International VLBI Service for Geodesy and Astrometry (IVS)

http://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 2011−2015. During a retreat in September 2011, the IVS Terms of Reference were modernized and the IVS Directing Board expanded by a second Analysis Representative to altogether 16 members. Two Directing Board elections were held, one from December 2012 to January 2013 and the other from December 2014 to January 2015. Axel Nothnagel succeeded Harald Schuh as the IVS Chair in February 2013. The first VLBI Training School was organized in March 2013; future training schools will be held in a three-year rhythm. The next-generation VLBI system was further developed and was named the VLBI Global Observing System (VGOS). The transition from the legacy S/X system to the VGOS broadband system will be undertaken in the next five years.

Activities

Introduction

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.

The VLBI technique has been employed in geodesy for more than 40 years. Science and applications set the requirements for the realization and maintenance of global reference frames at VLBI's technical limitations. Covering intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art and providing numerous quasar positions as the best approach to an inertial reference frame, VLBI significantly contributed to the tremendous progress made in geodesy over the last decades. VLBI was a primary tool for understanding the global phenomena changing the "Solid Earth". Today VLBI continuously monitors Earth orientation parameters as well as crustal movements in order to maintain global reference frames, coordinated within 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.

Organization and Meetings

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.

Taking effect in January 2013, Bill Petrachenko of Natural Resources Canada took over the position of the IVS Technology Coordinator from Alan Whitney. After 13 years of service, Axel Nothnagel handed over the responsibilities of the IVS Analysis Coordinator to John Gipson of NVI, Inc./NASA Goddard Space Flight Center on March 8, 2013.

The IVS held Directing Board elections for four representative and three at-large positions in Dec2012/Jan2013. The new sixteen Directing Board members elected Axel Nothnagel of the University of Bonn as the successor to Harald Schuh as chair of the IVS for the next four years (until spring 2017).

Table 1. Members of the IVS Directing Board during the report period (2011−2015).

a) ***Current Board members (May 2015)***			
Directing Board Member	**Institution, Country**	**Functions**	**Recent Term**
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Alessandra Bertarini	IGG, University of Bonn, Germany	Correlators and Operation Centers Representative	Feb 2015 − Feb 2019
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2013 − Feb 2017
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
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
Axel Nothnagel	IGG, University of Bonn, Germany	Analysis and Data Centers Representative, Chair	Feb 2013 − Feb 2017
Bill Petrachenko	Natural Resources Canada	Technology Coordinator	—
Torben Schüler	BKG, Germany	Networks Representative	Feb 2015 − Feb 2019
Harald Schuh	GFZ Potsdam, Germany	IAG Representative	—
Guangli Wang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2015 − Feb 2017

b) ***Previous Board members in 2011−2015***			
Jesús Gómez González	National Geographical Institute, Spain	At Large Member	Feb 2011 − Feb 2013
Hayo Hase	BKG, Germany; TIGO, Chile	Networks Representative	Feb 2011 − Feb 2015
Shinobu Kurihara	Geospatial Information Authority, Japan	At Large Member	Feb 2013 − Feb 2015
Fengchun Shu	Shanghai Astronomical Observatory, China	At Large Member	Feb 2013 − Feb 2015
Oleg Titov	Geoscience Australia	Analysis and Data Centers Representative	Feb 2009 − Feb 2013
Gino Tuccari	IRA/INAF, Italy	Networks Representative	Feb 2009 − Feb 2013
Alan Whitney	Haystack Observatory, USA	Technology Coordinator	—

In January 2013 Bill Petrachenko of Natural Resources Canada became the new IVS Technology Coordinator (succeeding Alan Whitney of MIT Haystack Observatory) and in March 2013 John Gipson of NVI, Inc./NASA Goddard Space Flight Center became the new IVS Analysis Coordinator (succeeding Axel Nothnagel).

From 21–22 September 2011, the IVS Directing Board (plus a few invited guests) held a retreat at Hohe Wand, Austria. The main goals of the retreat were a review of the IVS organization and its mandate, functions, and components as well as the definition of focus areas for future IVS work and activities. The retreat participants agreed that the IVS organization, mandate, and functions as outlined in the IVS Terms of Reference (ToR) continued to fulfill the requirements of the global geodetic/astrometric VLBI science and associated user communities. The ToR were revised to simplify and modernize the wording, to add the Global Geodetic Observing System (GGOS), and to increase the Board by the addition of a second Analysis Center representative. The revised ToR were approved by the Board in the subsequent Board meeting and then officially ratified by the IAG in December. The revised ToR can be found, for instance, on the IVS Web site at the URL http://ivscc.gsfc.nasa.gov/about/org/documents/ivsTOR.html. In terms of focus areas, the retreat participants felt that emphasis should be put on improving quality control, internal and external outreach, VLBI2010 infrastructure, real-time observation and product creation (including automation), and expanding research and research fields.

Table 2. IVS meetings during the report period (2011–2015).

Time	**Meeting**	**Location**
31 March 2011	12th IVS Analysis Workshop	Bonn, Germany
9–12 May 2011	6th IVS Technical Operations Workshop	Westford, MA, USA
13–16 November 2011	10th International e-VLBI Workshop	Broederstroom, South Africa
1–2 March 2012	VLBI2010 Workshop on Technical Specifications (TecSpec)	Bad Kötzting, Germany
4–9 March 2012	7th IVS General Meeting	Madrid, Spain
8 March 2012	13th IVS Analysis Workshop	Madrid, Spain
22–24 October 2012	1st International VLBI Technology Workshop	Westford, MA, USA
2–5 March 2013	VLBI Training School	Espoo, Finland
5 March 2013	14th IVS Analysis Workshop	Espoo, Finland
6–9 May 2013	7th IVS Technical Operations Workshop	Westford, MA, USA

10–12 October 2013	2nd International VLBI Technology Workshop	Seogwipo, Jeju Island, South Korea
2–7 March 2014	8th IVS General Meeting	Shanghai, China
7 March 2014	15th IVS Analysis Workshop	Shanghai, China
10–13 October 2014	3rd International VLBI Technology Workshop	Groningen, The Netherlands
4–7 May 2015	8th IVS Technical Operations Workshop	Westford, MA, USA
21 May 2015	16th IVS Analysis Workshop	Ponta Delgada, Azores, Portugal

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and VGOS technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 2 gives an overview of the IVS meetings during the report period.

The VLBI2010 Workshop on Technical Specifications (TecSpec), which was tailored towards the station side of VLBI2010 (now called VGOS, see below) and thus focused almost exclusively on the station specifications and hardware, covered items from fast-slewing antennas to wideband feeds and front-ends to back-ends and recorders. Additional topics included e-transfer and e-VLBI, monitor and control, as well as clock distribution. The TecSpec workshop attracted almost 100 people, testament to the very high interest in the new VLBI system. At the 7th IVS General Meeting (GM2012), a new acronym for the next generation VLBI network was introduced. From March 2012 onward the new system is called "**VGOS**" (VLBI Global Observing System).

The VLBI Training School in Espoo, Finland was the first training school organized by the IVS (through Working Group 6). Following its success, it is planned to organize such schools in a three-year rhythm (the next VLBI Training School is scheduled for March 2016 in South Africa). Over a period of four days, about 50 participants were schooled in all aspects of the VLBI technique. The school was very effective in training young researchers in the VLBI technique thus paving the way to preparing the next generation of VLBI experts in parallel to the development of the next-generation VLBI system

Working Groups

VLBI Data Structures. The Working Group 4 on VLBI Data Structures examined the data structure currently used in VLBI data processing and investigated what data structure would likely be needed in the future. Over several years the WG designed a new VLBI data structure based on the NetCDF data storage format. The resulting vgosDB format meets current and anticipated future requirements for individual VLBI sessions including a cataloguing, archiving, and distribution system. The WG prepared a final report, which is included in the 2013 Annual Report.

Space Science Applications. The Working Group 5 on Space Science Applications investigated synergies between the IVS and VLBI space science applications and looked into perspectives of future missions and the potential involvement of the IVS. The activities of the IVS in this field are not limited to providing the observations and initial data processing but also contain scientific data analysis and interpretation. The WG submitted a final report, which is posted on the IVS Web site.

VLBI Education. The Working Group 6 on VLBI Education organized a VLBI Training School (see above), compiled educational material, and established contacts to education institutions. Given the success of the WG work, the Directing Board approved the establishment of a permanent body within the IVS by creating the Committee on VLBI Education and Training.

Observing Program and Special Campaigns

Observing Program

The observing program for 2011–2015 included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 8 stations, some with 9 or 10 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 14–16 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 two such campaigns were observed (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. Sessions in the observing program that were recorded and correlated using K5 technology had the same accuracy and timeliness goals as those using Mark 5. On average, a total of about 1400 station days per year were used in around 180 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

CONT11

In September 2011, a 15-day continuous VLBI observation campaign called CONT11 was observed. The observing network consisted of thirteen IVS stations (see Figure 1). The actual observing was done at a rate of 512 Mbps on the basis of UT days with each CONT11 day running from 0 UT to 24 UT. UT-day observing is needed to facilitate the most accurate combination and comparison with results from other techniques. Among many possible studies, the data will be used for high-resolution Earth rotation studies, investigations of reference frame stability, and investigations of daily to sub-daily site motions. For the duration of the CONT11 campaign an ultra-rapid dUT1 determination was performed on the baseline Onsala–Tsukuba. Near real-time correlation and analysis was performed using a sliding window in the analysis with the analysis software C5++. dUT1 estimates were obtained with very low latency during the ongoing CONT11 campaign and displayed on a dedicated Web page.

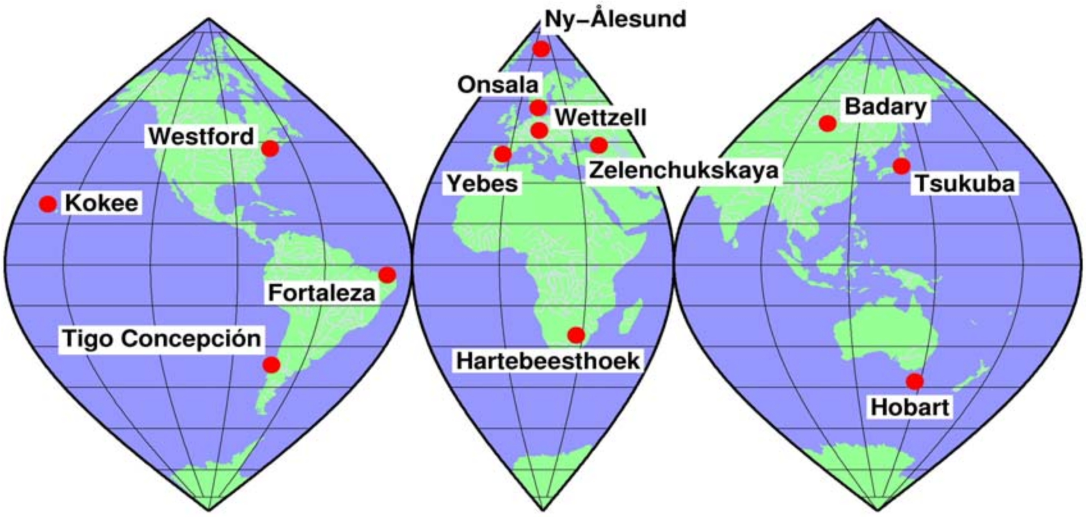

Figure 1. Geographical distribution of the thirteen IVS stations that participated in the CONT11 campaign in September 2011.

CONT14

The Continuous VLBI Campaign 2014 (CONT14) was successfully observed in early May 2014. Seventeen IVS stations at sixteen sites (see Figure 2) observed for fifteen consecutive days at a rate of 512 Mbps from 6–20 May 2014. The observing was again done on the basis of UT days. About half of the raw VLBI data was electronically transferred (e-transferred) to the target correlator. All CONT14 data were correlated at the Bonn Correlator, easing the logistics involved with module handling at the correlators and the stations as well as ensuring the creation of a homogeneous data set.

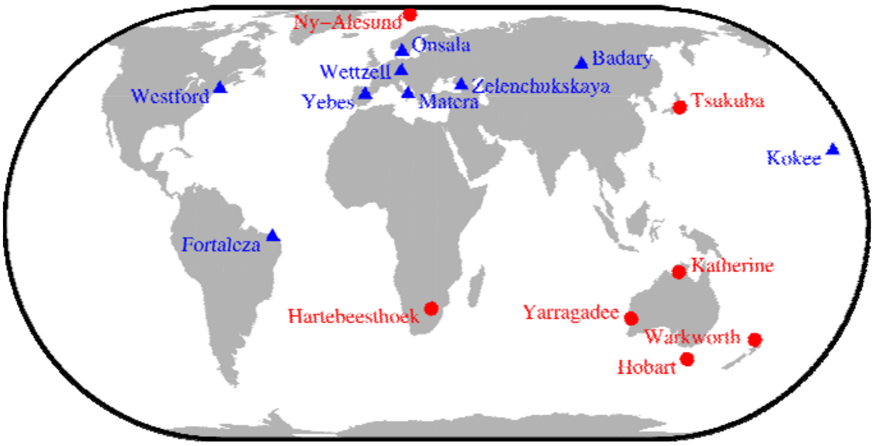

Figure 2. Geographical distribution of the sixteen CONT14 sites. The sites in red (circles) mostly e-transferred their data to the correlator, whereas the blue sites (triangles) physically shipped their recording modules.

Analysis

Earth Orientation Parameters.

The VLBI observables, mostly group delays, as produced by the IVS Correlating Centers are routinely analyzed by six to eight IVS Analysis Centers (AC) following the IERS Conventions 2010 (Petit and Luzum 2010) and individual processing strategies. Subsequently, the official IVS EOP product is generated by a combination process of the individual AC results. During the reporting period, the operational combination was carried out by the IVS Combination Center at the German Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt a.M. The input for the combination work were datum-free (constraint-free) normal equation systems in SINEX format (Solution INdependent EXchange format) containing elements for radio source positions, Earth orientation parameters, and radio telescope coordinates. Two primary combined EOP results were produced: rapid combination solutions and quarterly combination solutions. The rapid solutions were updated twice a week and contained only the IVS-R1 and IVS-R4 sessions; new data points were added as soon as the SINEX files of at least four IVS Analysis Centers were available. The long-term series were generated on a quarterly basis and included all 24-hour sessions since 1984. The quarterly series included long-term EOP series, station positions, and velocities. The results of the combination process were uploaded to the IVS Data Centers. The combined rapid EOP series, as well as the results of the quality control of the Analysis Center results, were also available directly at the BKG/DGFI Combination Center Web page (http://ccivs.bkg.bund.de/) or via the IVS Analysis Coordinator Web site (http://lupus.gsfc.nasa.gov/IVS-AC_products.htm). The inclusion of new Analysis Centers continued, a newly designed Web page was brought online, and the Web-based analysis tools were further enhanced.

Atmospheric Gradient Modeling

At the 13th IVS Analysis Workshop it was decided that the Chen and Herring model (1997) should be the conventional model of the IVS, using the constant C = 0.0031 for estimating the hydrostatic gradient. Since the hydrostatic contribution is the biggest one and the coefficient for the total gradient contribution is only slightly different (C = 0.0032), no noticeable effect on the estimates is expected. The MacMillan model (1995) produces essentially the same results, but for consistency with the analyses of the IGS, the Chen and Herring model was adopted.

Technology Development

The main focus of IVS technology development has been to achieve operational readiness for broadband observing as part of the VLBI Global Observing System (VGOS). This includes not only the development and proliferation of broadband systems but also the development of software and processes to enable efficient, and eventually automatic, operation of the VGOS stations and correlators. Already, a number of fully compliant (or nearly compliant) VGOS antennas have been constructed (many of these having already achieved first light and first fringes) with several more expected to come on line soon. The challenge is to ensure that signal chains are available for these antennas; that operating modes of the various systems are VGOS compliant, interoperable, and sufficiently robust against radio frequency interference from mobile phone transmitters and the like; and that systems can be controlled and thoroughly monitored remotely.

Automation and remote control are very important aspects of VGOS. With the expectation of 24/7 operations and a sharp rise in the number of observations per day, it is necessary (in order to keep operating costs at a reasonable level) to make all processes (including schedule generation, station operation, correlation, fringe processing, and analysis) as automated as possible. A necessary step to achieve automation and remote control is to have a language to concisely and completely describe the instrumentation, operating modes and schedule for a session. This has been the role of the VEX language over the past decades. However, with the advent of VGOS and the new broadband systems, instrumentation and operating modes, which had not been conceived of when the original version of VEX was developed, now need to be handled. As a result, over the past few years, a new version of VEX, called VEX2, has been developed. VEX2 was completed this year; it went through a brief period of community consultation; and it is now being used to write software to control instrumentation and processes in the complete VGOS operational chain.

Table 3. Progress in the build-out of the VGOS network as of early 2015.

Station	**Recent milestone**	**Broadband readiness**
GGAO	Test observations	now on fast RT
Westford	Test observations	now on legacy RT
Wettzell	Receiver tests	early 2015
Yebes	First fringes on X-band	late 2015
Noto	Receiver under construction	end 2015 on legacy RT
Ishioka	First fringes	end 2016 (initial S/X/Ka)
Santa Maria	RT constructed at site	2016
Badary	RT constructed at site	2015 (S/X/Ka)
Zelenchukskaya	RT constructed at site	2015 (S/X/Ka)
Kokee Park	RT being assembled at factory	2016
AuScope	Funding for upgrade secured	2016 on fast RTs
Tenerife	RT assembled at factory	2017
Ny Ålesund	Civil construction underway	2018

Successful 24-hour test of VGOS Broadband Delay System

On May 21, 2013, the first 24-hour session using the VGOS broadband delay system was observed on the GGAO12M–Westford baseline. The antennas, RDBE digital backends, and Mark-5C recorders were all operated under Field System control. The VGOS-ready 12-meter GGAO antenna and the 18-meter Westford antenna were each equipped with a cooled QRFH feed tailored to the specific antenna optics, followed by two cooled low noise amplifiers, one for each polarization. With a minimum scan length of 30 seconds and the minimum SNR set to 15 per band-polarization, the schedule achieved 48 scans per hour. Four 512-MHz-bands spanning 3.2 to 8.8 GHz within the available 2–12 GHz range were recorded at 2 Gbps (1 Gbps for each linear polarization) for a total of 37 Terabytes per station. Over 99% of the scans yielded good correlation.

Transition to VGOS Broadband Operations

The VGOS Project Executive Group (VPEG) developed an observing plan to guide the transition from current S/X to future VGOS broadband operations. The plan spans five years. It begins with a series of test campaigns in 2016 with as many as eight sites expected to participate. IVS technology development over the next year focuses on ensuring that systems and processes are ready for the test campaigns. Each campaign introduces a different aspect of the new VGOS mode of operation so that by 2017 the IVS will be ready to begin the VGOS pilot project. All campaigns will be roughly six weeks in duration to exercise the full “schedule to final products” operational chain in a sustained format. The Observing Plan focuses on the station aspect of the VGOS implementation. Further details were added in the Data Transmission and Correlation Plan. Currently work is actively done on an Analysis Plan.

In support and preparation of the test campaigns, a series of bi-weekly VGOS sessions have been initiated at the start of 2015 between Westford and GGAO, the goal being to establish a fully operational VGOS methodology. To support this, a so-called “parallel universe” has been put in place at Goddard that completely imitates the Master Schedules, ops mailing list, etc that have been used for years for the legacy S/X-band operations. In addition, processes are being put in place to automate as much as possible the full operational chain from schedule generation to analysis. The importance of this effort cannot be overemphasized in the quest to move from a VGOS test footing to a full VGOS operational capability.

DiFX Software Correlator for Geodetic VLBI

The so-called DiFX software correlator was originally developed at Swinburne University in Australia by Adam Deller, primarily for astronomical VLBI use. The development of an economical and powerful software correlator, a dream less than a decade ago, has been made possible by the relentless march of Moore’s Law to provide powerful inexpensive clustered PCs with high-speed data interconnections that can distribute and correlate VLBI data in an efficient manner. Several institutions that support geodetic VLBI correlation processing now have DiFX correlators (Max Planck Institute for Radio Astronomy [Bonn, Germany], U.S. Naval Observatory [Washington D.C., USA], and Haystack Observatory [Westford, MA, USA]) and have been working to augment the core DiFX software to meet the needs of geodetic VLBI. This includes the integration of much of the Mark IV post-correlation software involving data-management, output data formats, fringe finding and delay estimates, and editing/quality-assurance software. In addition, a substantial amount of work has been done to support the VDIF data-input format and to support correlation of mismatched sample rates and recording bandwidths.

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