Progress in Determining Ties Between Kinematic and Dynamic Reference Frames Through Differential Very Long Baseline Interferometry (D-VLBI)

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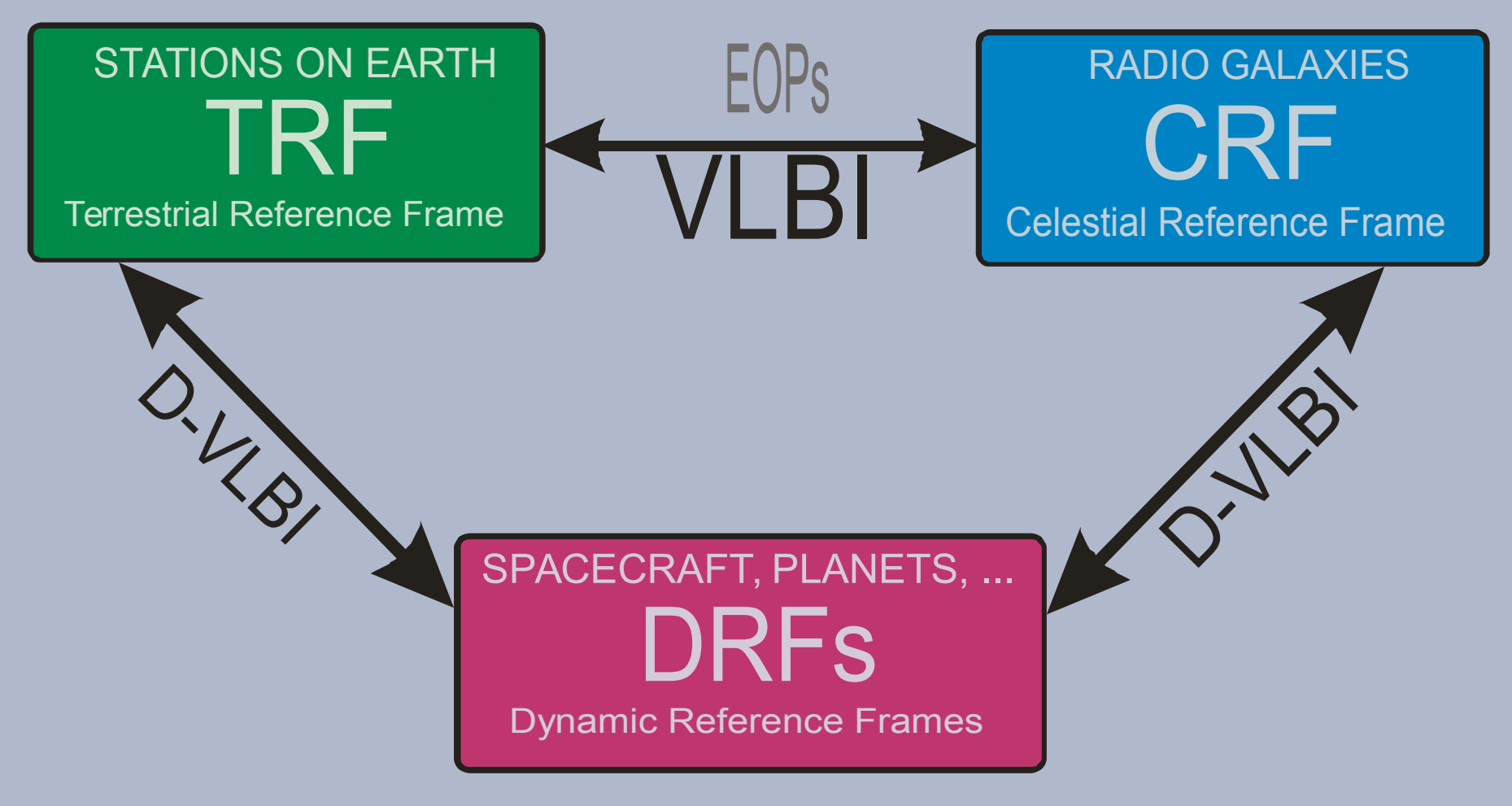
Establish ties between the dynamic reference frames of spacecraft and the ICRF by D-VLBI observations.

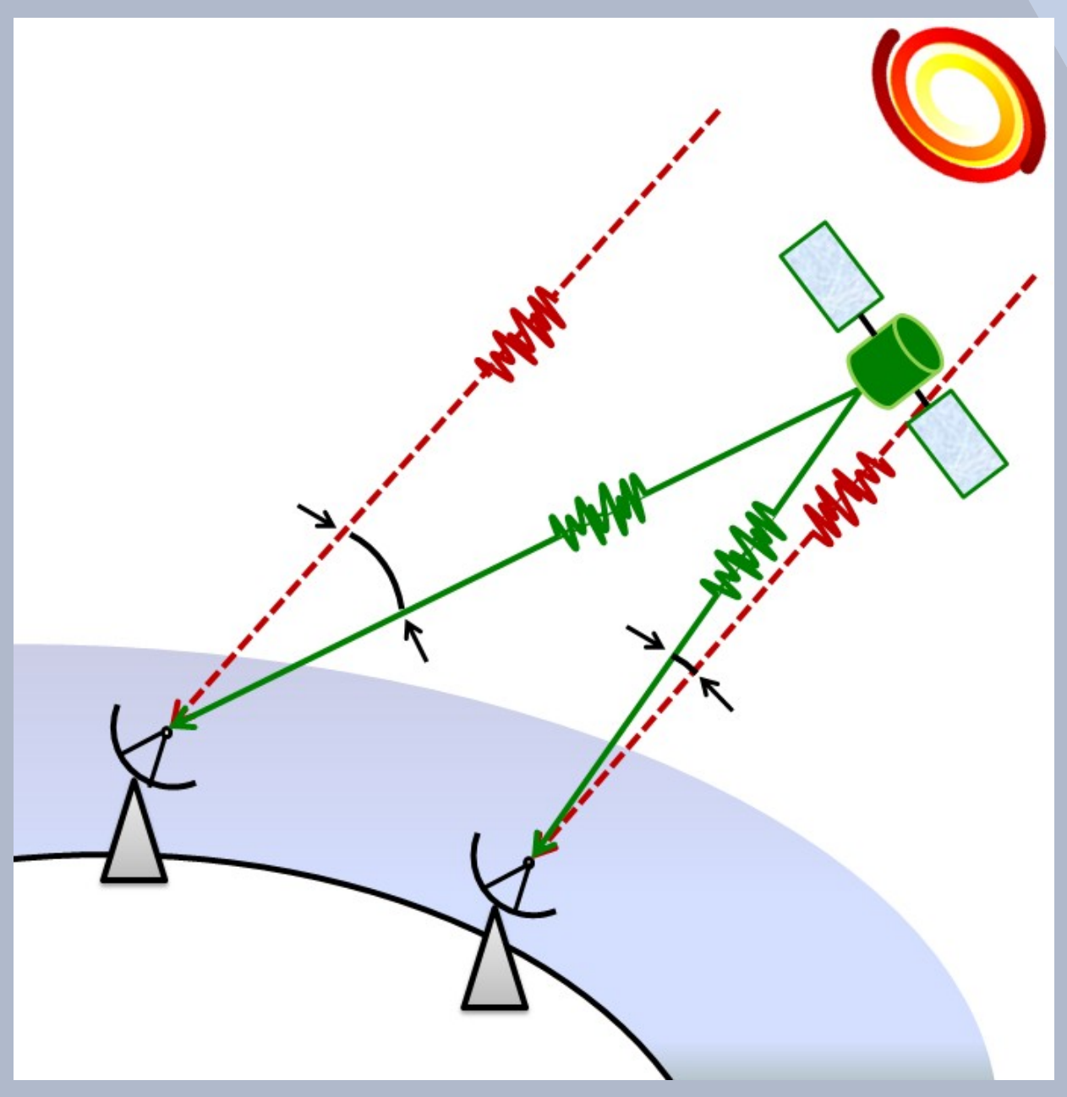
In the differential VLBI technique, a space probe's state vector is referenced to angularly nearby quasars by alternating VLBI observations between spacecraft and quasar signals.

Motivation

Distant celestial sources provide the most stable reference frame known. Standard geodetic VLBI observations tie the telescope positions in the kinematic International Terrestrial Reference Frame (ITRF) to the sources in the International Celestial Reference Frame (ICRF). Positions of spacecraft and planetary system bodies (planets, moons, asteroids) are typically realized in various dynamic reference frames that rest upon dynamical theories. Tying these dynamical frames to the celestial frame is essential in order to provide the most correct and reliable long-term results for applications including monitoring global change and climate variation and spacecraft navigation. **Differential VLBI** (known as phase referencing in the astronomical community), a technique that provides accurate, relative astrometric measurements by nearly canceling effects introduced by the instruments, troposphere, ionosphere, and delay models, has the capability to provide the most accurate positions of spacecraft and planetary bodies with respect to the ICRF, and thereby enables these dynamical frames to be tied to the ICRF.


STATIONS ON EARTH
TRF
Terrestrial Reference Frame
EOPs
VLBI
RADIO GALAXIES
CRF
Celestial Reference Frame
D-VLBI
D-VLBI
SPACECRAFT, PLANETS, ...
DRFs
Dynamic Reference Frames

Frames and observations to tie the frames



Principle of D-VLBI

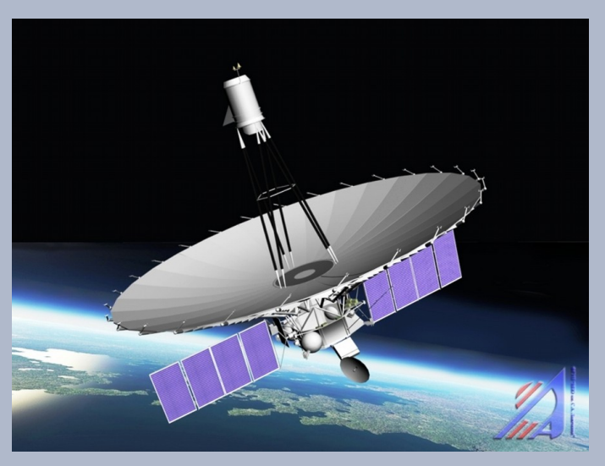
Dynamic reference frames are typically realized specifically for each satellite or satellite constellation; when it comes to the combination of various missions or follow-on satellites, precise ties between the various frames are essential for correct and long-term reliable results. D-VLBI provides the measurements that can tie all of these different frames to a single, highly stable frame, the ICRF.

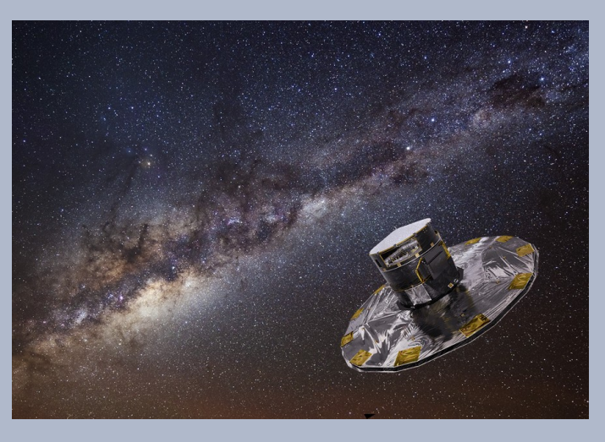
Objectives

The overall goal of our project is to assess the potential of the D-VLBI technique for the establishment of frame ties for geodesy and astrometry in the context of physically-nearby spacecraft targets as part of the research unit *Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space*. Practically we intend to:

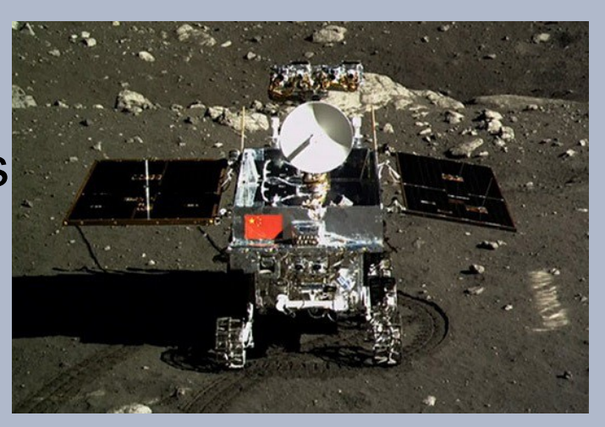
- Perform D-VLBI observations and analysis of selected spacecraft
  - Research and development projects to show proof of concept
  - Test D-VLBI observing strategies
  - Focus on three spacecraft/orbit types
    - GNSS satellites (GPS, GLONASS, BeiDou, Galileo) (~20 000 km altitude orbits)
    - RadioAstron (space-VLBI antenna, highly elliptical orbit influenced by the Moon)
    - Gaia (orbits about the 2nd Lagrange point)

- Collect and analyze available D-VLBI observations
  - Goal is to better tie the planetary ephemeris to the ICRF
  - MoU with Shanghai Astronomical Observatory to cooperate on the Chang'e mission series
    - Analyze Chang'e-1 and Chang'e-2 data to estimate Lunar barycenter
    - Chang'e-3 lander and rover data can locate Lunar surface
  - Provide transfer of knowledge for historical D-VLBI spacecraft measurements to other members of the research group
  - Simulate D-VLBI measurements and estimate uncertainties for future deep space missions to improve the ephemeris orientation





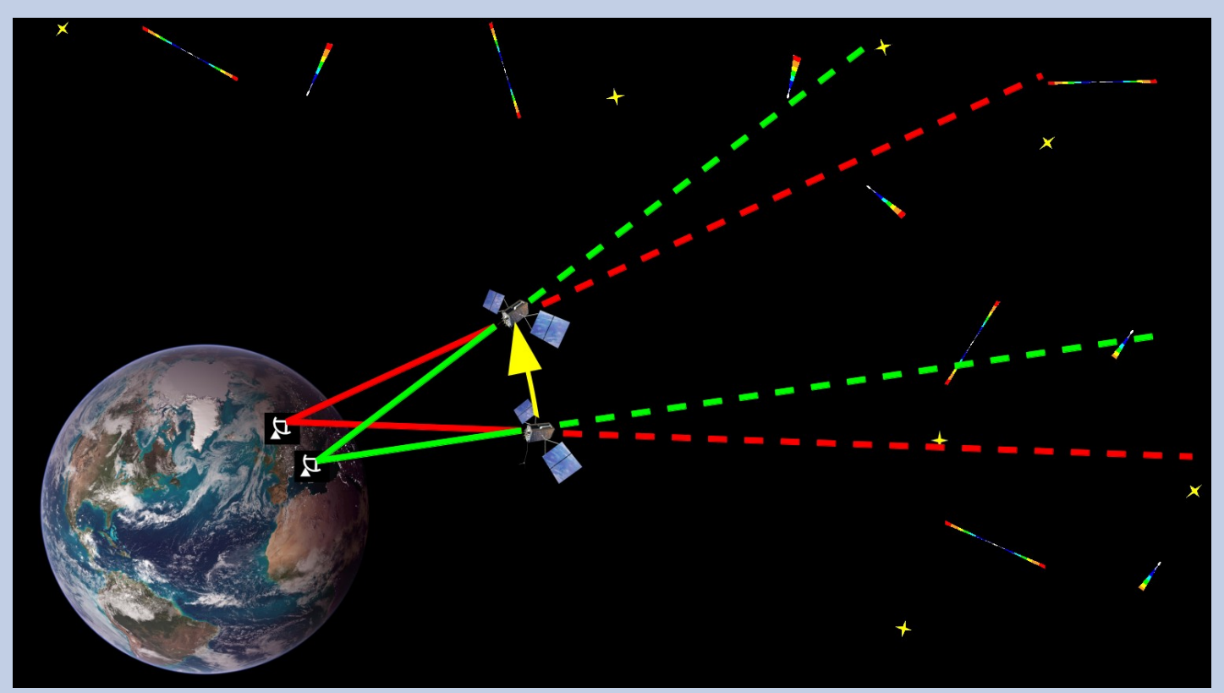
- Realize frame ties with the available D-VLBI observations
  - Provide spacecraft positions in the ICRF
  - For orbiters, spacecraft positions propagated through orbit model including ephemeris
  - For landers/rovers, can tie planetary body directly to ICRF
  - For spacecraft constellations (GNSS), at least several spacecraft within the constellation will need to be measured to realize the orientation of the constellation



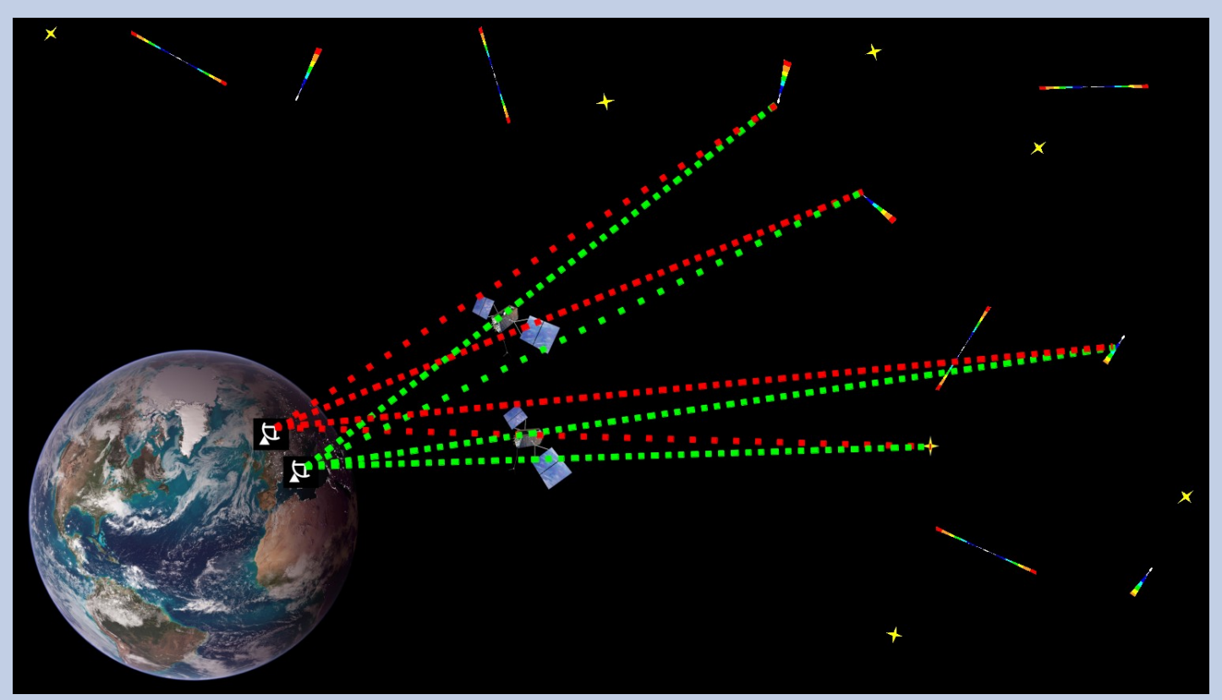
The main deliverables of our project are the frame ties in terms of precise positions of space probes in the ICRF. These products will be delivered to the other projects within our research unit as well as to the scientific community via publications and the research unit web server.

Approach

Our ultimate goals of ties between spacecraft realizing planetary dynamic frames and radio sources realizing the ICRF will be enabled through differential VLBI measurements and analysis. Although the D-VLBI technique has been applied astronomically and astrometrically for decades to (nearly) stationary targets, with continually refined differencing techniques, the application of D-VLBI to **nearby, rapidly moving targets** is still relatively new. The diagram to the right illustrates the problem.



VLBI measurements of a rapidly moving GNSS satellite



Corresponding calibrator measurements

- For a nearby target, each station sees the target at a different relative direction in the sky
  - Each station consequently needs a different calibration target on the sky to perform D-VLBI
  - Result: multiple calibrator observations required for each observation of the target, total observing time increased
- For rapidly moving targets, sequential observation scans of the target appear at different directions on the sky
  - Stations must use different calibrators as a function of time
  - Each calibrator will be observed less often (uncertainty larger)
  - Multiple different calibrators along track must be observed (accuracy improved)

Standard D-VLBI techniques for interpolation of atmospheric and instrumental effects from the calibrator positions to the target of interest must be modified to deal with a sequence of (often single) observations of different calibrators along a swath on the sky as the source moves.

We plan new D-VLBI observations of several different types of spacecraft with different orbital characteristics and downlink frequencies.

- Scheduling performed using software developed in the first term of this project, modified for various multi-calibrator strategies
- Correlated datasets analyzed using standard D-VLBI software (such as AIPS)
  - We will modify processing scripts/tasks to deal with our calibrator strategies
  - Will test how effectively different near-field delay models predict phases, group delays, and phase rates
- Frame ties using the D-VLBI position measurements will be realized in collaboration with other projects within our encompassing research unit.

Current Status

Pr09 GLONASS satellite was successfully tracked by Wettzell and Onsala 28.01.2013 at 13:15~13:59 (experiment: g130128, Pis: Neidhart, Haas).

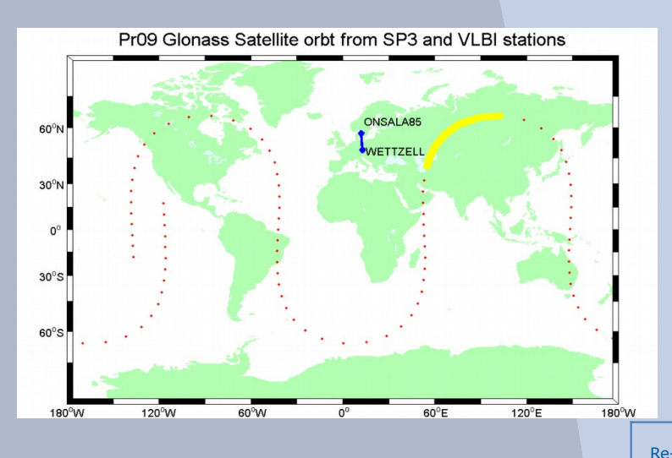


Fig. 1 Satellite tracking arc with single baseline

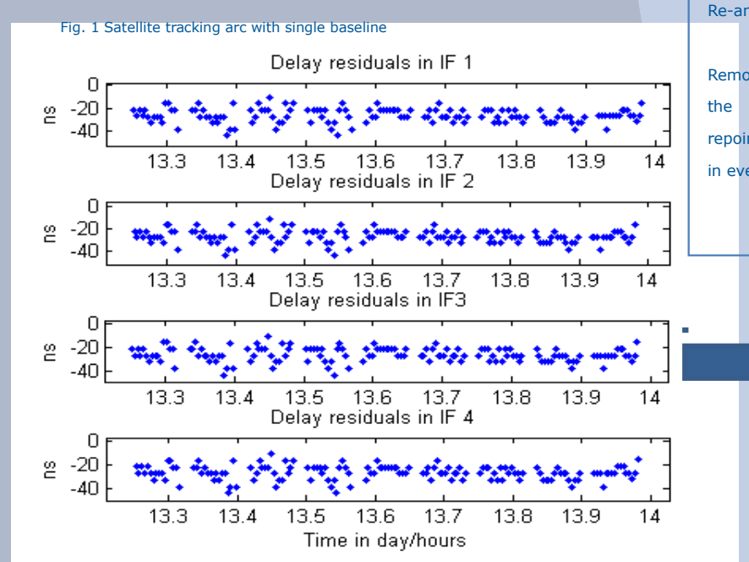


Fig. 2 Delay residuals in 4 IFs with sampling interval of 0.5s and solution interval of 15s in fringe-fitting

Re-analysis:

Removing the jumps at the beginning of repointing to the satellite in every 15s

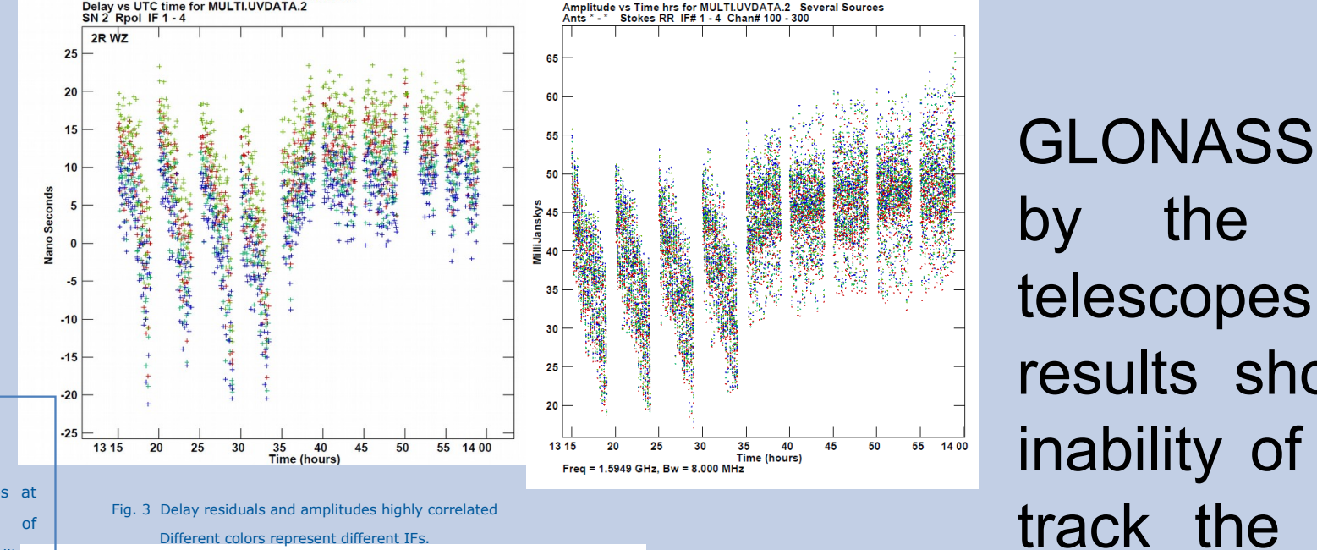


Fig. 3 Delay residuals and amplitudes highly correlated
Different colors represent different IFs.

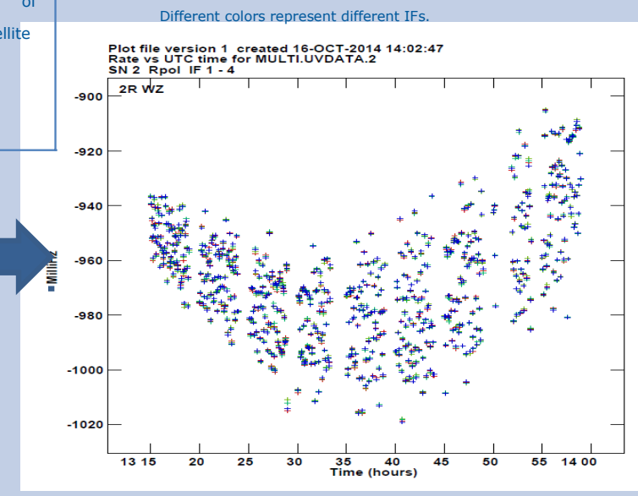


Fig. 4 Rate residuals from AIPS

Conclusion:

1) 15s stop-and-go tracking mode may not be suitable for satellite tracking, continuous tracking will be needed.

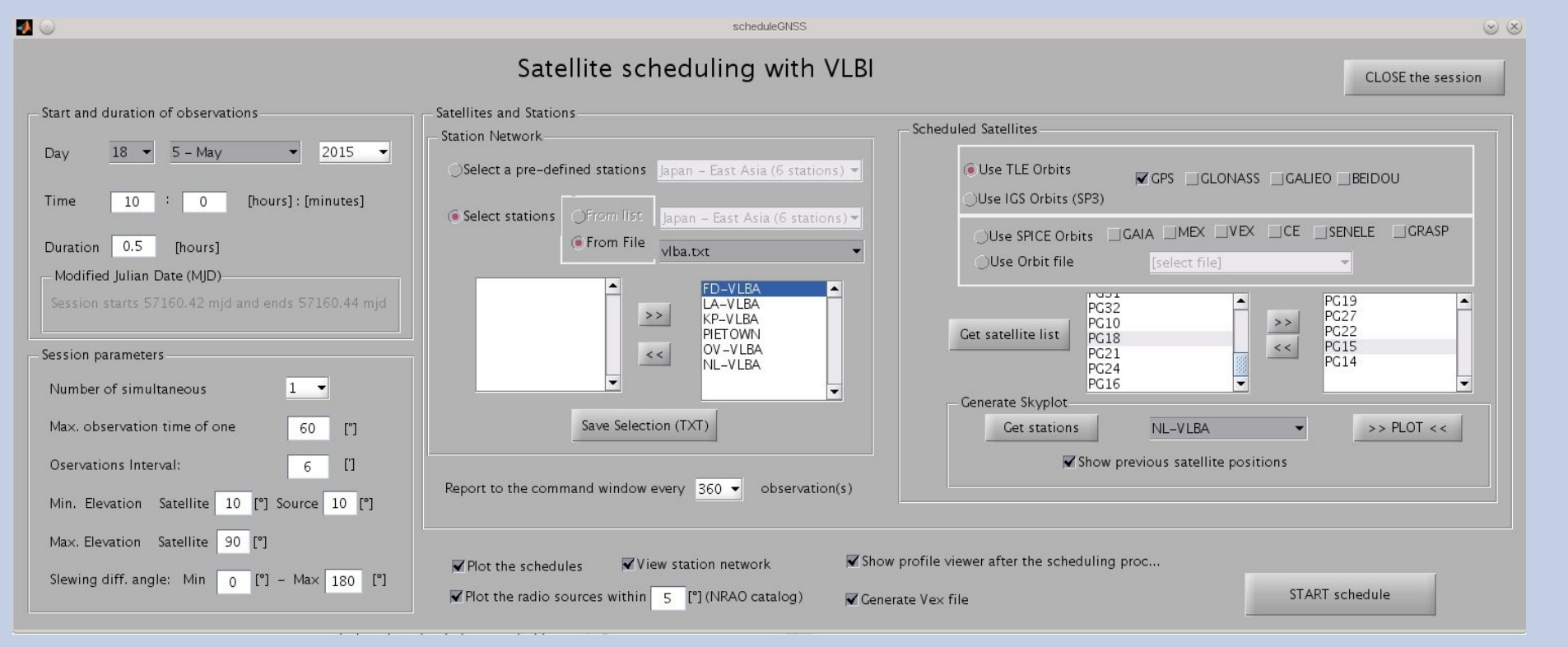
2) The rate residuals with 0.5s sampling interval are large. For enough resolution in phase changing, smaller interval could help to improve the results.

VLBI tracking of a GLONASS satellite

GLONASS satellite Pr09 was observed by the Onsala-85 and Wettzell telescopes on 2013-01-28. Analysis results show problems related to the inability of the Onsala-85 telescope to track the satellite, as well as large delay and rate errors related to deficiencies in the VLBI delay model for near-field applications. We are working with the VLBI community to resolve these problems.

Automated D-VLBI observation scheduling

We are developing software within the VieVS@GFZ package to automate the scheduling of D-VLBI observations of spacecraft. Using ephemeris models such as TLE or SPICE files, the software calculates the direction of the spacecraft on the sky as seen by each telescope. Then, taking a list of potential VLBI calibrator sources, the software selects calibrators based on criteria such as angular distance from the target, brightness, absence of source structure, and so on, taking care to select different calibrators for different telescopes when necessary. The software then schedules a series of D-VLBI observation scans, alternating between the spacecraft target and the calibrators, changing the calibrators used as the spacecraft moves across the sky. Finally, observing schedules with the apparent directions of the spacecraft for each telescope are written out.



Satellite scheduling with VLBI

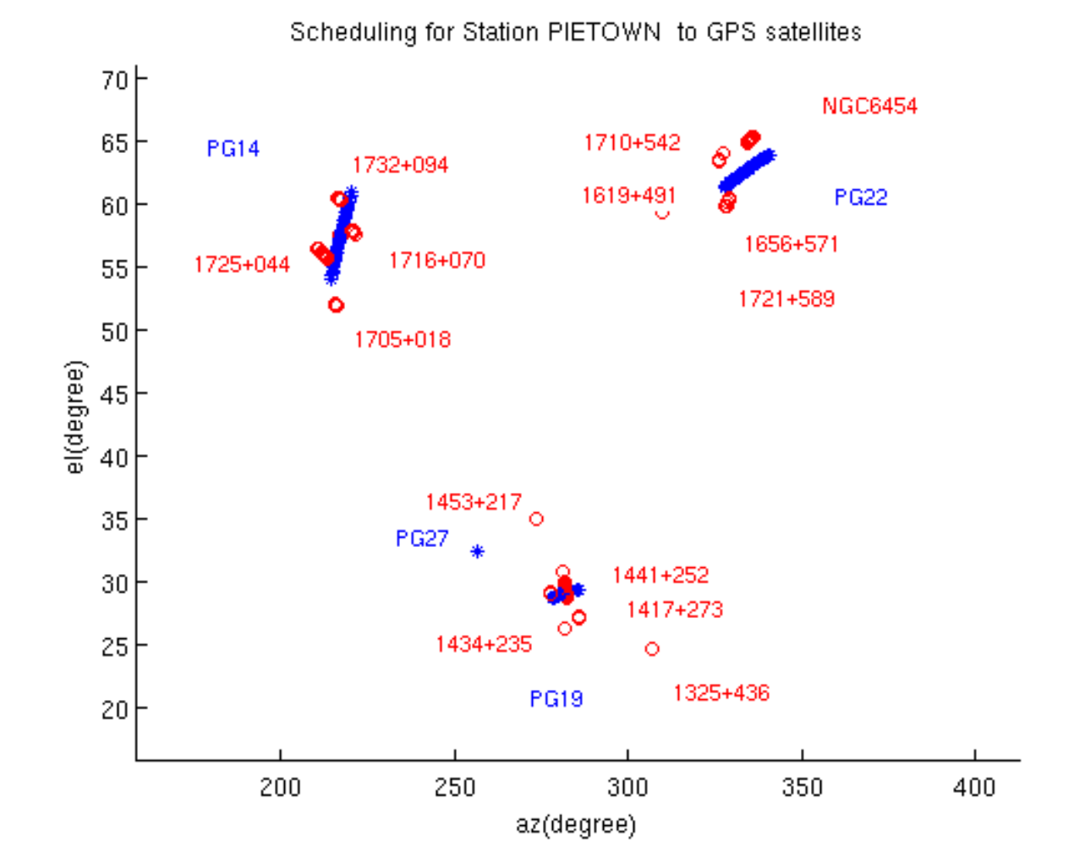
Start and duration of observations
Day: 18 | 5 – May | 2015
Time: 10 : 0 [hours] : [minutes]
Duration: 0.5 [hours]
Modified Julian Date (MJD): Session starts 57160.42 mjd and ends 57160.44 mjd

Session parameters
Number of simultaneous: 1
Max. observation time of one: 60 [']
Oservations Interval: 6 [']
Min. Elevation Satellite 10 [°] Source 10 [°]
Max. Elevation Satellite 90 [°]
Slewing diff. angle: Min 0 [°] – Max 180 [°]

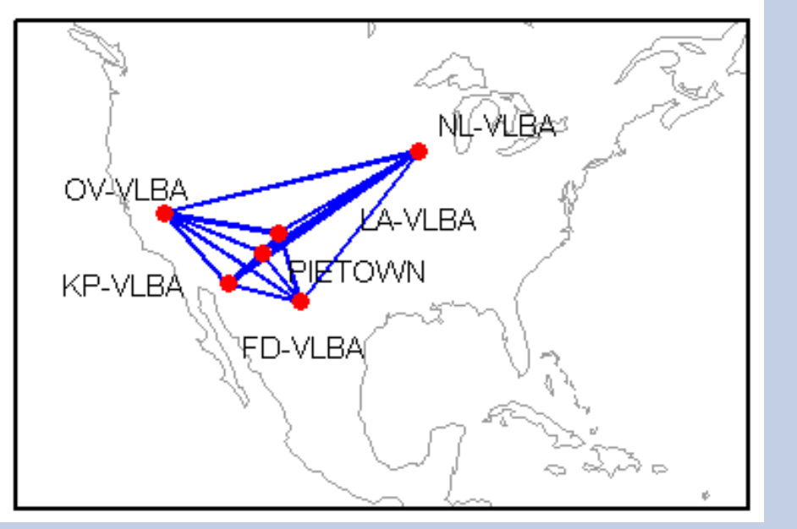
Satellites and Stations
Station Network
○ Select a pre-defined stations: Japan – East Asia (6 stations)
● Select stations ○ From list: Japan – East Asia (6 stations)
● From File: vlba.txt
FD-VLBA
LA-VLBA
KP-VLBA
PIETOWN
OV-VLBA
NL-VLBA
Report to the command window every 360 observation(s)

Scheduled Satellites
● Use TLE Orbits ☑ GPS ☐ GLONASS ☐ GALIEO ☐ BEIDOU
○ Use IGS Orbits (SP3)
○ Use SPICE Orbits ☐ GAIA ☐ MEX ☐ VEX ☐ CE ☐ SENELE ☐ GRASP
○ Use Orbit file: [select file]
PG32, PG10, PG18, PG21, PG24, PG16
PG19, PG27, PG22, PG15, PG14
Generate Skyplot: NL-VLBA
☑ Show previous satellite positions

☑ Plot the schedules ☑ View station network ☑ Show profile viewer after the scheduling proc...
☑ Plot the radio sources within 5 [°] (NRAO catalog) ☑ Generate Vex file



Left: Az-El plot of pointing directions for a 60 minute segment of simulated D-VLBI observations of GPS satellites as seen by the Pietown VLBI station
Right: VLBI array geometry used for the simulation



Credits:
Blue Marble Earth: NASA/NOASS (Blue Marble Earth)
GPS IIIa satellite: USAF http://en.wikipedia.org/wiki/File:GPS_Block_IIIA.jpg (downloaded 2014-10-15)
RadioAstron: Copyright Lavochkin (downloaded 2014-10-29)
Gaia: copyright ESA/ATG Medialab; background: ESO/S. Brunier,
http://www.esa.int/spaceinimages/Images/2004/05/Gaia_mapping_the_stars_of_the_Milky_Way
(downloaded 2014-10-15)
Chang'e-3 rover: http://upload.wikimedia.org/wikipedia/en/4/46/Yutu.jpg (downloaded 2014-11-04)

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http://ww2.erdrotation.de/EN/Home/home_node.html