarini	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2015 − Sep 2017
Ludwig Combrinck	Hartebeesthoek Radio Astronomy Observatory, South Africa	IAG Representative	—
Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2013 − Feb 2017
David Hall	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Sep 2017 − Feb 2019
Thomas Hobiger	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2017 − Feb 2019
Alexander Ipatov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2015 − Feb 2017
Ryoji Kawabata	Geospatial Information Authority, Japan	At Large Member	Feb 2015 − Feb 2017
Jim Lovell	University of Tasmania, Hobart, Australia	Networks Representative	Feb 2013 − Feb 2017
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2015 − Feb 2019
Bill Petrachenko	Natural Resources Canada	Technology Coordinator	—
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 − Feb 2019
Takahiro Wakasugi	Geospatial Information Authority, Japan	At Large Member	Feb 2017 − Feb 2019
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2017 − Feb 2019

During the report period two Directing Board elections were held. Following the elections from December 2016 to February 2017, the Board re-elected Axel Nothnagel of the University of Bonn for a second four-year term as chair of the IVS (until spring 2021). In March 2016, Gino Tuccari of the Italian Istituto di Radioastronomia (IRA/INAF) took over the position of IVS Technology Coordinator from Bill Petrachenko of Natural Resources Canada.

Following a call for proposals in July 2018, the Board approved the creation of an IVS Office for Outreach and Communications (OOC) at the MIT Haystack Observatory (lead: Nancy Kotary) at the end of 2018. The OOC will promote awareness and understanding of geodesy's unique and vital role in science and society to the larger scientific community, decision makers, and the general public. Activities will include the creation of a dedicated Web site, of social media accounts, and of extensive educational materials. It is anticipated that the OOC will improve collaboration across institutions, sponsor organizations, and scientific associations on education and outreach work.

IVS Strategic Plan for the Period 2016–2025

Based on the discussions at the IVS Retreat, the IVS Directing Board developed a Strategic Plan for the Period 2016–2025. The main goal is to provide overall planning guidelines and to give the stakeholders and IVS Associates reasonable indications for the investments and activities needed. In the period 2016 to 2025 the IVS will enter the era of the VLBI Global Observing System (VGOS), which will be composed of a transition period and subsequent full VGOS operations.

The strategic plan was developed on the basis of the current composition and framework of the IVS' operations. The IVS acts as a truly international entity consisting of hardware distributed all over the world, a global organizational structure, and the associated personnel for organizing and administering the IVS. The IVS is not a formal global institution but a collaboration, which operates on a best-effort basis. The full potential of geodetic and astrometric VLBI can only be exploited if baselines beyond a length of about 6000 km are employed for Earth orientation parameter (EOP) and celestial reference frame (CRF) determinations. The same also applies to any terrestrial reference frame (TRF) application. Because of this it would be difficult for the IVS to be replaced by a single country running its own VLBI network, operating its own telescopes, correlating and analyzing the results, and producing the final VLBI products. The IVS is essential for the monitoring of the Earth orientation parameters and for the maintenance of the celestial and terrestrial reference frames. However, the IVS is little known for its products beyond the geodetic and astrometric communities. For this reason, the organizational relationships of the IVS, external as well as internal, and the administration of the IVS must be developed further. In this context the IVS may benefit from the GGOS and UN-GGIM initiatives (Global Geodetic Observing System, UN-Global Geospatial Information Management), which will help to raise awareness in political circles of the needs for geodetic products.

Another challenge of the future is that many experienced colleagues have reached or are close to retirement age. Hence, an active recruiting and staff structure development is needed to replace them. An increased awareness of this issue is needed within the IVS components up to the highest level of their administrations.

On the product side, several separate requirements compete: accuracy, resolution, and timeliness. These need to be balanced for an optimum satisfaction of the product users. There may arise conflicts between what is actually feasible given the current economic and organizational circumstances and the users' desires for higher accuracy, resolution, and timeliness.

Working Groups

Working Group 7 on Satellite Observations with VLBI. This WG was established by the IVS Directing Board in May 2015. WG7 studies possibilities to observe Earth satellites with the VLBI ground network affiliated with the IVS. In particular the development of corresponding observing schedules, of the necessary technology at the observing stations, data correlation, and data analysis are looked into. Experts from the various fields, who are able to perform one or more of the different tasks, were brought together to enable observations of Earth satellites by VLBI.

Working Group 8 on Galactic Aberration. This WG was established by the IVS Directing Board in October 2015. WG8 investigated the issues related to incorporating the effect of galactic aberration in the analysis of the IVS. The aberration effect is not negligible in terms of future microarcsecond astrometry. The WG prepared a final report, recommending a galactic aberration model, and was then officially closed in March 2019. The recommended value of the aberration constant is $A_G = 5.8 \pm 0.3$ µas/yr.

Observing Program and Special Campaigns

Observing Program

The observing program for 2015–2019 with the legacy S/X system (production system) included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 9–12 stations, depending on station availability. These networks were designed with the goal of having comparable x_p and y_p 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, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Tsukuba (Japan).
- TRF: Bi-monthly TRF sessions with 14–18 stations using all stations at least two times per year.
- CRF: Bi-monthly sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus 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.
- Triennial ~two-week continuous VLBI observing campaigns to produce continuous VLBI time series and to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy. During the report period the continuous campaign CONT17 was organized (see below).

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. On average, a total of about 1650 station days per year were used in around 200 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

With the VGOS broadband system (future system under development to be operational in the early 2020ies) a network of 3–7 stations observed a VGOS Test (VT) session roughly every other week for about 26 sessions per year. While in 2015 and early 2016 the lengths of the sessions were limited to one, two, or six hours, from mid-2016 onward the test sessions were extended to the full 24-hour duration. The test sessions were used to shake out problems with the new system and establish standard operational procedures. From 2019 onward, the results of the VT sessions are made available through the IVS Data Centers for general analysis. The network size is typically six stations; the network size is expected to grow gradually to 10–12 stations in the later part of 2019 and in 2020.

CONT17

The IVS organized a continuous VLBI campaign (CONT17) during the period from November 28 to December 12, 2017. The campaign consisted of three separate networks: two legacy S/X networks observing for 15 consecutive days and one VGOS broadband network observing for five consecutive days in the middle of the CONT17 period. The use of the two legacy networks allows to study the accuracy of VLBI estimates of EOP and to investigate possible network biases. A special issue on CONT17 is planned to be published in Journal of Geodesy.

Analysis

ITRF2014

In 2013, the IERS requested the geometric services (IDS, IGS, ILRS, and IVS) to contribute to the determination of the next International Terrestrial Reference Frame (ITRF). Initially it was anticipated to include data through 31 December 2013, with the various techniques providing their solutions in early 2014. Then the data coverage period was changed to include all available data through 2014, with a firm deadline for submissions to the IERS of 28 February 2015. Ten IVS Analysis Centers submitted solutions to the IVS Combination Center. The software and the number of ACs using it are, in order of popularity: (a) Calc/Solve (five), (b) VieVS (two), (c) Geosat (one), (d) Occam (one), and (e) Quasar (one). For the first time, all analysis centers applied thermal expansion modeling for the majority of telescopes involved. The IVS Combination Center compared the input from the various ACs and produced a combined solution for use by the IERS Combination Centers (DGFI, IGN, and JPL). In the process of comparing the input from different ACs numerous issues were uncovered, most of which were subsequently fixed. Two of the submissions had such serious problems that they were not used in the IVS combination solution.

ITRF2014 differs from previous ITRFs in that it includes models for post-seismic deformation (PSD) at sites that had earthquakes. These models were derived by using data from GPS receivers located at these sites. Previously, PSD was handled on an ad-hoc basis by different VLBI analysis packages. For example, Calc/Solve estimated splines for sites. Several IVS ACs compared the use of ITRF2014 vs. ITRF2008, and the general consensus was that ITRF2014 was a better a priori model.

In December 2016, the IERS Directing Board requested that the geometric services begin using ITRF2014 in their analysis as soon as possible. In order to have a smooth transition the IVS Analysis Coordinator requested that the IVS ACs submit two sets of SINEX files: one using ITRF2008 and the other ITRF2014 until a sufficient number of ACs had made the transition. GSFC began doing so in October 2016, and GFZ in January 2017. Several ACs indicated that they would switch over to ITRF2014 in the beginning of 2017.

ICRF3

Several IVS Analysis Centers (ACs) in cooperation with the International Astronomical Union (IAU) Working Group on the third realization of the International Celestial Reference Frame (ICRF3) prepared CRF solutions as input to ICRF3. The new frame was adopted at the IAU General Assembly in Vienna, Austria on August 30, 2018 under Resolution B2. ICRF3 contains positions of more than 4000 extragalactic radio sources at three frequencies and became the Fundamental Astrometric Reference Frame on 01 January 2019.

Transition to Multi-tone Phase Calibration

In VLBI measurements the measured delays are corrupted by unknown and unstable phase shifts in the signal as it travels down the signal path from the front end to the sampler. Many of these effects can be removed through the use of phase calibration. The most common approach is to inject a calibration signal near the front of the signal chain. The calibration signal consisting of a set of tones (‘phase-cal tones’) equally spaced in frequency and derived from the station frequency standard. These signals are extracted during the correlation process and used to adjust the phases prior to fringe-fitting. Since the spurious phase shifts are frequency dependent, each frequency channel is calibrated independently. Historically, only a single phase-cal tone was used in each frequency channel.

Due to the ever-broader channel bandwidth and advances in correlator software, for the past several years the correlators have been able to use multiple phase-cal tones in each channel. This latter approach is called multi-tone phase-cal. Naively, the use of multiple phase-cal tones should reduce the noise. A verification by correlating the CONT14 data set with both multi-tone and single-tone phase calibration revealed that multi-tone was generally slightly better than single-tone. On average, the multi-tone sessions had ~1% more observations. The session fit was slightly better, again on the ~1% level, indicating that the data within a session was less noisy and more consistent. Lastly, the RMS baseline scatter across all of the CONT14 sessions was generally lower. All of these are arguments for using multi-tone phase-cal. However, it also turned out that for Zelenchukskaya there was a difference of 8 mm in the vertical position (3-sigma level) depending on whether you used multi-tone or single-tone phase-cal. There are differences for other stations, but none of these are greater than 1-sigma. These issues were discussed publicly within the IVS at a few occasions (e.g., IVS Analysis Workshop in Ponta Delgada, a special meeting devoted to this subject held at MIT Haystack Observatory in October 2016). Following a recommendation coming out of these discussions, the IVS Directing Board decided to switch over to multi-toned phase-cal for all sessions observed on or after 1 January 2017. It is expected that this will yield an improvement in the quality of the data; but it may also introduce a discontinuity in some station positions.

Gravitational Deformations of Radio Telescopes

With the advent of powerful and affordable terrestrial laser scanners (TLS), the issue of path delay variations and position changes due to gravitational deformations of the radio telescopes surfaced again around the year 2010. From these investigations, it became clear that gravitational deformations have a direct effect on the delay observables. As a consequence, these delay effects then change the vertical position of the telescope in a global frame by several millimeters. Within the reporting period, a few more telescopes were investigated by TLS measurements and subsequent data analysis. From these, empirical correction models were developed, which can now be applied in VLBI data analysis. For a full positive impact on the scale of the ITRF, more telescopes need to be measured and modeled. The IVS has called for increased endeavors in this respect. However, this is costly and sophisticated work which will need considerable time and efforts.

Technology Development

The main focus of the IVS technology development was placed on the build-out of the next-generation VLBI system (VLBI Global Observing System, VGOS) network and achieving operational readiness with the various installations of the signal chain realizations. Over the next several years a number of new VGOS stations will come online. Operational readiness for the existing VGOS stations was worked on in a series of test sessions of initially 1-, 2-, and 6-hour lengths in 2015/16 and then extended to 24-hour sessions from the second half of 2016 onward. These tests uncovered a number of smaller and larger issues of high-level, low-level, and transient nature that were successively ironed out or identified and actively being worked on. Since 01 January 2019 the currently available six-station VGOS network was operating in a stable way, so that the session results could be made available on the IVS Data Center for general use. Aside from increasing the VGOS network size in the next couple of years, the focus of the VGOS effort will be on the data transport and correlation parts of the processing chain. Here the use of cloud services and distributed correlation to deal with the large amount of data are aspects that will be investigated.

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