Connecting kinematic and dynamic reference frames by VLBI

Harald Schuh
Lucia Plank
Johannes Böhm
Matthias Madzak
Motivation

Frame ties
- ties between TRF and CRF by EOP
- ties between various realizations of the CRS
  - optical ↔ radio frequencies
  - kinematic ↔ dynamic (ephemerides)
- but: direct ties between TRF ↔ DRF (satellites, spacecrafts) and CRF ↔ DRF are also needed
Frame ties: general remarks

- Ties between the ICRF and dynamical realizations of the ICRS (satellite orbits, spacecraft ephemerides) can be established by differential VLBI (D-VLBI) observations.

- The IERS Earth Orientation Parameters (EOP) provide the permanently changing tie between the ICRF and the ITRF.

- Inter-technique co-location sites are the backbone of the current combined solution of the ITRF.

- Local ties on ground (on fundamental geodetic sites) need to be improved for future ITRF improvement.

- Local ties in space (e.g. various techniques on the same satellite) need also to be established.
VLBI for space applications

... VLBI with sources (=targets) alternatively to quasars, mostly within the solar system
Observing modes (1)

- **„classical“ VLBI**

- **differential (D-)VLBI**
  
  - switching between satellite/spacecraft and quasar
  
  - or same-beam method (e.g. SELENE, Chang‘e)
  
  - signals travel through the same atmosphere
    → many errors cancel out
Recent developments

- Promising recent missions and tests
  - Japanese SELENE lunar mission
  - Chinese Chang‘e lunar mission
  - VLBI observations to GLONASS satellites (Tornatore & Haas)

- Recent technical developments
  - VLBI transmitters as payload
  - VLBI2010
  - ‘Twin telescopes’ (two identical radiotelescopes at same site, e.g. Wettzell) offer new observing modes

SELENE: same-beam D-VLBI improved the orbit consistency from several hundreds to several tens of meters (Goossens et al., JoG, 2010)
... as determined empirically from SELENE D-VLBI observations [Plank et al., Proc. IVS GM 2012]

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>( \tau )</th>
<th>( \Delta \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna ±5 cm</td>
<td>300 ps</td>
<td>1-2 ps</td>
</tr>
<tr>
<td>Orbit ±10 m</td>
<td>150-1000 ps</td>
<td>2-8 ps</td>
</tr>
<tr>
<td>EOP</td>
<td>5 (60) ps</td>
<td>&lt; 0.05 (0.1) ps</td>
</tr>
<tr>
<td>dUT1: 5 ms/xp, yp: 200 mas/dX, dY: 300 mas</td>
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<table>
<thead>
<tr>
<th>ATMOSPHERE</th>
<th>( \tau )</th>
<th>( \Delta \tau )</th>
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<tbody>
<tr>
<td>Hydrostatic troposphere, a priori</td>
<td>2-20 (10-60) ns</td>
<td>30-300 (50-1000) ps</td>
</tr>
<tr>
<td>Wet troposphere, ECMWF</td>
<td>1-3 (4) ns</td>
<td>4-40 (10-60) ps</td>
</tr>
<tr>
<td>Ionosphere, TEC-maps</td>
<td>1.5 (2-10) ns</td>
<td>10 (80) ps</td>
</tr>
</tbody>
</table>

“single” delay \( \tau \) approx. factor 100 differenced delay \( \Delta \tau \)
Observing modes (2)

- **Differential (D-) VLBI**
- **Co-location in space**
  - VLBI-transmitters as payload
  - Studies: GRASP (JPL), Micro-GEM, Nano-GEM (GFZ)
Co-location in Space

Proposed NASA Mission: Geodetic Reference Antenna in Space (GRASP)

- Co-location of geodetic techniques contributing to the TRF
- Determine TRF with 1 mm accuracy and 0.1 mm/yr stability
- Orbit: 1350 x 850 km polar, sun-synchronous

GPS receiver

SLR retroreflector

DORIS receiver

VLBI beacon

Orbit: 1400 or 2000 km altitude, circular, sun-synchronous (~101.4° or ~105° inclination). No eclipses
Visibility

- Can we observe satellites in VLBI mode?
- Visibility study with possible VLBI2010 network
- GRASP can be observed in VLBI mode only partly,
- by 2 to max. 3 regional antennas at the same time.
- June 2012: GRASP was not selected by NASA but further studies/projects are planned.
Observing modes (3)

- Differential (D-) VLBI
- Co-location in space
- VLBI observations of GNSS-Satellites
  - VLBI observations of GLONASS-Satellites successfully done (Tornatore & Haas)
GNSS satellites can be observed in VLBI mode easily!
e.g.

- **Satellite orbit /spacecraft position**
  - not sensitive in line-of-sight
    → constrain satellite height
e.g.

- **satellite position/orbit**
  - not sensitive in line of sight
    → constrain satellite height

- **station position repeatabilities**
  - simulations with GNSS networks (4 stations)
  - accuracies are not very good yet (cm-level)
    → special scheduling strategies are needed
GNSS simulation

Station position repeatabilites

![Graph showing station position repeatabilities with different colors for north, east, and h.]

- Zelenchek
- Svetloe
- Badary
- Urumqi

Turbulent
Cn = 2.5e-7
GNSS simulation

Station position repeatabilities

**turbulent**

Cn = 2.5e-7

Station position repeatabilities

**less turbulent**

Cn = 1.0e-7
Target parameters

e.g.

- **satellite position /orbit**
  - not sensitive in line of sight
    → constrain satellite height

- **station repeatabilities**
  - simulations with GNSS networks (4 stations)
  - accuracies are not very good yet (cm-level)
    → better scheduling is needed

- **frame ties (described by e.g. 3 angles)**
Target parameters

e.g.

- **satellite position /orbit**
  - not sensitive in line of sight
  → constrain satellite height
- **station repeatabilities**
  - simulations with GNSS networks (4 stations)
  - accuracies are not very good yet (cm-level)
  → better scheduling
- **frame ties (e.g. 3 angles)**

Remark: troposphere is once again the limiting factor!
Conclusions

- Recent results motivate to use VLBI measurements to satellites for local ties, space ties, and frame ties.

- However, more research on the technical realization and observing strategies is needed.

- Modified VLBI Software (e.g. Vienna VLBI Software, VieVS) allows to simulate observations to satellites and gain information about achievable accuracies.

- Currently, VLBI observations to GNSS satellites are tested and several proposals for missions with a dedicated VLBI ‘signal‘ are going on.
THANK YOU FOR YOUR ATTENTION!

harald.schuh@tuwien.ac.at
Motivation 1

Navigation in space

– deep space navigation
  • routinely done (NASA, ESA)
  • sensitive perpendicular to the line of sight (LoS)

– lunar missions
  • SELENE, Chang’e
Motivation 3

Co-location in space

Inter-technique ties in space: e.g. GNSS-VLBI

Realizations:
- co-location in space (a)
  • studies: GRASP (JPL), MicroGEM (GFZ), ...
- using GNSS satellites as VLBI targets (b)
GNSS visibilities

NAVSTAR 56
- Observing stations
- Observing time per station

NAVSTAR 64
- Observing stations
- Observing time per station

GNSS satellites can be observed in VLBI mode easily!
Simulated turbulence

- Vienna VLBI Software (VieVS) simulator
  [Pany et al., 2010]; N = 30
Effect of trop. turbulence in diff. delays

- VieVS-simulator [Pany et al., 2010]; N = 30

JAN08 simulated residual turbulence
D-VLBI

- **but: for close satellites/spacecrafts it is difficult to find nearby radio sources**
  - e.g. SELENE (sc-sc): max. separation angle \(0.56^\circ\) (same beam)
  - 4-station GNSS network:
    the satellite vector is different for each baseline
    \(\Rightarrow\) angular distance between satellite & quasar:
    \[\Delta\text{el} = \pm 4^\circ\]
    \[\Delta\text{az} = \pm 10^\circ\]