International VLBI Service (IVS)

Dirk Behrend, Axel Nothnagel, Hayo Hase
on behalf of the IVS

Implementation of the GGRF in Latin America

Buenos Aires, Argentina
September 18, 2019
VLBI Site: E.g., Onsala Space Obs.

Legacy system (S-band)

25 m

VGOS (VLBI Global Observing System)

OTT2

OTT1

Legacy S/X system

20 m

Courtesy R. Haas
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
IVS Goals and Activities

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 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.
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 Geodesy

Celestial Reference Frame (CRF)

Quasars

Orientation of the Earth in Space

Terrestrial Ref Frame (TRF) Scale
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

**Quasars**

**Celestial Reference Frame (CRF):**

**Orientation of Earth In Space:**

**Terrestrial Reference Frame (TRF):**

**UT1**
Organization of the IVS

IVS Directing Board

IAG
IERS
IAU

Network Stations

Correlators

Coordinating Center
- Publications
- Web Site
- Master Schedule

Data Centers

Analysis Centers

Operation Centers

Technology Development Centers

Technology Coordinator

Network Coordinator

schedules

raw data 10-20Gb/s

produc e d for EOP, TRF, CRF

data bases

Users

analyzed results and products

corrected data bases

feedback

feedback

feedback
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**

**International VLBI Service for Geodesy and Astrometry**

**2015–2016 Biennial Report**

The goals of IVS are:

- To provide a service to support geodetic, geophysical, and astrometric research and operational activities.
- To interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.
- To promote research and development activities in all aspects of the geodetic and astrometric VLBI technique.

**IVS Home Page**

https://ivscc.gsfc.nasa.gov/

**Call for 2017+2018 Biennial Report**

The IVS Data Center invites all IVS components to submit reports for the IVS 2017+2018 Biennial Report. The 2017+2018 Biennial Report will cover the calendar years 2017 and 2018 spanning the period from 1 January 2017 through 31 December 2018. Reports are due by April 30, 2019.

**December Newsletter (January 10)**

The December issue of the IVS Newsletter was posted on the Web site. This edition includes updates and announcements for the IVS community.

https://ivscc.gsfc.nasa.gov/
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)
VLBI Sites in South America

Fortaleza, Brazil

AGGO, La Plata, Argentina
IVS Observing Program

- about 180 sessions per year, 3.5 sessions per week
- Complete EOP in two weekly 24-hr sessions:
  - R1 on Mondays, R4 on Thursdays
  - 15-day rapid turnaround
- UT1–UTC in daily 1-hr Intensive sessions
- CRF sessions: CRF, CRD (CRF with emphasis on deep south)
- TRF sessions: global (T2); regional (EURO, OHIG, APSG, JADE, AUSTRAL)
IVS Observing Program: S/X System

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

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Constant observation with 16+ station network
Individual stations have maintenance days
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 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)
## Comparison: S/X vs. VGOS

<table>
<thead>
<tr>
<th></th>
<th>Legacy S/X System</th>
<th>VGOS System</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna size</strong></td>
<td>5–100 m dish</td>
<td>12–13 m dish</td>
<td>reduced cost</td>
</tr>
<tr>
<td><strong>Slew speed</strong></td>
<td>~20–200 deg/min</td>
<td>≥ 360 deg/min</td>
<td>more observations for troposphere</td>
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<tr>
<td><strong>Sensitivity</strong></td>
<td>200–15,000 SEFD</td>
<td>≤ 2,500 SEFD</td>
<td>more homogeneous</td>
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<tr>
<td><strong>Frequency range</strong></td>
<td>S/X band [2 bands]</td>
<td>~2–14 GHz [1 broadband w/ 4 bands]</td>
<td>increased sensitivity, data precision</td>
</tr>
<tr>
<td><strong>Recording rate</strong></td>
<td>128, 256, 512 Mbps</td>
<td>8, 16, 32 Gbps</td>
<td>increased sensitivity</td>
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<tr>
<td><strong>Data transfer</strong></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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<tr>
<td><strong>Signal processing</strong></td>
<td>analog/digital</td>
<td>digital</td>
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</table>
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*
Status of RAEGE Project

Yebes (Spain)  Courtesy J.A. López Fernández

Santa Maria (Eastern Azores, Portugal)  Courtesy F. Colomer
## VGOS Roll-out Status (1/2)

<table>
<thead>
<tr>
<th>Station</th>
<th>Recent milestone</th>
<th>VGOS broadband</th>
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<tbody>
<tr>
<td>GGAO</td>
<td>VGOS CONT17, VT sessions</td>
<td>ready</td>
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<tr>
<td>Westford</td>
<td>VGOS CONT17, VT sessions</td>
<td>ready</td>
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<td>Wettzell South</td>
<td>VGOS CONT17, VT sessions</td>
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<td>Yebes</td>
<td>VGOS CONT17, VT sessions</td>
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<td>Ishioka</td>
<td>VGOS CONT17, VT sessions</td>
<td>ready</td>
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<td>Kokee Park</td>
<td>VGOS CONT17, VT sessions</td>
<td>ready</td>
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<td>Onsala (Oe, Ow)</td>
<td>VT sessions</td>
<td>ready</td>
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<td>Badary</td>
<td>Fixed broadband system</td>
<td>2017 (S/X/Ka)</td>
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<td>Zelenchukskaya</td>
<td>Fixed broadband system</td>
<td>2017 (S/X/Ka)</td>
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<td>AuScope (Hobart, Katherine)</td>
<td>Successful fringe tests</td>
<td>Q4 2019</td>
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<tr>
<td>Santa Maria</td>
<td>Started S/X observing</td>
<td>end 2019</td>
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<tr>
<td>AuScope (Yarragadee)</td>
<td>Upgrade work in progress</td>
<td>early 2020</td>
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<td>Station</td>
<td>Recent milestone</td>
<td>VGOS broadband</td>
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<td>Sheshan</td>
<td>Fringe test</td>
<td>2019</td>
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<tr>
<td>Ny-Ålesund South</td>
<td>Started S/X observing</td>
<td>2019</td>
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<td>Ny-Ålesund North</td>
<td>Installation of broadband receiver</td>
<td>end 2019</td>
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<td>HartRAO</td>
<td>RT erected, signal chain work</td>
<td>2019</td>
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<td>Svetloe</td>
<td>RT erected, stability tests</td>
<td>2019 (S/X/Ka)</td>
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<td>McDonald</td>
<td>First fringes</td>
<td>end 2019</td>
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<td>Gran Canaria</td>
<td>RT in warehouse, civil works</td>
<td>2020</td>
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<td>Metsähovi</td>
<td>RT SAT, signal chain work</td>
<td>2020</td>
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<tr>
<td>Tahiti</td>
<td>Site selected, RFI survey</td>
<td>2022</td>
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<tr>
<td>Brazil (Fortaleza)</td>
<td>Under discussion</td>
<td>2022</td>
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<tr>
<td>Flores</td>
<td>RFI surveys</td>
<td>2022+</td>
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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>17 stations</td>
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<td>17 + LP</td>
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<td>+2%</td>
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<td>17 + Co, LP</td>
<td>12.3</td>
<td>+2%</td>
<td>13.5</td>
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VGOS: Data Transport, Correlation

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

Challenges: transport bandwidth, storage capacity

Correlation:
- Software correlator on PC cluster with off-the-shelf components (scalable)
- Challenge: power consumption (for processors and cooling)
VGOS: Data Analysis

Analysis:
- Tremendous increase in observables
- High degree of automatization required
- Different levels of latency (next slide)
- Dependency on rapid availability of auxiliary data, e.g.,
  - Meteorological data
  - Mapping functions from numerical weather models
### VGOS: Possible Product Portfolio

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<th>Product</th>
<th>Granule</th>
<th>Update every</th>
<th>Expected Accuracy (WRMS)</th>
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<tbody>
<tr>
<td>Ultra-rapid</td>
<td>0.5 hours</td>
<td>0.5 hours</td>
<td>UT1−UTC: 7 µs</td>
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<tr>
<td>Rapid w/ continuous near-real time correlation</td>
<td>3 hours</td>
<td>3 hours</td>
<td>UT1−UTC: 5 µs Polar motion: Nutation offsets: 75 µas 75 µas</td>
</tr>
<tr>
<td>Rapid w/ batch correlation of 3-hr or 24-hr blocks</td>
<td>3–24 hours</td>
<td></td>
<td>UT1−UTC: 3 µs Polar motion: Nutation offsets: 45 µas 45 µas</td>
</tr>
<tr>
<td>Intermediate w/ continuous near-real time correlation</td>
<td>3 hours</td>
<td>24 hours</td>
<td>UT1−UTC: 3 µs Polar motion: Nutation offsets: 45 µas 45 µas</td>
</tr>
<tr>
<td>Intermediate w/ batch correlation of 3-hr or 24-hr blocks</td>
<td>24 hours</td>
<td></td>
<td>UT1−UTC: 1 µs Polar motion: Telescope coord.: Source positions: 15 µas 15 µas 3 mm 15 µas</td>
</tr>
<tr>
<td>Final</td>
<td>3 hours</td>
<td>7 days</td>
<td>UT1−UTC: 1 µs Polar motion: Telescope coord.: Source positions: 15 µas 15 µas 3 mm 15 µas</td>
</tr>
</tbody>
</table>
VGOS Technology in EHT

- 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
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

| Antenna: pad clear of obstructions |  
| Antenna: has a kangaroo pressed the pedestal e-stop button? |
| Antenna: Time OK (i.e. SNTP server OK) |  

Questions?