International VLBI Service (IVS)

Dirk Behrend, Axel Nothnagel, Harald Schuh
on behalf of the IVS

GGOS Days 2019

Rio de Janeiro, Brazil
November 12, 2019
A network of antennas observes a quasar

The delay between times of arrival of a signal is measured

Using the speed of light, the delay is converted to a distance
The distance is the component of the baseline toward the source

By observing many sources, all components of the baseline can be determined.
Role of VLBI in Science

**Science:**
- Astrometry & Astrophysics
- Earth mass Exchanges
- Deep Space Tracking
- Solar System Exploration
- GNSS apps LEOS apps
- Sea level change

**VLBI Antenna:**
- Stable structure
- Stable phase center
- No multipath

**Celestial Reference Frame (CRF):**
- Orientation of Earth In Space

**Terrestrial Reference Frame (TRF):**
- Precise Orbit Determination

**Quasars**
What is the IVS?

The **International VLBI Service for Geodesy and Astronomy (IVS)** is an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components:

- IVS inauguration was on **1 March 1999**.
- 83 permanent components supported by 41 institutions in 21 countries.
- ~300 Associate Members.

**IVS is a recognized service of**

- **IAG** – International Association of Geodesy
- **IAU** – International Astronomical Union
- **WDS** – ISC World Data System
The **goals** of the IVS are to:
- provide a service to support geodetic, geophysical, and astrometric research and operational activities;
- promote research and development in the VLBI technique;
- interact with the community of users of VLBI products and integrate VLBI (as a part of GGOS) into a global Earth observing system.

The **main activities** of the IVS are to:
- provide EOP, maintain ICRF, and support maintenance of ITRF;
- coordinate VLBI observing programs;
- set performance standards for the observing stations;
- establish conventions for data formats and products;
- issue recommendations for analysis software;
- set standards for analysis documentation;
- institute appropriate product delivery methods in order to insure suitable product quality and timeliness.
Organization of the IVS

1. IAG
2. IERS
3. IAU

IVS Directing Board

Network Stations
- Coordinating Center
  - Publications
  - Web Site
  - Master Schedule

Correlators

Data Centers

Analysis Centers

Operation Centers

Technology Development Centers

Network Coordinator

Performance feedback

Raw data 10-20Gb/s (magnetic tapes, disks, ftp)

Corrected data bases

Schedules

Users

Produced products for EOP, TEC, CRF

Analyzed results and products

Technology Coordinator
IVS: Training and Meetings (1/2)

- **IVS Technical Operations Workshop (TOW)**
  - Hands-on training of technical station staff
  - Organized every two years at MIT Haystack Observatory
  - Most recent: 10th TOW, May 5–9, 2019

- **VLBI School**
  - Schooling of young researchers in VLBI
  - Organized every three years at different venues
  - Most recent: 3rd VLBI School, March 14–16, 2019, Gran Canaria
    http://wp.portal.chalmers.se/evga/ivs-cte/
IVS General Meeting (GM)
- Technical Meeting for all IVS components and interested scientists
- Organized every two years at different venues

Meetings with special topics/groups
- IVS Analysis Workshop: organized yearly
- VLBI Technology Workshop: organized yearly
- VLBI Observations of Near-Field Targets
- IVS Directing Board: twice a year
IVS Publications and Web Presence

- **IVS Newsletter**: thrice a year
- **IVS Biennial Report**: every two years
- **GM Proceedings**: every two years
- **Web site**
- **Mailing lists**

https://ivscc.gsfc.nasa.gov/
IVS Network Stations

- **IVS Network Station**
- **Cooperating VLBI Site**
VLBI Sites in South America

Fortaleza, Brazil

AGGO, La Plata, Argentina
Typical weekly layout for IVS observing sessions

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= INT1 (Intensive session Kokee-Wettzell)
= INT2 (Intensive session Tsukuba-Wettzell)
= INT3 (Intensive session NyAlesund-Tsukuba-Wettzell)
IVS Products

- Earth Orientation Parameters (EOP):
  - 24-hour sessions (all EOP)
  - 1-hour Intensives (UT1–UTC)
- Terrestrial Reference Frame (TRF)
  - VLBI Terrestrial Reference Frame (VTRF)
- Celestial Reference Frame (CRF)
- Daily EOP + station coordinates (SINEX-files)
- Tropospheric Parameters (TROPO)
- Baseline Lengths (BL)
**Note:** Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products.

- **EOP:** two rapid turnaround sessions each week, 10–11 stations, depending on station availability. Data bases are available no later than 15 days after each session.
- **TRF:** bi-monthly sessions with 12–14 stations using all stations at least two times per year; regional sessions for Europe, Antarctica, Asia-Pacific, Australia.
- **CRF:** astrometric sessions to observe mostly southern sky sources, plus bi-monthly RDV sessions using the VLBA together with up to ten geodetic stations.
- **R&D:** ~monthly sessions to investigate instrumental effects and study ways for technique and product improvement.
- **CONT:** triennial ~two-week continuous sessions to demonstrate the best results that VLBI can offer.
VGOS: Why do we need it?

Aging systems (now ~40 years old):
- Old antennas
- Obsolete electronics
- Costly operations
- RFI

New technology:
- Fast, affordable antennas
- Digital electronics
- Hi-speed networks
- Automation

New system

New requirements:
- Sea level rise
- Earthquake processes
- 1-mm accuracy
- GGOS
VGOS: Goals of new system

1-mm position accuracy (*based on a 24-hour observation*)

Continuous measurements of station position and EOP

Turnaround time to initial products < 24-hrs
VGOS (VLBI Global Observing System)

Features:
- small and agile telescopes
  - small: 12–13 m dish diameter
  - fast: 12°/s and 6°/s slew speeds
- large bandwidth: 2–14 GHz
- flexible frequency allocation
- dual linear polarization

Implies:
- dense sampling of atmosphere
- up to 2 observations per minute (2880/day)
### IVS Observing Program: VGOS

- **Expected weekly observing coverage for VGOS (mid-2020s)**

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- Constant observation with 16+ station network
- Individual stations have maintenance days
New VGOS Radio Telescopes

Ny-Ålesund (NO)
*Courtesy D. Behrend*

Ishioka (JP)
*Courtesy Y. Fukuzaki*

GGAO (US)
*Courtesy A. Niell*

Metsähovi (FI)
*Courtesy N. Zubko*
Projected VGOS Network by early 2020s

- VGOS antenna broadband ready
- VGOS antenna under construction or planned
VGOS in So. America: EOP Simulations

- Monte-Carlo simulations
- 24-hour session
- Simulated delay from clock noise, tropospheric turbulence, and observation noise

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<td>+2%</td>
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VGOS: Data Transport, Correlation

Data transport (raw data) in early 2020s:
- Legacy S/X network: $\sim 2000$ TB/year
- VGOS: $\sim 1000$ TB/day (~40 TB/day/site)
- Required network data rates at...
  - each site: 5.6 Gbps \([\text{now } \sim 1-10 \text{ Gbps}]\)
  - correlator: 134 Gbps \([\text{now } 1-20 \text{ Gbps}]\)
- Challenges: transport bandwidth, storage capacity

Correlation:
- Software correlator on PC cluster with off-the-shelf components (scalable)
- Challenge: power consumption (for processors and cooling)
The Event Horizon Telescope (EHT) project has just unveiled the first direct image of a black hole (in the Messier 87 galaxy)

EHT and VGOS both used the same broadband VLBI technology synergistically developed at MIT Haystack Observatory

EHT operates at 230 GHz, VGOS at 10 GHz, but the signal chain backends (i.e., RF distributors, down-converters, digitizers, recorders) are the same

The broadband cluster correlator and post-processing software are leveraged efforts between both projects at MIT
## Comparison: S/X vs. VGOS

<table>
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<tr>
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<th><strong>Legacy S/X System</strong></th>
<th><strong>VGOS System</strong></th>
<th><strong>Benefit</strong></th>
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<tr>
<td>Antenna size</td>
<td>5–100 m dish</td>
<td>12–13 m dish</td>
<td>reduced cost</td>
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<tr>
<td>Slew speed</td>
<td>~20–200 deg/min</td>
<td>≥ 360 deg/min</td>
<td>more observations for troposphere</td>
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<td>Sensitivity</td>
<td>200–15,000 SEFD</td>
<td>≤ 2,500 SEFD</td>
<td>more homogeneous</td>
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<td>Frequency range</td>
<td>S/X band [2 bands]</td>
<td>~2–14 GHz [1 broadband w/ 4 bands]</td>
<td>increased sensitivity, data precision</td>
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<tr>
<td>Recording rate</td>
<td>128, 256, 512 Mbps</td>
<td>8, 16, 32 Gbps</td>
<td>increased sensitivity</td>
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<td>Data transfer</td>
<td>usually e-transfer, some ship disks</td>
<td>e-transfer, ship disks when required</td>
<td>stable instrumentation</td>
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<td>Signal processing</td>
<td>analog/digital</td>
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<td>Product</td>
<td>Granule</td>
<td>Update every</td>
<td>Expected Accuracy (WRMS)</td>
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<td>Ultra-rapid</td>
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<td>UT1−UTC: 7 µs</td>
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<td>Rapid w/ continuous near-real time correlation</td>
<td>3 hours</td>
<td>3 hours</td>
<td>UT1−UTC: Polar motion: Nutation offsets: 5 µs 75 µas</td>
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<td>Rapid w/ batch correlation of 3-hr or 24-hr blocks</td>
<td>3 hours</td>
<td>3–24 hours</td>
<td>UT1−UTC: Polar motion: Nutation offsets: 3 µs 45 µas</td>
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<td>Intermediate w/ continuous near-real time correlation</td>
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<td>UT1−UTC: Polar motion: Nutation offsets: 3 µs 45 µas</td>
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<td>UT1−UTC: Polar motion: Nutation offsets: 3 µs 45 µas</td>
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<td>Final</td>
<td>3 hours</td>
<td>7 days</td>
<td>UT1−UTC: Polar motion: Telescope coord.: Source positions: 1 µs 15 µas 15 µas 3 mm 15 µas</td>
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Has a kangaroo pressed...

**Serious design flaw:**

- It happened at Yarragadee in Western Australia.
- You cannot think of everything.
- Pedestal emergency stop button at head-height for a kangaroo
- Kangaroo pressed e-button
- Extension of experiment checklist

```markdown
Antenna: pad clear of obstructions
Antenna: has a kangaroo pressed the pedestal e-stop button?
Antenna: Time OK (i.e. SNTP server OK)
```
Thanks for your attention!