Geodetic VLBI: Science, IVS, etc.

John Gipson
NVI,Inc/NASA GSFC

2019 Workshop on Regional VLBI
Mexico City, Mexico

http://www.nap.edu/catalog/12954.html
Who Am I?

PhD in Theoretical Particle Physics
Started doing VLBI ~ 1985.
Senior scientist in the NASA Goddard VLBI group
Specialty is analysis (and scheduling)
Special interest in Earth Orientation
IVS Analysis Coordinator
John.M.Gipson@nasa.gov
Agenda

Overview of Geodetic VLBI
The IVS Organization
The International Celestial Reference Frame
Earth Orientation Parameters
The VLBI observable is the difference in arrival time of the signal at the two antennas.

By looking at a variety of sources you can determine the vector connecting the two antennas.

The signal is very weak which means you need large antennas.

Anything that affects the delay is a candidate for estimation.
Radio sources

Active galactic nuclei, galaxies, quasars
Distance 2 – 8 billion light years
Point sources

→ quasi-inertial reference system

We want sources with no structure!

Ugly!!
Some IVS Radio telescopes

Greenbelt, USA

Ishioka, Japan

O'Higgins, Antarctica

Urumqi, China

Effelsberg, Germany

+ 40 more
VLBI principles I

Number of correlated bits determine accuracy
Can increase accuracy by:
- More Bandwidth
- Increased scan length

Data volume of several TeraByte per day
Data transfer to correlator
- Originally recorded on video tape.
- Now recorded on computer disks
- By transfer over the internet: eVLBI
VLBI principles II

Number of scans limited by:
- Slew speed of antenna
- Required SNR: Higher SNR => longer scans
VLBI principles II

- Recording time 20 – 200 s (= 1 scan) (Integration time for signal-to-noise)
- Earth rotates
- Geometry not stationary
- Makes group delay determination complicated
- 1 scan produces one group delay/delay rate

- Multiple scans in one observing session (1hr or 24 hour duration)

- Intermediate step: Correlation
VLBI principles II
Placement of bands chosen to have
A) high peak and
B) minimize side lobes when you do FFT

Need to observe at 2-bands to correct for ionosphere
Correlation

Cross correlation process

Fringe fitting = Search for max. correlation amplitude (time lag and fringe rate)
Anything that affects the delay must be calculated/ calibrated and/or is a candidate for prediction.

- **Station related effects.**
  - Station position
  - Earth tides
  - Loading (atmosphere, ocean, hydrology)
  - Pole tide

- **Source related effects:**
  - Position of sources
  - Core shift
  - Source structure
What affects the VLBI Delay?(2)

- Earth orientation Parameters ("EOP"): Orientation of the TRF with respect to the CRF
  - Precession/Nutation: Orientation of the spin axis in space
  - Polar Motion: Location of the spin axis on the Earth.
  - UT1: Rotation about the spin axis
What affects the VLBI Delay?(3)

- Source structure
  - Becoming major research area

- Miscellaneous things
  - Ionospheric Delay
  - Tropospheric Delay
  - General relativistic effects
  - Antenna Thermal deformation
  - Antenna Gravitational deformation
  - Changes in cable length
  - Clock drift
  - RFI
  - …
Data analysis

- 3000-30,000 observations per 24 hour session.
- Typically each station has 200-400 scans/session

\[
\tau = -\frac{1}{c} \vec{b} \cdot R(t) \cdot \vec{k}
\]
VLBI is Cooperative

You need 2 (or more) antennas observing the same source at the same time.

One VLBI antenna is like one hand clapping.

This means that you need to plan and coordinate observations ahead of time.

The organization that coordinates geodetic VLBI is: International VLBI Service for Geodesy & Astronomy
Does not include decommissioned or mobile VLBI sites

IVS Network Station

Some Cooperating VLBI Site
IVS home page

https://ivscc.gsfc.nasa.gov

Link to all things IVS.

IVS is a service of:
- International Association of Geodesy
- International Astronomical Union
- ICSU World Data System

Part of GGOS:
Global Geodetic Observing System
The IVS Directing Board provides overall guidance. 16 members on the IVS board.
Working groups have a finite charter and address a specific task. There have been 8 working groups. Latest was on Galactic Aberration.
The coordinating center provides overall coordination. Only 1 of these.
Stations take the data.
About 40 IVS stations, and ~30 cooperating stations.
Correlators correlate the data.
~5-10 IVS correlators
Data centers store IVS data. 3 of these which are mirrored.
Analysis centers analyze the data.

~10-20 of these

A few (~3) have primary responsibility for initial processing.
Operations centers are responsible for producing specific schedules. ~5 of these
Technology development centers focus on improving specific aspects of IVS. This can be hardware or software.~10-20 of these
Important IVS Meetings (1)

- **IVS General Meeting.**
  - Even years
  - Roughly 150 participants. Meeting and splinter meetings last ~1 week.
  - 2018 in Svalbard, Norway
  - 2020 in Annapolis, USA

- **EVGA Meeting.**
  - Even years.
  - Roughly 100 participants. Meeting and splinter meetings last ~1 week
  - 2017 in Gothenburg, Sweden
  - 2019 in Las Palmas (Canary Islands), Spain

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Important IVS Meetings (2)

- IVS Analysis Workshop
  - Every year.
  - Occurs in conjunction with IVS-GM or EVGA

- Technical Operations Workshop.
  - Odd years.
  - Geared towards station operators

- IVS VLBI school
  - Every three years.
  - Occurs in conjunction with IVS-GM or EVGA
International Celestial Reference Frame

- The position of some set of celestial objects in a consistent reference frame.
- Early realizations used the positions of optical sources determined by optical astronomy.
  - The last was the “Fifth Fundamental Catalog” FK5 in 1988.
- In 1995 the ICRF was defined in terms of the positions of quasars determined by VLBI.
ICRF1: Adopted 1998

- 212 “Defining” Sources
- 396 Additional
- Noise floor ~250 microarcseconds

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ICRF2: Adopted by IAU in 2009

295 Defining sources (97 of them in ICRF1)
3019 Other sources
Noise floor ~40 microarcseconds

ICRF3: Adopted August, 2018
303 Defining sources
4233 Other sources
Includes Galactic Aberration

Note sparseness in the south

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International Celestial Reference Frame (ICRF)
Aberration

The movement of the Earth causes an apparent change in the position of a source.

If the velocity is constant, this is just a constant shift.

If the velocity changes over time, the apparent source position will change over time.
Galactic aberation

As the Earth rotates around the galaxy, the direction of the velocity changes.

You are here
ICRF3 used 5.8 µas/yr. Value from a recent VLBI solution.

Stellar astronomy:
range of 6 estimates: [4.8 - 5.4] µas/yr
mean = 5.0 µas/yr ;
Standard deviation of estimates = 0.21

Remember: Noise floor of ICRF is 40 uas!
VLBI is used in spacecraft navigation to determine the angular position of spacecraft.

This complements other techniques (radar, laser) which measure the range to the spacecraft.

JPL uses this routinely in deep space navigation.
Chang‘E-3 lander

Picture taken by Yutu rover (2012.12) – Courtesy Tang Geshi
Interactions of Earth System

After Schuh and Haas, 1995 (modified)
Precession and Nutation
Nutation is due to gravitational torques on the Earth. By measuring nutation we can determine properties of the interior of the earth. These measurements provide the most accurate model of the ellipticity of the inner core.
Polar motion

Size is roughly that of a baseline diamond (90ft=27m)
Direction of motion is clockwise

Two dominant periods: 365d and 435d
Beating causes change in size.
Spectrum of LOD

Seasonal

Tides

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The day is about 1ms longer in Northern Hemisphere winter.

More angular momentum in the atmosphere.
Seasonal Behavior

Seasonal Dependence LOD
Decomposition of LOD

Observed Changes in Earth's Length of Day

(a) Total
(b) Decadal
(c) Interannual
(d) Seasonal
(e) Intraseasonal

Scale (milliseconds)

Time in years since 1900.0

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MEI & Residual LOD

El Nino

La Nina

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Sub-daily EOP variation

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Questions & Comments
Geodetic VLBI: VGOS+ ITRF...

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NVI, Inc/NASA GSFC

2019 Workshop on Regional VLBI
Mexico City, Mexico
Agenda

The VLBI Terrestrial Reference Frame
Gravitational Deformation of Antennas
VLBI Geodetic Observing System (VGOS)
The International Terrestrial Reference Frame
Other Space Geodesy Techniques
Global Geodetic Observing System

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Does not include decommissioned or mobile VLBI sites

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Westford - Wettzell

In 30 years the distance increased by ~0.5 m

VLBI was the first technique to demonstrate that continental drift happens in real time!
Europe – South Africa

In 20 years distance decreased by a few cm.
Annual signal in station heights

WETTZELL

FORTLEZA

$\Delta$ Height [mm]

fraction of year

BKG DGFI GSFC IGGB OPA SHAO USNO
VLBI and SLR define the scale of ITRF2014
Clark and Thomsen (1988) model for signal path delay depends on variations of

1) focal length
2) vertex position
3) receiver position

\[ \Delta L(e) = \alpha_F \Delta F(e) + \alpha_V \Delta V(e) + 2\alpha_R \Delta R(e) \]

- Coefficients depend on dimensions and structure of antenna
- The functions F, V and R have to be measured or modeled for each antenna
Effect at Gilcreek

\[ \Delta L(\text{el}) = 2.4(\sin(\text{el}) - 1) \text{mm} \]

Change in up estimate of 2.4 mm

At the time (1988—30 years ago!) this was considered a small effect, which is why no one paid much attention.

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<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>Gilcreek 26M</td>
<td>Clark &amp; Thomsen</td>
</tr>
<tr>
<td>2005</td>
<td>Hobart 26M</td>
<td>Dawson et al <em>(Never published)</em></td>
</tr>
<tr>
<td>2009</td>
<td>Medicina 32M Noto 32M</td>
<td>Sarti, Negusini, Abbondanza</td>
</tr>
<tr>
<td>2014</td>
<td>Yebes 40M</td>
<td>Nothnagel, et al</td>
</tr>
<tr>
<td>2014</td>
<td>Efflesberg 100M</td>
<td>Atz, Springer, Nothnagel</td>
</tr>
<tr>
<td>2018</td>
<td>Onsala60</td>
<td>Nothnagel et al</td>
</tr>
</tbody>
</table>

Each author gives a different functional form for $\Delta L(\text{el})$

- This makes it difficult to incorporate in an antenna
- Difficult to understand what the effect on estimated parameters will be
Only a small minority of VLBI antennas have models.

Some antennas were destroyed or decommissioned, and it is unlikely we will ever have models for these.

This figure only lists some of the defunct antennas.
Models vary in sign and magnitude between different antennas.

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Approach:
For each antenna, do a least squares fit to the delay of the form:

\[ \Delta L(el) \approx \frac{A}{\sin(el)} + C + U \sin(el) \quad [+X \cos(el)] \]

We estimate the coefficients A, C, U and X, where the last term is optional.

The physical interpretation is:
A \rightarrow \text{Change in Atmosphere}
C \rightarrow \text{Change in Clock}
U \rightarrow \text{Change in Up}
X \rightarrow \text{Change in axis offset (if estimated)}
### Results of Least Squares Fit

<table>
<thead>
<tr>
<th></th>
<th>ATM</th>
<th>CLK</th>
<th>UP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WRMS</td>
<td>1/Sin(el)</td>
<td>1</td>
</tr>
<tr>
<td>EFLESBERG</td>
<td>1.02</td>
<td>2.12</td>
<td>-117.16</td>
</tr>
<tr>
<td>GILCREEK</td>
<td>0.00</td>
<td>0.00</td>
<td>-2.40</td>
</tr>
<tr>
<td>MEDICINA</td>
<td>0.04</td>
<td>-0.13</td>
<td>-1.29</td>
</tr>
<tr>
<td>NOTO</td>
<td>0.15</td>
<td>0.11</td>
<td>-0.72</td>
</tr>
<tr>
<td>ONSALA60</td>
<td>0.08</td>
<td>-0.10</td>
<td>1.72</td>
</tr>
<tr>
<td>YEBES40M</td>
<td>0.04</td>
<td>0.10</td>
<td>49.38</td>
</tr>
</tbody>
</table>

Last column is ‘predicted’ change in Up due to applying model.

Fit Delay curve from 7-90 degrees.
Sarti, Abbondanza, Petrov and Negusini (2011) found a change in local Up of 8.9 for Medicina and 6.7 for Noto. For most antennas there is good agreement between predicted and actual change in local Up.

The notable exception is YEBES40M which I will discuss later.
Goals:
Position precision of ~1mm
Stability of 0.1 mm/year
Globally distributed VLBI network of ~30 sites
24/7 measurement
Near real time EOP.
How can VLBI get to GGOS goals?

\[ \sigma_{UEN}^2 = \frac{\sigma_{obs}^2}{N} + \sigma_{modeling}^2 \]

To reduce \( \sigma_{obs}^2 \), need to record more bits:
- Increase scan time
- Increase BW

To increase N need to
- Reduce scan time
- Reduce slewing time

Did a series of Monte Carlo simulations with values for different values for
- \( \sigma_{obs} \)
- Clock stability
- Atmospheric turbulence

Key findings:
- Once you get below 2-5 ps for \( \sigma_{obs} \), little additional improvement.
- Dominant remaining source of error is atmosphere mismodeling.
  - Which can be somewhat fixed by dense sampling.
Atmosphere modeled as a piece-wise-linear function, and estimated from the data.
Mismodeled atmospheric delay is dominant error source. One way to reduce is increase the sampling of the sky.
Concept of VGOS

• New generation VLBI infrastructure
  – dense sampling of atmosphere
  – agile telescopes
    → small (12 – 13 m) \(12^\circ/\text{sec}\)
  – up to 2 observations per minute
    (2880/day)

\[
\sigma_t \propto \sqrt{\frac{1}{A_1 A_2 \cdot B}}
\]

=> Large bandwidth needed
  – wide band receivers (2 – 14 GHz [3 - 18])
  – Flexible frequency allocation
  – Dual linear polarization
CONT17 VGOS Bands

4 bands, each band 500 MHz wide

\[ \text{SNR} \sim A \times \sqrt{\text{#Bits}} = A \times \sqrt{2 \times 4 \times 500 \times 10^6} = A \times 63.3 \times 10^3 \]

4 times the SNR as S/X
Compensates for \((12/20)^2 = 36\%\) factor due to antenna size

Future VGOS sessions will be more sensitive because they will observe more of the 2-14 GHz band.

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“Design Aspects of the VLBI2010 System”

Name later changed to VGOS

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>VLBI2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>antenna size</strong></td>
<td>5–100 m dish</td>
<td>~ 12 m dish</td>
</tr>
<tr>
<td><strong>slew speed</strong></td>
<td>~20–200 deg/min</td>
<td>≥ 360 deg/min</td>
</tr>
<tr>
<td><strong>sensitivity</strong></td>
<td>200–15,000 SEFD</td>
<td>≤ 2,500 SEFD</td>
</tr>
<tr>
<td><strong>frequency range</strong></td>
<td>S/X band</td>
<td>~2–14 (18) GHz</td>
</tr>
<tr>
<td><strong>recording rate</strong></td>
<td>128-512 Mbps</td>
<td>8–16 Gbps</td>
</tr>
<tr>
<td><strong>data transfer</strong></td>
<td>usually ship disks, some e-transfer</td>
<td>e-transfer, e-VLBI, ship disks when required</td>
</tr>
</tbody>
</table>

VGOS Telecopes

Wettzell (DE)

Zelenchukskaya (RU)

Ishioka (JP) Courtesy Y. Fukuzaki

GGAO (US) Courtesy A. Niell

Badary (RU)

Courtesy A. Ipatov
New VGOS Telescopes for IVS

Need more stations in the southern hemisphere!

Data current as of Dec 2018
International Terrestrial Reference Frame (ITRF)

- Provides the stable coordinate system that allows us to measure change (link measurements) over space, time and evolving technologies.
- An accurate, stable set of station positions and velocities.
- Foundation for virtually all space-based and ground-based metric observations of the Earth.
- Established and maintained by the global space geodetic networks.
- Network measurements must be precise, continuous, and worldwide.
- Must be robust, reliable, geographically distributed
  - proper density over the continents and oceans
  - interconnected by co-location of different observing techniques
Does not include decommissioned or mobile VLBI sites

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All sites in ITRF2014

VLBI, SLR, GNSS and DORIS

Figure taken from CDDIS

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Tsukuba post-seismic movement

Green line is linear motion
Red line is post-seismic model.

GPS measurements       VLBI measurements
ITRF2014 replaces, and is more accurate than previous global coordinate systems. As techniques improves, have more stations and greater accuracy.

- Agrees with original WGS84 at the 1 meter level
- Agrees with revised WGS84 (which used GPS in its definition) at the 5 cm level.
  - WGS84 is the coordinate system of GPS
- Agrees with ITRF2005 at the few cm.
  - GTRF (Galileo Terrestrial Reference Systems) is identical to ITRF2005
ITRF2014

Uses Earth Centered, Earth Fixed Frame

Goal is to have a coordinate system that spans the world with:

- 1 mm accuracy
- 0.1 mm/yr stability.
- Currently about a factor of 3-5 away from this.

For each site:

- Position
- Velocity
- Sometimes… post-seismic deformation models

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Space Geodetic Systems

- Very Long Baseline Interferometry (VLBI)
- Global Navigation Satellite System (GNSS)
- Satellite Laser Ranging (SLR)
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

http://www.nap.edu/catalog/12954.html
Good overview on:
1. Space geodesy
2. NASA’ Space Geodesy Project.
Very Long Baseline Interferometry (VLBI)

- 40 IVS stations worldwide acquiring data, some daily.
  - ~20-30 cooperating stations
  - NASA runs 3 VLBI sites (and number is growing)
  - Provides support for 3 partner sites.
- Observable is difference in arrival time of signal originating from quasar
  - Signal is weak → antennas must be large
- Determines:
  - Station position
  - Scale
  - Source position
  - EOP
  - Scale
- Cost of new VGOS antenna ~$10M
  - Please take all cost numbers as very approximate.
Satellite Laser Ranging (SLR)

- Currently 23 operational stations worldwide acquiring data daily.
  - NASA runs 5 SLR sites
  - Provides support for 3 partner sites
- Observable is round trip travel time of laser signal.
- Determine:
  - Station position
  - Scale
  - Orbits
- Cost: ~$10M
Global Navigation Satellite Systems (GNSS)

- 440 GNSS tracking stations within the International GNSS Service (IGS) network.
  - 68 NASA Stations
  - 1000s of other stations
- Signal is transmitted by satellite and detected by ground based receiver.
- Determine
  - Station position
  - Polar Motion
  - Orbits
- Cost: $10K-$50K
DORIS

- Currently 60 operational stations worldwide acquiring data daily.
- Signal originates on ground, and received by satellite.
- Determine:
  - Station position
  - Orbits
- Cost: Can’t buy.
Global Geodetic Observing System

VGOS is part of GGOS
CORE Sites

- Each technique has strengths and weaknesses.
- The best results come from combining the techniques.
- This requires having two or more techniques at each site.
  - You also need good local surveying ties.
- A CORE site has all 4 techniques.
- Goal is to have ~30 globally distributed CORE sites.
- NASA is planning on running 10 CORE sites.
- NASA currently has 3 CORE sites:
  - Greenbelt, Maryland. First prototype.
  - Kokee Park, Hawaii. Second site.
  - McDonald, Texas. Operational later this year.
Global Geodetic Observing System

DORIS

GPS

VLBI

SLR
# The Geodetic Measurement System

<table>
<thead>
<tr>
<th>Technique</th>
<th>Functionality</th>
</tr>
</thead>
</table>
| **VLBI** | • Orientation of ITRF with respect to ICRF  
            • ITRF Scale |
| **SLR**  | • Origin of ITRF (Earth’s CM)  
            • ITRF Scale  
            • Position spacecraft in ITRF (“Orbits”) |
| **GNSS** | • Precise monitoring of Polar Motion and Rotation Rate  
            • Position spacecraft in ITRF (“Orbits”)  
            • Position instruments on Land and Sea (Tide Gauges and Buoys, Geodetic Instruments) |
| **DORIS** | • Position spacecraft in ITRF (“Orbits”)  
            • Enhances global distribution of ITRF Station positions and velocities |

- **Low-Density Global Distribution**
- **High-Density Global Distribution**
- **Fully Define ITRF**
- **VTS: ITRF Performance Improvement**

- **Origin, Scale, Orientation**
- **Technique Connectivity (Station Co-Location)**
Goddard Geophysical and Astronomical Observatory (GGAO) is located 5 km from Goddard Space Flight Center in the middle of the Beltsville Agricultural Research Center. GGAO is one of the few sites in the world to have all four geodetic techniques co-located at a single location.

- Legacy GNSS
- New GNSS
- MOBLAS-7
- DORIS
- REGINA GNSS
- VLBI2010
- MV-3 VLBI
- NGSLR
- Reference mark
Geodetic Observatory Wettzell
Site Selections: Ideal versus Reality

Current Co-located Sites (VLBI, SLR, GNSS)

Ideal

- 4 Stations per Site

Reality Circle

- Agreements, NASA Contributions, International Plans, GGOS Call

Conceptual Network Distribution

Current & Proposed Sites under Discussion

- Operational, Technology, Deployment Costs
- Site Assessments
- ITRF Performance Predictions
- Phasing Plan
- Other factors

Iterative Analysis
Introduction and Justification
- What is a Fundamental Station?
- Why do we need the Reference Frame?
- Why do we need a global network?
- What is the current situation?
- What do we need?

Site Conditions
- Global consideration for the location
- Geology
- Site area
- Weather and sky conditions
- Radio frequency and optical Interference
- Horizon conditions
- Air traffic and aircraft Protection
- Communications
- Land ownership
- Local ground geodetic networks
- Site Accessibility
- Local infrastructure and accommodations
- Electric power
- Site security and safety
- Local commitment

(http://cddis.gsfc.nasa.gov/docs/GGOS_SiteReqDoc.pdf)
UN Adopted 1st Geospatial Resolution

- Global Geodetic Reference Frame (ITRF and ICRF combination) for Sustainable Development (GGRF) resolution - No. A/69/L.53 -

- adopted by the United Nations General Assembly on 26\textsuperscript{th} of Feb, 2015

- co-sponsored by 52 Member States including Japan

- … first resolution recognizing the importance of a globally coordinated approach to geodesy – the discipline focused on accurately measuring the shape, rotation and gravitational field of planet Earth.

- The General Assembly resolution, \textit{A Global Geodetic Reference Frame for Sustainable Development}, outlines the value of ground-based observations and remote satellite sensing when tracking changes in populations, ice caps, oceans and the atmosphere over time.

Introduced by
Ambassador Peter Thomson, Fiji
#GGRF - Core to building a better world
Inaugural Meeting: Mexico City in 2017

Strengthening the role of geodesy

Mexico City: The inaugural meeting for the United Nations Subcommittee on Geodesy was convened on November 26th and
Summary: VGOS & GGOS

- Challenging program with very important science and societal benefits
- Technologies are maturing; new technologies are on the horizon
- Global distribution is essential; success needs the enhanced networks that will depend on partnerships
- Very large opportunity for participation in analysis and scientific research
- Need to engage young scientists and students
Questions?

Thanks for your attention!

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