3.4.3 International VLBI Service for Geodesy and Astrometry (IVS)

IVS Organization and Activities

During 2016, the IVS continued to fulfill its role as a service within the IAG and IAU by providing necessary products for the maintenance of global reference frames: TRF, CRF, and EOP. Some highlights of the IVS organization and activities were:

- Based on discussions at the 2015 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 IVS published three IVS Newsletters in April, August and December, keeping the community informed about IVS activities. In the fall of 2016 the Proceedings volume of the 9th IVS General Meeting was published.

- The 2nd VLBI Training School was organized at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa. The purpose of the School was to help prepare the next generation of researchers to understand VLBI systems and inspire them in their future careers. A large group of attendees included 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.

Table 1: IVS meetings in 2016.

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<thead>
<tr>
<th>Event</th>
<th>Location</th>
<th>Date</th>
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<tr>
<td>2nd VLBI Training School</td>
<td>Hartbeesthoek, South Africa (ZA)</td>
<td>March 9–12, 2016</td>
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<td>9th IVS General Meeting</td>
<td>Johannesburg, ZA</td>
<td>March 13–17, 2016</td>
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<td>17th IVS Analysis Workshop</td>
<td>Johannesburg, ZA</td>
<td>March 18, 2016</td>
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<td>35th IVS Directing Board meeting</td>
<td>Johannesburg, ZA</td>
<td>March 19, 2016</td>
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<td>1st International Workshop on VLBI Observations of Near-field Targets</td>
<td>Bonn, Germany</td>
<td>October 5–6, 2016</td>
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<td>5th International VLBI Technology Workshop</td>
<td>Westford, MA, USA</td>
<td>October 12–14, 2016</td>
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<td>36th IVS Directing Board meeting</td>
<td>Westford, MA, USA</td>
<td>October 15, 2016</td>
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Network Stations and observing sessions

A total of 190 geodetic/astrometric 24-hour sessions were observed during the year 2016. The number of observing sessions coordinated by IVS was about \(\sim 3.6\) days per week, which is about the same level of observing as for the year 2013. The increased number of sessions for the observing years 2014 and 2015 (\(\sim 4.7\) days/week and \(\sim 4.5\) days/week) was mostly due to the high number of regional AUSTRAL sessions in that time period; because of budget constraints this is back to pre-2014 numbers. However, there was an increase of about 8% in the number of station days from 2013 to 2016. As the number of stations was more or less constant, this increase can mostly be attributed to the stations providing more observing days, that is on average the observing networks were larger in 2016. The major observing programs during 2016 were:

**IVS-R1, IVS-R4**
Weekly (Mondays and Thursdays) 24-hour, rapid turnaround measurements of EOP. Databases were available no later than 15 days after each session. The NASA Goddard Space Flight Center (R1) and the U.S. Naval Observatory (R4) coordinated these sessions.

**Intensive**
Daily 1-hour UT1 Intensive measurements were made 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-Alesund (Norway), and Tsukuba (Japan).

**IVS-T2**
Bi-monthly sessions coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, Germany, with 16–18 stations per session. Seven of these sessions were observed to monitor the TRF with all IVS stations.

**IVS-CRF**
The Celestial Reference Frame (CRF) sessions, coordinated by the U.S. Naval Observatory, provide astrometric observations that are required for improving the current CRF and for extending the CRF by observing ‘new’ sources. Twelve sessions were observed for the maintenance of the CRF in 2016.

**VLBA**
The Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory (NRAO) and, since October 2016, by the Long Baseline Observatory (LBO), allocated six observing days for astrometry/geodesy. These sessions included the 10 VLBA stations plus up to 5 geodetic stations, providing state-of-the-art astrometry as well as information for mapping ICRF sources.
Europe  The European geodetic network, coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, continued with six sessions in 2016.

IVS-OHIG  The purpose of the IVS-OHIG (Southern Terrestrial Reference Frame) sessions is to tie together optimally the sites in the southern hemisphere. In 2016 six OHIG sessions were observed.

APSG  The Asia-Pacific Space Geodynamics (APSG) program operated two sessions in 2016.

AUSTRAL  In 2016, 21 Austral sessions were observed. The purpose is to determine the station coordinates and their evolution in the Australia (AuScope) and New Zealand geodetic VLBI network.

AOV  The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) had 6 sessions during 2016.

IVS-R&D  Thirteen research and development sessions were observed in 2016. The goals of the 2016 R&D sessions included the observation of link sources between Gaia and the ICRF2, the improvement of the scheduling technique of the Intensives and the observation of the Chang’E-3 lander with VLBI.

Correlators  The correlator at Haystack Observatory (USA), the correlator at the U.S. Naval Observatory in Washington (USA), the BKG/MPIfR correlator at the Max Planck Institute for Radio Astronomy in Bonn (Germany), the correlator at the Shanghai Astronomical Observatory (China), and the correlator at the Geospatial Information Authority of Japan (GSI) in Tsukuba efficiently processed the data recorded for the IVS. The majority of the 24-hour sessions were processed by the Bonn and Washington correlators. Both correlators used the DiFX software correlator; while the Bonn correlator processed the R1, EURO, T2, Int3, and OHIG sessions, the Washington correlator was responsible for the R4, Int1, and CRF deep south sessions. The Shanghai correlator analyzed CRF, APSG, and AOV sessions. The Haystack correlator processed R&D sessions and some T2 sessions. The Int2 sessions were processed at the Tsukuba correlator.

Data Centers  The IVS Data Centers continued to receive databases throughout the year and made them available for analysis within one day of correlation. The Data Centers also continued to receive solutions from Analysis
Data Analysis

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 consists 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. 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.

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. Figure 1 shows the currently available VGOS broadband stations (inverted blue triangles)
as well as the stations expected to become VGOS capable by the year 2020. That is, 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 1-, 2-, 6-, and 24-hour lengths. 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. In the near future the focus is likely to shift from the station side to 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.

Fig. 1: Evolution of the VGOS broadband network. By the year 2020 a network of 22 VGOS sites is anticipated to be operational. By the end of 2016 there were six stations (inverted blue triangles) participating in the VGOS test sessions. The other sixteen stations (red triangles) are expected to realize their VGOS signal chains in the next few years.

Publications
