Current State of Global Geodesy Supply Chain
From the ITRF perspective/experience

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Meeting of Expert Consultation on Strengthening the
Global Geodesy Supply Chain
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Key points

• The ITRF supply chain, part of the Global Geodesy Supply Chain
• Space geodesy techniques contributing to the ITRF
• Why is the ITRF needed?
• Critical points impacting the ITRF accuracy
• Strengths and weaknesses of space geodesy techniques

• Focus on SLR and VLBI, and why?

• Illustrations based on ITRF2020 input data
What is a Reference Frame in practice?

- **Earth fixed/centered Reference Frame**: allows determination of point positions and satellite orbits as a function of time.

- When analyzing space geodesy data, we have to take into account:
  - Relativity theory
  - Forces acting on the satellite
  - The atmosphere
  - Earth rotation
  - Solid Earth and ocean tides
  - ...

- Linear and nonlinear variations/deformations

  ==> Station coordinates are function of time

  Accuracy: few mm and few 0.1 mm/yr for the best stations
ITRF Supply Chain: an International Effort

Observations & Data Collection

Data analysis & Product Generation per Technique

Technique Unification & ITRF generation

NMAs
Space Agencies
Universities

Research Groups from:
NMAs, Space Agencies & Universities

Schematic illustration of the chains leading to the ITRF generation
Space geodetic techniques contributing to the ITRF
Geodetic Infrastructure: our heritage

884 GNSS
124 VLBI
96 SLR
71 DORIS

BUT: only 35% of VLBI and SLR sites are in operation today
Most of the old decommissioned sites were of poor quality
Colocation site

Yarragadee Geodetic Observatory, Western Australia
Under the responsibility of Geoscience Australia
Why is the ITRF needed?

Operational geodesy applications:

- Positioning: Real Time or a posteriori
- Navigation: Aviation, Terrestrial, Maritime
- Regional/National geodetic frames
- Today: via GNSS only!
- Require the availability of the IGS orbits and the reference frame (ITRF)
- Many, many users…

GNSS-specific reference frames:

- GTRF/Galileo, WGS84/GPS, PZ-90/GLONASS, CGCS2000/Beidou, JGS/QZSS
- All are aligned to the ITRF

Science applications:

- Earth’s Center of Mass sensed by SLR
- Precise Orbit Determination
- Co & Post-Seismic deformations
- Volcano eruptions & their observations
- Post-Glacial Rebound
- Tectonic motion & deformation
- Ice melting through satellite altimetry
- Sea-level variations via satellite & Tide Gauges
- Crust response to loading effects
- Requirement: Accuracy of ITRF parameters: 1 mm & 0.1 mm/yr

Continuous observations are fundamental

Positioning geospatial information to address global challenges
Resolutions on ITRS & ITRF

- **IUGG2007**: adopted the ITRS as the preferred Geocentric Terrestrial Reference System (GTRS) for scientific and technical applications
- **CGPM2011**: recommends that the ITRS, as defined by the IUGG and realized by IERS, be adopted as the unique international reference system for terrestrial reference frames for all metrological applications
- **ICG2012**: recommendation to align GNSS-specific reference frames (WGS84, PZ90, GTRF, CGCS2000, JGS) to the ITRF
- **IUGG2019**: recommend to the user community that the ITRF be the standard for positioning, satellite navigation and Earth Science applications, …
- **UN-GGIM-2019**: adoption of the ITRS and the ITRF as the standard for scientific, geospatial and operational geodetic applications
- **ISO Standard on ITRS/ITRF**
Critical points impacting the ITRF accuracy

1. **Reference frame definition**:
   - Origin, scale, orientation and their time evolution
   - Science requirement: 1 mm accuracy and 0.1 mm/yr stability

2. **Network geometry / coverage of the 4 technique networks over the Earth surface**: Well distributed networks are needed

3. **Accurate, continuous & regular observations to accurately model linear and nonlinear station motions**: long time series are needed to maintain the frame over decades

4. **Accurate / repeated local ties at colocation sites**
Why Multiple Techniques for the ITRF?

- **VLBI & SLR:**
  - Fundamental for an accurate definition of the ITRF physical parameters/properties
  - SLR determines Earth Center of Mass ==> ITRF origin
  - SLR & VLBI define the ITRF scale
  - VLBI places the Earth in space ==> Link to the ICRF

\[
\begin{bmatrix} GCRS \end{bmatrix} = Q(t)R(t)W(t) \quad [ITRS]
\]

  - But their ground networks are poorly distributed and in danger of degradation

- **DORIS:** disseminates ITRF in satellite orbit determination

- **GNSS:**
  - Ensures the link between SLR, VLBI & DORIS networks
  - Is the tool today to access the global ITRF by the regions and nations using IGS products
Technique systematic errors

- **DORIS**: mis-modelling of the solar radiation pressure ==> inaccurate geocenter components, and nonlinearity in the long-term TRF scale
- **GNSS** have multiple weaknesses in recovering the Earth center of mass position and the TRF scale (in the absence of satellite metadata)
- **SLR** range biases have significant impact on the TRF scale
- **VLBI** antenna gravitational deformation ==> impact on the TRF scale

**Progress towards improving the TRF scale determination**:
- **GNSS**: Metadata are now available for Galileo, Beidou, QZSS, GPS Block III
- **SLR**: ILRS adjusts RBs since ITRF2020, improving the scale and its agreement with VLBI
- **VLBI**: Deformation models for a number of antennas are now available
- **DORIS**: Investigations by IDS are in progress
# ITRF2020 Input Data

<table>
<thead>
<tr>
<th>TC</th>
<th># of solutions</th>
<th>Time-span</th>
<th># of sites</th>
<th>Frame Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDS/DORIS</td>
<td>1456 weekly</td>
<td>1993.0 – 2021.0 (28 yrs)</td>
<td>87</td>
<td>CM</td>
</tr>
<tr>
<td>IGS/GNSS/GPS</td>
<td>9861 daily</td>
<td>1994.0 – 2021.0 (27 yrs)</td>
<td>1159</td>
<td>CN</td>
</tr>
<tr>
<td>ILRS/SLR</td>
<td>243 fortnightly</td>
<td>1983.0 – 1993.0</td>
<td>100</td>
<td>CM</td>
</tr>
<tr>
<td></td>
<td>1460 weekly</td>
<td>1993.0 – 2021.0 (38 yrs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVS/VLBI</td>
<td>6178 session-wise</td>
<td>1980.0 – 2021.0 (41 yrs)</td>
<td>117</td>
<td>CN</td>
</tr>
</tbody>
</table>
Positioning geospatial information to address global challenges

VLBI and SLR stations used in ITRF2020

**VLBI**
36 stations

Red: no data after 2021.0
Circle size according to the number of sessions.

**SLR**
34 stations

Red: no data after 2021.0
Circle size according to the number of weeks.

RF stations: 24
Not active: 7

RF stations: 16
Not active: 5

VLBI stations:
- Total: 36 stations
- RF stations: 24
- Not active: 7

SLR stations:
- Total: 34 stations
- RF stations: 16
- Not active: 5
Current SLR & VLBI Networks

Colocated with GNSS

Current SLR-VLBI Networks

Positioning geospatial information to address global challenges
Animation / movie
Evolution of VLBI Sessions during the year 2020:

142 sessions all in all
Notice regional sessions not well designed for the TRF:
xxx sessions
Positioning geospatial information to address global challenges
Animation / movie
Weekly SLR processing residuals using measurements of Lageos I & II, Etalon I & II, Year 2023
Measurements on LAG1, LAG2, ETA1 and ETA2

JJCNES between 26649 and 26655

GINS processing residuals (cm)
Animation / movie
Evolution of weekly SLR network during the year 2023
List of all stations used between JJCNES 26649 and 26655
Stations observing LAG1, LAG2, ETA1 and ETA2
VLBI & SLR Data Volume in years up to 2021.0

Shown are stations with data volume > 1 year

Positioning geospatial information to address global challenges
## ITRF2020: Local tie Discrepancies

LT Discrepancies: Differences between terrestrial ties and space geodesy estimates
Local tie vectors between GNSS and the 3 other techniques at co-location sites

<table>
<thead>
<tr>
<th>GNSS to:</th>
<th>Total tie vectors</th>
<th>Discrepancy</th>
<th>% Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ITRF2020</td>
<td>&gt; 5 mm</td>
</tr>
<tr>
<td>VLBI</td>
<td>77</td>
<td>39</td>
<td>50</td>
</tr>
<tr>
<td>SLR</td>
<td>53</td>
<td>34</td>
<td>64</td>
</tr>
<tr>
<td>DORIS</td>
<td>123</td>
<td>84</td>
<td>68</td>
</tr>
</tbody>
</table>
ITRF : Uncertainty in the frame definition/specification

- **Origin**: Rely on one technique: SLR
  - Long-term uncertainty: at epoch 2015.0: up to 5 mm
  - Stability / rate: up to 0.5 mm/yr

- **Scale**: Average of SLR & VLBI
  - Long-term uncertainty (level of agreement between SLR & VLBI):
    - ITRF2014: 1.4 ppb (~8 mm at the equator)
    - ITRF2020: 0.15 ppb (~1 mm at the equator)
  - Stability / rate: depend on “agreement of site velocities”
  - SLR & VLBI scale time series are not linear!!

- **Orientation**: Alignment of successive ITRF solutions using a selection of reference frame stations
  - Long-term & stability / rate uncertainty: dictated by the so-called network effect: up to 30µas (1mm)
### Future / Planned VGOS stations

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat, Lon</th>
<th>Type</th>
<th>Responsible Agency</th>
<th>Planned Commissioning Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>39 N, 116 E</td>
<td>China</td>
<td>upgrade of core site by new VGOS station</td>
<td>2024</td>
</tr>
<tr>
<td>Hangzhou</td>
<td>30 N, 120 E</td>
<td>China</td>
<td>new VGOS station</td>
<td>2024</td>
</tr>
<tr>
<td>Urumqi</td>
<td>43 N, 87 E</td>
<td>China</td>
<td>upgrade of core site by new VGOS station</td>
<td>2024</td>
</tr>
<tr>
<td>Nanjing</td>
<td>31 N, 121 E</td>
<td>China</td>
<td>new VGOS station</td>
<td>2024</td>
</tr>
<tr>
<td>Naples</td>
<td>40 N, 16 E</td>
<td>Italy</td>
<td>upgrade of core site by new VGOS station</td>
<td>2024</td>
</tr>
<tr>
<td>Helsinki</td>
<td>60 N, 24 E</td>
<td>Finland</td>
<td>upgrade of core site by new VGOS station</td>
<td>2024/2025</td>
</tr>
<tr>
<td>Pretoria</td>
<td>25 N, 28 E</td>
<td>South Africa</td>
<td>upgrade of core site by new VGOS station</td>
<td>2024/2025</td>
</tr>
<tr>
<td>Madrid</td>
<td>40 N, 36 W</td>
<td>Spain</td>
<td>new VGOS station</td>
<td>2025/2026</td>
</tr>
<tr>
<td>Florence</td>
<td>43 N, 10 W</td>
<td>Italy</td>
<td>upgrade of core site by new VGOS station</td>
<td>2025/2026</td>
</tr>
<tr>
<td>Lisbon</td>
<td>39 N, 31 W</td>
<td>Portugal</td>
<td>new VGOS station</td>
<td>2030</td>
</tr>
<tr>
<td>La Plata</td>
<td>35 S, 56 W</td>
<td>Argentina</td>
<td>upgrade of core site by new VGOS station</td>
<td>2030</td>
</tr>
<tr>
<td>Tahiti</td>
<td>17 S, 149 W</td>
<td>French Polynesia</td>
<td>new VGOS station</td>
<td>2030</td>
</tr>
</tbody>
</table>

### Future / Planned VGOS stations (additional)

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat, Lon</th>
<th>Type</th>
<th>Responsible Agency</th>
<th>Planned Commissioning Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batam</td>
<td>1 N, 101 E</td>
<td>Indonesia</td>
<td>upgrade of radio telescope to VGOS station (1)</td>
<td>2030/2031</td>
</tr>
<tr>
<td>Flores</td>
<td>16 S, 124 E</td>
<td>Indonesia</td>
<td>new VGOS station</td>
<td>2030/2031</td>
</tr>
</tbody>
</table>

Positioning geospatial information to address global challenges
# Future / Planned SLR stations

## Table 1. Future ILRS Network Developments

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Type</th>
<th>Agency</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Plata, Argentina</td>
<td>Upgraded core site</td>
<td>BKG, Germany</td>
<td>2024 – 2025</td>
</tr>
<tr>
<td>San Juan, Argentina</td>
<td>Upgraded SLR system</td>
<td>NAOC, China</td>
<td>2024 – 2025</td>
</tr>
<tr>
<td>Metsähovi, Finland</td>
<td>New SLR system</td>
<td>FGI, Finland</td>
<td>2024 – 2025</td>
</tr>
<tr>
<td>Greenbelt, MD, USA</td>
<td>Replacement core site</td>
<td>NASA, USA</td>
<td>2024 – 2024</td>
</tr>
<tr>
<td>Haleakala, HI, USA</td>
<td>Replacement core site</td>
<td>NASA, USA</td>
<td>2024 – 2026</td>
</tr>
<tr>
<td>McDonald, TX, USA</td>
<td>Replacement core site</td>
<td>NASA, USA</td>
<td>2024 – 2025</td>
</tr>
<tr>
<td>Ny Alesund, Norway</td>
<td>New core site</td>
<td>NMA, Norway/NASA, USA</td>
<td>2024 – 2025</td>
</tr>
<tr>
<td>Ensenada, Mexico</td>
<td>New SLR site</td>
<td>IPIE, Russian Federation*</td>
<td>2024 – 2026</td>
</tr>
<tr>
<td>Java, Indonesia</td>
<td>New SLR site</td>
<td>IPIE, Russian Federation*</td>
<td>2024 – 2026</td>
</tr>
<tr>
<td>Gran Canaria, Spain</td>
<td>New SLR in core site</td>
<td>IPIE, Russian Federation*</td>
<td>2024 – 2026</td>
</tr>
<tr>
<td>Tahiti, French Polynesia</td>
<td>New SLR system</td>
<td>IPIE, Russian Federation*</td>
<td>2024 – 2026</td>
</tr>
<tr>
<td>Mt Abu, India</td>
<td>New SLR site</td>
<td>ISRO, India*</td>
<td>2025 – 2026</td>
</tr>
<tr>
<td>Pommundi, India</td>
<td>New SLR site</td>
<td>ISRO, India*</td>
<td>2025 – 2026</td>
</tr>
<tr>
<td>Ishioka, Japan</td>
<td>New SLR site</td>
<td>Hitotsubashi U., NAOJ and U. Tokyo, Japan</td>
<td>2024</td>
</tr>
<tr>
<td>Yebes, Spain</td>
<td>New SLR site</td>
<td>IGS, Spain</td>
<td>2024</td>
</tr>
<tr>
<td>Irkutsk (Tochka)</td>
<td>New SLR site</td>
<td>VNIIFTRI, Russia</td>
<td>2025 – 2026</td>
</tr>
<tr>
<td>Mendeleevo (Tochka)</td>
<td>New SLR site</td>
<td>VNIIFTRI, Russia</td>
<td>2025 – 2026</td>
</tr>
</tbody>
</table>

*Situation uncertain
Summary

– ITRF is fundamentally based on colocations: Strengthen ITRF parameters
– The origin (CM) of the ITRF needs improvement by a factor of 5.
– SLR & VLBI are critical for the frame definition: origin (SLR), scale (SLR & VLBI)
– SLR & VLBI collocations (~ 10 sites) are poorly distributed
– A number of SLR & VLBI instruments are old-generation systems
– Both networks need improvement, especially in the southern hemisphere
– Quantitatively: Data yield is poor for both techniques
– VLBI sparse sessions, with less than 10 stations in average
– Need to evolve toward more frequent global sessions, with increased number and well-distributed stations

– GNSS links together SLR, VLBI & DORIS networks
– More than 50 % of tie discrepancies are larger than 5 mm,
– Caused mainly by technique systematic errors
**SCoG Geodetic Infrastructure Questionnaire 2019/2020**

**Summary of SLR & VLBI needs**

<table>
<thead>
<tr>
<th># Instruments needed to fill the gaps in the network</th>
<th># of additional Data Centers</th>
<th># of additional Analysis Centers</th>
<th>New technology development</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4</td>
<td>6</td>
<td>~$200M</td>
</tr>
<tr>
<td>Cost for one instrument: ~$8M</td>
<td>Total annual cost per center: ~$250K</td>
<td>Total annual cost per center: ~$600K</td>
<td></td>
</tr>
</tbody>
</table>

Cost for one instrument: ~$8M
Total annual cost per center: ~$250K
Total annual cost per center: ~$600K

~$200M
Many Thanks for their contributions

• ILRS and IVS

• Florent Deleflie (IMCCE, Paris)

• David Sarrocco (ASI, Italy)

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  – Paul Rebischung
  – Julien Barnéoud