IVS Infrastructure Development Plan 2030

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Axel Nothnagel, James Anderson, Dirk Behrend, Johannes Böhm, Patrick Charlot, Francisco Colomer, Aletha de Witt, John Gipson, Rüdiger Haas, David Hall, Hayo Hase, Ed Himwich, Nancy Kotary Wolfe, Jinling Li, Evgeny Nosov, Chester Ruszczyk, Gino Tuccari (IVS Directing Board)

Executive Summary

The International VLBI Service for Geodesy and Astrometry (IVS) is a collaboration of organizations performing globally organized Very Long Baseline Interferometry (VLBI) observations primarily for the determination of Earth orientation parameters (EOP) as well as for terrestrial and celestial reference frames. All products of the IVS are disseminated to the users directly or through other institutions such as the International Earth Rotation and Reference Systems Service (IERS), and they are essential for the realization of the Global Geodetic Reference Frame (GGRF) for sustainable development as stressed by the United Nations General Assembly Resolution 69/266. The IVS operates in a service environment because more than 80% of the member institutions of the IVS see their predominant involvement in the IVS triggered by service interests of their institutions.

Over the course of its existence, the IVS has made possible the generation of state-of-the-art results in many areas of geodetic and astrometric VLBI through a well-working organizational structure. For this reason, we strive to develop the IVS further by fostering progress in all aspects of its operations. To provide a basis for a discussion with its stakeholders, in this document the IVS Directing Board expresses its views of the current status and the foreseen future path of developments.

It is common knowledge that the highly variable Earth's phase of rotation, UT1-UTC, is needed for a variety of important societal applications of positioning, navigation and environmental monitoring, preferably in real-time. Since the VLBI technique is the only one to determine this parameter with sufficient accuracy and due to the need for low latency results, the regular UT1-UTC determinations have the highest priority in the IVS's endeavors and justify the maintenance of global critical infrastructure. However, all other components of EOP as well as those of terrestrial and celestial reference frames, though with different latency requirements, are equally essential for numerous applications in services of general interest. At the same time, all products are highly correlated with each other and need to be monitored diligently with the same level of energy.

Starting from its current level of operations, the IVS embarks on organizing IVS observing networks in operation for 24 hours, seven days a week and on producing products with reasonable accuracies and latencies. Within these observing sessions, it will be warranted that all products, i.e., the complete set of EOP components including UT1-UTC as well as terrestrial and celestial reference frames, are produced with the same level of quality.

The IVS relies on voluntary contributions of national agencies and institutions acting in a global context. The work load is large and the investments are costly. At present, not all of the resources needed for the targets named above, such as coordination, data transfer and *Level 1 Data Analysis*, have been committed in full or even in part. For this reason, much of the progress to be seen in the next ten years will heavily depend on increased commitments and investments of active and new IVS contributors.

Preamble

The International VLBI Service for Geodesy and Astrometry (IVS) is a collaboration of organizations performing globally organized Very Long Baseline Interferometry (VLBI) observations primarily for the determination of Earth orientation parameters and geodetic reference frames in a service environment on a non-profit basis. It is a service of the International Association of Geodesy (IAG) and of the International Astronomical Union (IAU). More than 80% of the IVS member institutions see their mandate in supporting operational activities for regularly providing geodetic and astrometric information.

It is common knowledge that only a global approach of VLBI activities implicitly guarantees the ultimate geometric sensitivity in terms of accuracy which is needed for optimal state-of-the-art determinations of these parameters. With this mission and due to its global nature, the IVS guarantees synergies for sustainable technological developments as well as standardization for the intrinsically necessary compatibility of equipment and procedures. Individual institutions or even nations are not able to achieve this alone.

Geodetic VLBI is the only technique to observe the phase of Earth rotation, UT1-UTC, which is needed for the operations of Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Beidou and Galileo, and the IVS provides the infrastructure to sustainably maintain delivery of this product. Furthermore, VLBI observations are the only means for tying the global terrestrial reference frame (TRF) to the celestial reference frame (CRF) by the full set of Earth orientation parameters (EOP) which includes polar motion, UT1-UTC, and two nutation components. It should be emphasized here that CRF, EOP and TRF are mutually dependent in this entire geometric triple with VLBI being the only technique to determine the CRF in the radio frequency domain.

The TRF, besides results from other space-geodetic observing techniques, consists of precise coordinates and velocities of IVS radio telescopes. Here, the IVS strives for 1 mm position accuracy as set by the Global Geodetic Observing System (GGOS) Project of the International Association of Geodesy (IAG), which includes IVS operations, to provide the needed information for Global Change studies in general and for monitoring global sea level change in particular. Beyond providing positions and velocities of individual sites, the IVS TRF is one of two backbone techniques for determining the scale parameter of the International Terrestrial Reference Frame (ITRF) which is the basis for many global and regional applications. In the same vein, Resolution 69/266 of the United Nations pursues an identical goal when calling its member states to contribute to “A global geodetic reference frame for sustainable development”, to be realized as the Global Geodetic Reference Frame (GGRF). This also includes highly accurate coordinates of radio telescopes maintained within the IVS.

Concerning the CRF, the fundamental reference system for astronomical applications, according to Resolution B2 of the International Astronomical Union (IAU) General Assembly 1997, is realized as the International Celestial Reference Frame (ICRF), a space-fixed frame based on high accuracy radio positions of extragalactic sources measured by VLBI and using observational data from the IVS.

The radio telescopes of the VLBI Global Observing System (VGOS) as the currently expanding global infrastructure of the IVS, but also the many stations maintaining legacy S/X band equipment, are essential for all these applications. Their operations have to be developed and organized in a structured way according to the voluntary capabilities of the member institutions and the needs for the individual products.

For any nation, the need for investments in the IVS arises from the fact that in any region of the world there are applications making use explicitly or implicitly of the fundamentals provided by the IVS. In the context of this document, it has to be emphasized that the southern hemisphere is greatly under-represented compared to the northern hemisphere and that more investments in the southern hemisphere have to be sought. Only when global endeavors are performed with every country contributing its share according to its grand-national product, the benefits for each nation can be guaranteed with the necessary results freely available anywhere and at any time.

For the last twenty years, the IVS has been a well-working collaboration with an effective organizational structure and with many institutions contributing a great share of resources for the benefit of general interests. With this, the IVS has made possible the generation of state-of-the-art results in many areas of geodetic and astrometric VLBI. For this reason, we will continue to develop the IVS further for fostering progress in all aspects of its operations and the quality of its results. However, it cannot be ignored that the IVS is operating on a best-effort basis. To provide a basis for a discussion with its stakeholders, the IVS Directing Board expresses in this document its views of the current status and the foreseen future path of developments.

A. Vision for the next 10 years

The following sections summarize the views of the IVS Directing Board on products and infrastructure in a tabulated form to define the mandate of the IVS and to give some guidance for imminent developments. The envisaged accuracies heavily depend on accepted latencies and it is assumed that the IVS will always endeavor to provide the best results achievable. As set forth in the *Strategic Plan of the IVS for the Period 2016 – 2025* (https://ivscc.gsfc.nasa.gov/about/strategic/index.html), the IVS strives for accuracies of 1 µs for UT1-UTC, 15 µs for polar motion and nutation, and of 3 mm for telescope positions for one observing session of 24 hours in a weighted root mean squared (WRMS) sense as the final product after an acceptable latency of seven days until 2025. The goal then is to improve by a factor of about three by the end of the decade.

A.1. Core products and observing sessions

	Product / Purpose	Sessions	Latency of results	Comments
a	UT1-UTC	Twice daily 1h, (730 x 1 h)	12 h	Ultra-rapid extraction, transfer, processing and analysis of observation data from VGOS network as in b. * More details below
b	EOP/TRF	daily 24 h (365 x 24 h)	96 h	16 VGOS stations each out of global VGOS pool, 0h – 0h
c	CRF/Source characterization	50 x 24 h		16 telescopes each, ~½ of the sessions legacy and ~½ VGOS
d	Research and development	16 x 24 h		** see details below
e	Frame ties to navigation satellites	16 x 24 h		*** see details below

*) Rapid observations of UT1-UTC are inherently embedded in 24 h network sessions. The data to be extracted in an ultra-rapid fashion are prepared by suitable scheduling methods. Parallel sub-sessions/baselines can be foreseen for increased robustness.

**) 16 sessions (4 per quarter) on a proposal basis with deadlines 6 months before the respective quarter, telescope allocation according to justified needs. Purposes need to be in the interests of the IVS. Includes legacy and VGOS telescope usage. Correlator resources are provided by IVS. *Level 1 Data Analysis* (for definitions see Appendix 1) to be performed by proposers if non-standard. *Level 2 Data Analysis* limited solely to proposers only for 6 months after correlation. A report to the OPC is due 6 months after correlation.

***) 16 sessions (4 per quarter) on a proposal basis with deadlines 6 months before the respective quarter. VGOS telescopes only. Telescope allocation according to justified needs. Purposes need to be in the interests of the IVS. If needed, correlator resources are provided by IVS. Setups of *Level 0 Data Analysis* (see Appendix 1) as well as *Level 1 Data Analysis* to be performed by proposers. *Level 2 Data Analysis* limited solely to proposers only for 6 months after IVS correlation. A report to the OPC is due 6 months after correlation.

A.2. Required infrastructure

To be able to achieve the above goals in cadence and accuracy, the IVS will require the following list of infrastructure components. The majority of these components is also necessary to even maintain the status quo.

- 1 Coordination center (3 Full time equivalent staff [FTE])
- 1 Network Coordinator (1 FTE)
- 1 Analysis Coordinator (1 FTE)
- 1 Technology Coordinator (1 FTE)
- 1 Frequency monitoring, defense and allocation manager (1 FTE)
- 7 Operations centers (at least one for every weekday)
- 3 Data centers (mirrored for permanent availability)
- Pool of 40 globally distributed VGOS telescopes (twin telescopes at locations with next telescope at > 2500 km) for observing session types a) - e)
- Pool of 30 globally distributed legacy telescopes, for observing session type c) and d)
- 1 Correlation center (CorC) with a capacity of 2 daily sessions of 1 h each every day, including respective Internet network capabilities (7 days a week sustainable) [called *CorC type 1*]
- 7 Correlation centers (at least one for every weekday) with a capacity of 60 – 65 24 h sessions per year each including respective Internet network capabilities [called *CorC type 2*]
- 5 Hardware development centers
- 7 Analysis Centers (AC) for 1 h UT1-UTC sessions (3 h latency 7 days a week sustainable) [called *AC type 1*]
- 7 Analysis Centers for 24 h EOP sessions (12 h latency 7 days a week sustainable) [called *AC type 2*]
- 5 Analysis Centers for session types c) and e) [called *AC type 3*]
- 1 Combination Center (ComC) for UT1-UTC sessions (3 h latency 7 days a week sustainable) [called *ComC type 1*]
- 1 Combination Center for 24h EOP/TRF sessions (6 h latency 7 days a week sustainable) [called *ComC type 2*]
- 1 Office for Outreach and Communications

Comments:

The numbers quoted for the individual components are minimum requirements, e.g., for guaranteeing correlation every day of the week. It is highly desirable that more units of each component be established and maintained for guaranteeing uninterrupted operations and cross-validation of results.

Correlation centers can possibly also perform distributed correlations (setups, monitoring and export under the responsibility of 1 correlation center) instead of one entire session per correlation center.

Number of required analysis centers should be considered as those with independent software packages.

All components require redundancy in personnel for sickness, vacation, and other absences. Where possible, all components should ideally be labeled as critical infrastructure to safeguard their operations at adverse environmental and global health conditions.

Analysis and combination centers can/should explore automatic processing to guarantee 24/7.

B. Current realization 2020 (operational aspects only)

At present, the IVS operates with the following cadence of sessions and the infrastructure listed below.

B.1. Core products and observing sessions

a) UT1-UTC, 1 hour every day, selected legacy stations, product latency ~24 h

b) EOP/TRF, product latency 14 d, ~3 sessions per week, up to 12 legacy stations each, start times depending on working hours

c) CRF/Source characterization: several 24 h sessions per year

d) 10 – 14 R&D sessions, telescopes and dates allocated in previous year

e) Frame ties to navigation satellites: none

B.2. Available infrastructure

- 1 Coordination center (2 FTE)
- 1 Network Coordinator (fraction of 1 FTE)
- 1 Analysis Coordinator (fraction of 1 FTE)
- 1 Technology Coordinator (fraction of 1 FTE)
- 3 Operations centers
- 3 Data centers
- Pool of 35 globally distributed legacy telescopes (~1570 station days)
- 10 VGOS telescopes (~240 station days in 2021)
- 5 Correlation centers with a total capacity of 400 1 h INT and ~150 24 h network sessions
- 5 Analysis Centers for 1 h UT1-UTC sessions
- 7 Analysis Centers for 24 h EOP sessions
- Analysis Centers for session types c)
- 1 Combination Center for 24 h EOP/TRF sessions
- 1 Office for Outreach and Communications

C. Components needed to reach the IVS goals (operational aspects only)

C.1. Core products and observing sessions

All session series and product lines as listed in Section A.1 need to be ramped up in a structured way.

C.2. IVS components needed

The IVS requires upgrades of the following components:

- Increase in Coordination Center (CC) resources

  To perform the increased duties of the CC as set forth in the IVS Terms of Reference (ToR) #1.7, the CC needs an increase in staff by at least 1 FTE.

- Increase in Network Coordinator (NC) resources

  To perform the increased duties of the NC as set forth in the IVS Terms of Reference (ToR) #3.1, the NC position needs to be equipped with an equivalent of 1 FTE which is considerably more than the 0.2 FTE available today.

- Increase in Analysis Coordinator (AC) resources

  To perform the increased duties of the AC as set forth in the IVS Terms of Reference (ToR) #3.2, the AC position needs to be equipped with an equivalent of 1 FTE which is considerably more than the 0.1 – 0.2 FTE available today.

- Increase in Technology Coordinator (TC) resources

  To perform the increased duties of the TC as set forth in the IVS Terms of Reference (ToR) #3.3, the TC needs to be equipped with an equivalent of 1 FTE which is considerably more than the 0.1 – 0.2 FTE available today.

- Establishment and funding of a new component of a Frequency (monitoring, defense and allocation) Manager for VGOS (1 FTE,)

  The Frequency Manager is a new position due to the VGOS broadband feed capabilities and needed for the following functions:

  - works on the defense of the VGOS observation spectrum at spectrum management conferences in the 3 ITU-regions
  - maintains contact to ITU, IUCAF, CRAF, CORF, RAFCAP and national/regional spectrum authorities
  - coordinates frequency friends at observatories for common actions on the national/supranational level
  - authors reports and conducts compatibility studies for working parties and study groups
  - reports to the IVS-DB

- Increase in number and resources of the IVS Operations Centers (OCs)

  To perform the increased duties of the OCs as set forth in the IVS Terms of Reference (ToR) #2.2, the number of OCs needs to be increased from 3 to 7. Each OC needs to be equipped with equivalents of 0.5 FTE each. For the existing OCs, this is considerably more than the 0.1 FTE per OC available today.

- Increase in resources of the 3 Data Centers (DC)

  To cope with the increased requirements of the VGOS operations, the higher demand for data exchanged and the increased security precautions, the IVS Data Centers need to be augmented with additional staff and modern storage architecture.

- Increase in number of VGOS telescopes

  To allow for continuous operations of a 16-telescope network in variable configurations at least 40 VGOS telescope are needed worldwide. In particular in South America, Africa, the South Pacific and South Asia regions additional telescopes are needed for strengthening the geometry of the IVS network. This is an increase of 30 from currently about ten. If the next telescope is at a distance > 2500 km, the establishment and operation of twin telescopes is advisable to guarantee uninterrupted observations.

- Maintaining continued operations of 30 globally distributed legacy telescopes

  For observing session type c) and d) it is essential that highly sensitive telescopes (20 m diameter and larger) are kept operational through investments in personnel, upgrades and spare parts. New telescopes of larger diameters for primarily astronomical applications but also with S/X band capabilities are always welcome to join the IVS network for these types of observations.

- Establishment and operations of one correlation center CorC type 1

  For correlations and *Level 1 Data Analysis* of 2 daily sessions of 1 h each every day sustainable, a correlation center type 1 needs to be established and operated. This includes availability of the respective network capabilities, also sustainable on a daily basis. This can also be realized through shared agreements.

- Establishment and operations of seven correlation centers CorC type 2

  The operation of the VGOS network 24 hours seven days a week with processing by seven correlation centers requires that two new correlation centers are established and the existing five centers are augmented. All of these correlator centers should have a capacity of 60 – 65 24 h sessions per year each including the respective network and storage capabilities.

- Hardware development

  Making use of progressing hardware developments, the IVS should maintain VLBI hardware development centers for all types of hardware needed in VLBI observations, such as feed horns, receivers, digital backends, system delay monitoring, data transfer, recording etc.. Since each of these parts need special expertise, at least five different hardware development centers are required.

- 7 Analysis Centers [type 1]

  The 1 h UT1-UTC sessions, which are observed twice a day, need to be analyzed and results be disseminated within 3 h after correlation has been completed. This needs to be guaranteed seven days around the clock. Different analysis software packages should be used to warrant independency of the analyses.

- 7 Analysis Centers [type 2]

  The 24 h EOP sessions, which are observed every day, need to be analyzed and results be disseminated within 12 h after correlation has been completed. This needs to be guaranteed seven days a week around the clock. Different analysis software packages should be used to warrant independency of the analyses.

- 5 Analysis Centers [type 3]

  The session types c) ICRF and e) frame tie GNSS, which are observed in regular intervals, should be analyzed and results be disseminated within three months after correlation has been completed. Different analysis software packages should be used to warrant independency of the analyses.

- 1 Combination Center [type 1]

  For the results of the UT1-UTC sessions from different analysis centers, combination needs to be performed for final integrity control. This needs to be guaranteed 7 days a week with 3 h latency sustainable.

- 1 Combination Center [type 2]

  For the results of the EOP/TRF sessions from different analysis centers, combination needs to be performed for final integrity control. This needs to be guaranteed 7 days a week with 6 h latency sustainable.

Appendix 1

Nomenclature for data types and analysis steps

The IVS Directing Board proposes to use a conventional nomenclature for data types and analysis steps for proper unambiguous referencing. This nomenclature consists of the following dividers: *Level 0 Data* is the raw digitized noise gathered at the radio telescopes. Consequently, the correlation process falls under *Level 0 Data Analysis*. The output of this processing step are the fringe visibilities, subsumed as *Level 1 Data*. The analysis steps needed to produce the observables phase and group delays as well as their time derivatives, such as polarization combination and fringe fitting of the visibilities including any other necessary analysis steps at this stage be called *Level 1 Data Analysis*. The output is the *Level 2 Data*. The analysis steps working with phase and group delays and their rates and resulting in geodetic parameters be called *Level 2 Data Analysis*. This also includes work on source imaging and source structure effects. The results of this are geodetic and astrometric parameters forming *Level 3 Data*. The final combination work of several *Level 3 Data*, e.g., from different analysis centers, is *Level 3 Data Analysis*.