Ties between kinematic and dynamic reference frames (D-VLBI)

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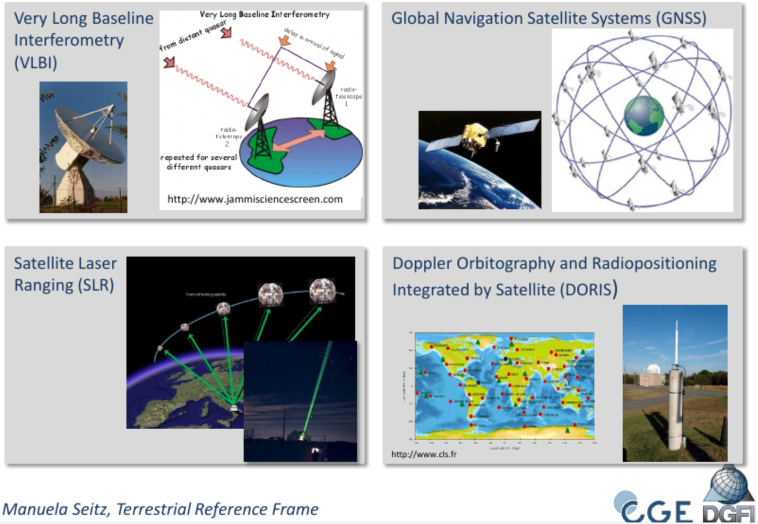
Outline

Geodesy and Astrometry Background Material

Geodetic Space Observation Techniques



- VLBI
- GNSS (historically GPS)
- SLR
- DORIS

Credit: Seitz (2013)

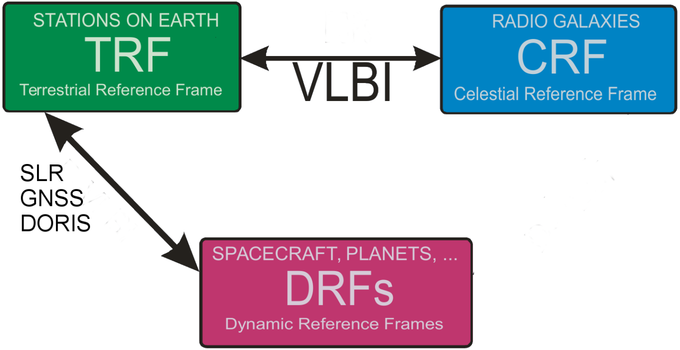
Geodetic Parameters

	Earth Orientation Parameters (EOP)					Indirect parameters: datum parameters	
	Station coordi-nates	Terrest-rial pole	ΔUT1	Length of day (LOD)	Nutation para-meters	Origin	Scale
VLBI	x	x	x	x	x		x
SLR	x	x		x		x	x
GNSS	x	x		x			
DORIS	x	x		x			

Credit: Seitz (2013)

- No single space geodetic technique is sensitive to all of the necessary geodetic parameters
- VLBI is the only space geodetic technique that can see the celestial reference frame to provide an inertial reference frame

Different Reference Frames



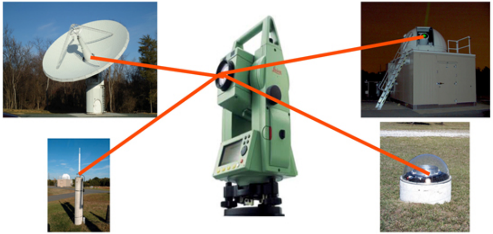
- VLBI measures the ICRF and a VLBI terrestrial frame
- GNSS measures the various GNSS frames and a GNSS terrestrial frame
- SLR measures various satellite orbits and an SLR terrestrial frame
- DORIS measures the DORIS satellite frame and a DORIS terrestrial frame
- In order to connect the frames we need some ties between the frames

How Do We Connect the Frames?: Solution 1: Local Ties

Site with multiple instruments

Credit: für Kartographie und Geodäsie (2013)

Use a total station to measure position vectors



Credit: NASA (2013)

- Used for historical ITRF realizations
- Difficult to do well — residuals typically at level of up to centimeters

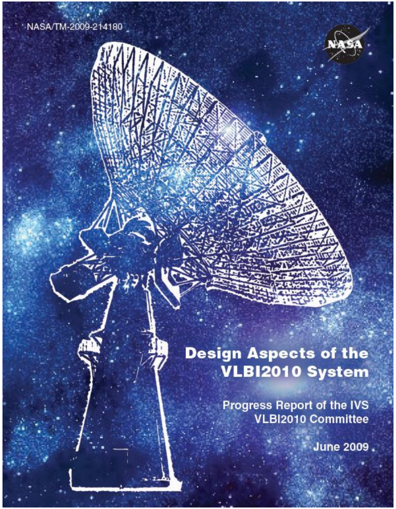
Where is the Geodetic Community Heading?

The Global Geodetic Observing System (GGOS)

- Within the International Association of Geodesy (IAG)
- Need to answer globally significant problems
- Climate change (global warming, sea level rise, . . .)
- Natural hazards
- And more

Credit: GGOS (2010)

The VLBI2010 Global Observing System (VGOS)



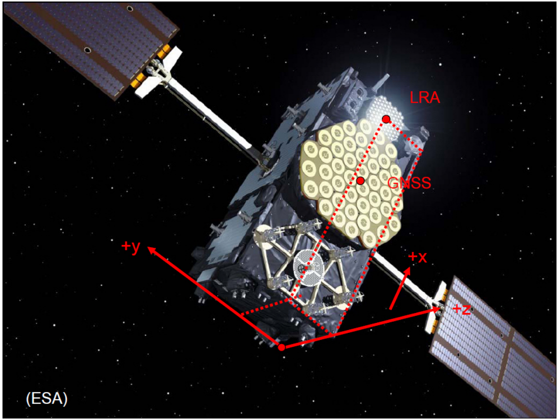
Credit: Committee (2009)

- Within the International VLBI Service for Geodesy and Astrometry (IVS)
- VLBI portion of GGOS improvements
- See, for example, Petrachenko et al. (2013) or IVS (2014)
- General goals include
  - Station positions accurate to 1 mm
  - Station velocities accurate to 1 mm yr^{-1}
  - Continuous (24/7/365) measurements
  - Rapid turnaround time for analysis results
- Position/velocity improvements by a factor of 10 over current results will require great efforts to deal with systematic errors within individual techniques and among the difference space-geodetic techniques

Improving the Geodetic Products Requires Better Frame Ties

How Do We Connect the Frames?: Solution 2: Space Ties

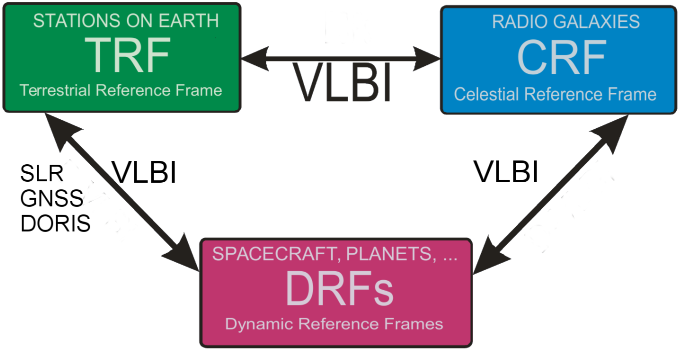
Multi-technique Spacecraft



Credit: ESA (2015)

- Instead of measuring the distances between different instruments on the ground, use the different techniques to measure the same spacecraft
- Underway for GNSS–SLR connection — GLONASS, Galileo, and BeiDou have retroreflectors for SLR, GPS including retroreflectors on new satellites
- Greatly increases the number of tie points between frames

VLBI Connections to Dynamic Frames



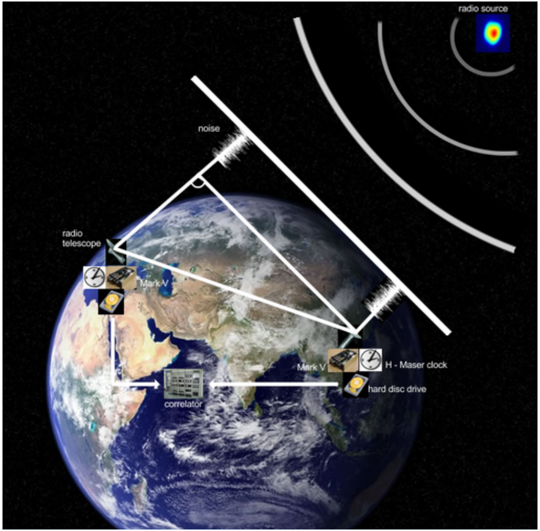
- Intent to also connect the dynamical spacecraft systems through VLBI measurements of spacecraft
- VLBI observations of spacecraft and celestial sources can provide a more direct link between the ICRF and the spacecraft, allowing the orbits to be determined directly in the celestial frame

Intertechnique Comparison

- Simultaneous measurements of the same spacecraft, carried out over extended periods of time, will enable us to study systematic effects (biases, trends, cycles) among the different techniques
- By identifying such systematic effects, we should be able to make significant improvements in each of the systems alone as well as in the combined products

Quick Background About How VLBI Works

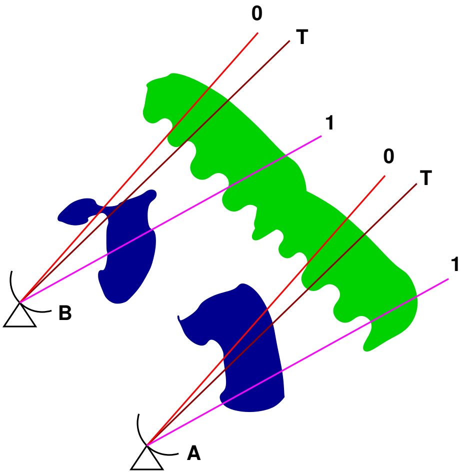
VLBI Measurement Technique



- The idealized concept is that we measure $\tau_{\mathrm{g}} c = \boldsymbol{B} \cdot \hat{\boldsymbol{s}}$, where
  - $\boldsymbol{B}$ is the baseline vector from station 1 to station 2
  - $\hat{\boldsymbol{s}}$ is the unit vector in the direction of the infinitely distant source
  - τ_{g} is the geometric delay — the amount of time that the signal arrives at station 1 after it arrives at station 2
- Resolution of interferometer is $\theta = \frac{c}{2\nu B \sin\alpha}$, where
  - ν is the observing frequency
  - α is the angle from $\hat{\boldsymbol{s}}$ to $\boldsymbol{B}$
  - For an 8000 km baseline, observing at 8.5 GHz, the resolution θ is about 0.5 mas

Credit: GFZ (2015a)

D-VLBI (Phase Referencing)



- Use one or more calibrator sources (0, 1, . . .) angularly nearby to a target source (T) to calibrate the location of the target
- Use a sequence of observations to correct to time variations in the delay errors in the direction of the target
  - For a single calibrator, do 0–T–0–T–0–. . .
  - For multiple calibrators do something like 0–T–1–T–0–T–1–. . .
- The closer the calibrators are to the target, the better the results
- If you are lucky/patient/smart, you find a calibrator that is located within the same beam of your telescope as the target, and can do simultaneous calibration

D-VLBI Capabilities and Limitations

- Corrects for errors in the atmosphere (troposphere, ionosphere), instrument (clock, cable delays), and delay model (EOPs) to provide accurate *relative* astrometry
- Absolute position uncertainty limited mostly by atmospheric propagation effects and the positional accuracy of the calibrator
  - Typical absolute position errors at 8.5 GHz are 0.4 mas (Jones et al. 2015) to 0.5 mas (Fomalont et al. 2011)
- Relative position uncertainty limited mostly by SNR and residual atmospheric gradients
  - Relative position errors at centimeter wavelengths of ∼10 µas are becoming routine
- For targets that move significantly during an observation, velocity accuracy can be far better, limited by SNR, atmospheric effects, and unmodeled source effects
- For nearby spacecraft, the velocity information from D-VLBI observations is more constraining than the positional information
- ΔDOR (delta-differential one way ranging) is a form of D-VLBI (usually only performed with a small number of stations)

What Are We Doing at the GFZ?

Deutsches GeoForschungsZentrum (GFZ)

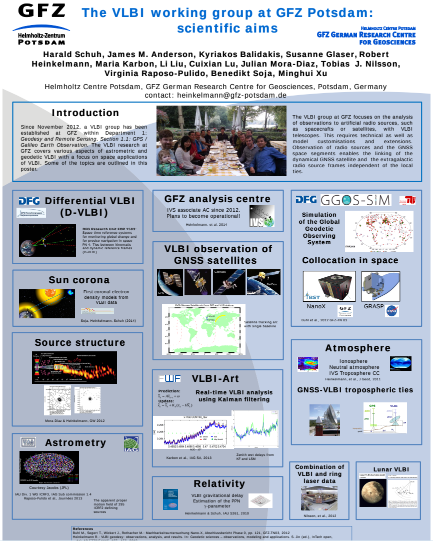
Credit: GFZ (2015b)

- German Earth Science Center in Potsdam with over 1100 employees, part of the Helmholtz Association of German Research Centres
- http://www.gfz-potsdam.de/en/home/

GFZ Geodetic VLBI Group

- Group formed in 2012 November
- Part of GFZ's Department 1: Geodesy and Remote Sensing, Section 1.1: GPS/Galileo Earth Observation
- Headed by H. Schuh, director of Dep. 1, also recently elected president of the IAG
- Research areas covering astrometric and geodetic VLBI with a focus on space applications of VLBI

GFZ VLBI Research Areas



- On our way to becoming an IVS operational analysis center
- Varied interests including atmospheric calibration and science applications, Solar wind measurements, understanding source structure effects on geodesy and astrometry, . . .
- A large focus on reference frames, including the upcoming celestial radio frame ICRF3, the upcoming terrestrial frame ITRF2014, and constraining the ties between reference frames, especially through spacecraft measurements

Credit: Heinkelmann, in prep.

DFG Research Unit FOR1503

Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space

Group photo from 2015 February. Credit: FOR 1503 (2015)

- Research *unit* with members from various universities and institutes around Germany, Switzerland, and Austria
- Headed by A. Nothnagel (current IVS chair) at the Bonn University
- Research group funded by the German Research Foundation (DFG Deutsche Forschungsgemeinschaft) and corresponding Swiss and Austrian research foundations
- `http://ww2.erdrotation.de/EN/Home/home_node.html`

FOR1503 Projects

- Project 1: Barycentric Ephemeris
- Project 2: Combination Approaches for ICRF3
- Project 3: Lunar Reference Systems
- Project 4: Ties between kinematic and dynamic reference frames (D-VLBI)
- Project 5: Consistent celestial and terrestrial reference frames by improved modelling and combination
- Project 6: Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters
- Project 7: Co-location of Space Geodetic Techniques on Ground and in Space

FOR1503 Project D-VLBI

Scientific Goals

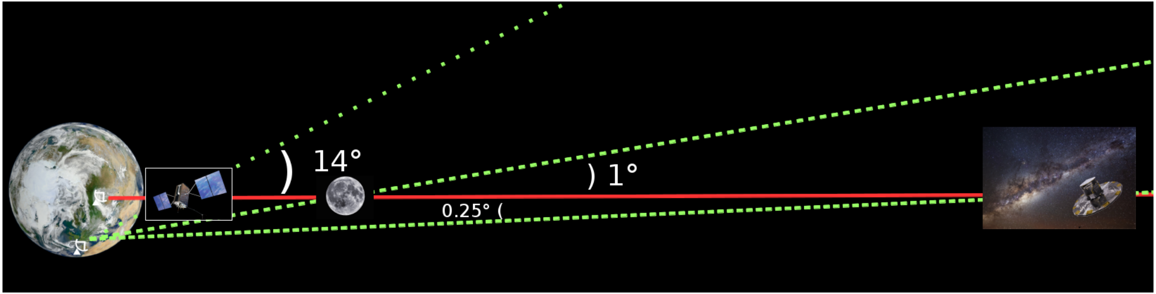
- Demonstrate the potential of D-VLBI for the establishment of frame ties to spacecraft and Solar System dynamical reference frames with the ITRF and ICRF
- Moving targets require different D-VLBI observing and analysis strategies from stationary, astronomical D-VLBI — test various methods to learn what works best
- Perform test observations on different spacecraft orbit types, including LEO, GNSS, Lunar, and Lagrangian orbit types.

What is New Here?

ΔDOR/D-VLBI has been done for decades, so what is new within this project?

- This work is examining near-Earth spacecraft as opposed to deep-space spacecraft
- The spacecraft move significantly during a single observation
- Geocentric parallax requires different calibrators for different telescopes
- Need automated scheduling and control software to deal with preparing a VLBI array for observations
- Spacecraft signals are so strong that they cause cause problems (signals must be attenuated at the telescopes, potential delay changes, sometimes cannot see calibrator targets)

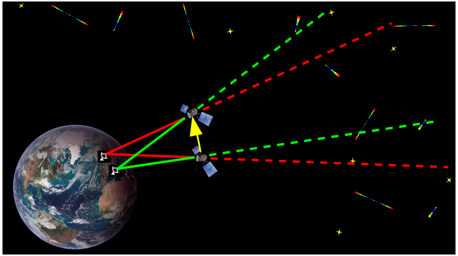
Geocentric Parallax

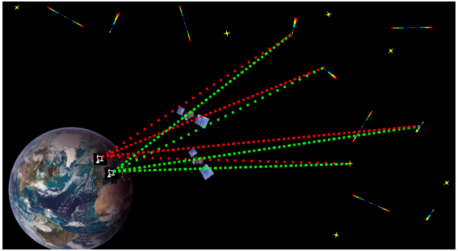


Credit: ESA/ATG medialab/ESO/S. Brunier (2004), NASA/Sean Smith (2008), Norman Kuring, NASA/GSFC/Suomi NPP (2012), and USAF (2010)

- Telescopes must point in different directions
- There is effectively no VLBI standard way to observe nearby/moving targets
  - VEX 1.5b1 supports Earth satellite orbital parameters, but not spacecraft outside of Earth orbits
  - Few stations provide a Field System/station interface mechanism supporting moving targets without human intervention — crucial for D-VLBI observations (the VLBA is a significant exception here)
  - Need VEX 2.0, Field System, and station interface support in future
- For now, must separately schedule each station with topocentric (α, δ), add correlator hack

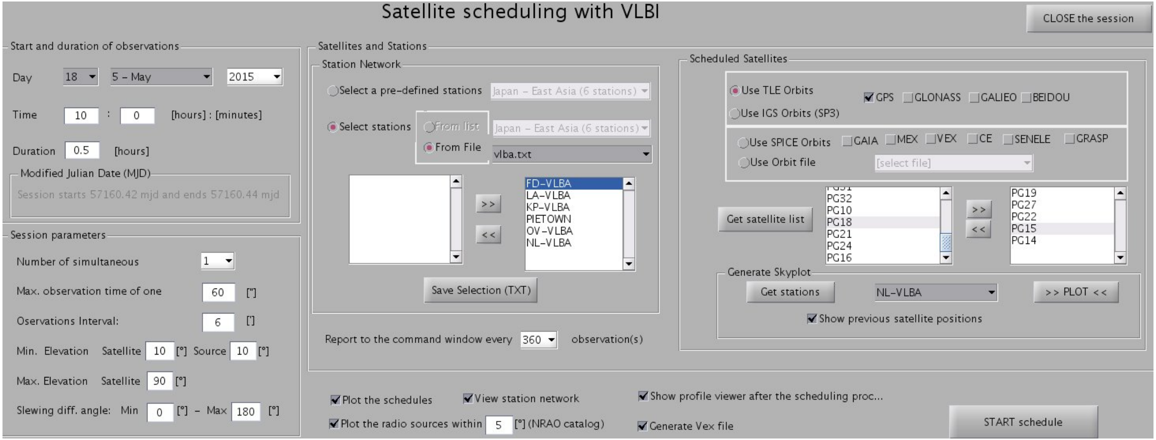
Moving Near-Field Targets and Phase Calibrators





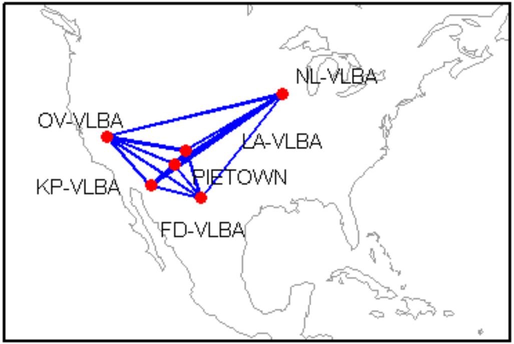
- Each station sees the target in a different direction (Geocentric parallax)
  - Result: different stations require different phase calibrators
  - Depends on projected baseline distance, distance to spacecraft, maximum allowed angular separation
- As the spacecraft moves, the stations must look in different directions
  - Result: stations require different calibrators as a function of time. For GNSS satellites, new calibrators will be needed every few minutes; at L2, new calibrators will be needed on daily timescales
- Many, many phase calibrators and calibrator scans must be used — need an automated system to select and schedule calibrators and targets
  - For an hour-long GNSS D-VLBI experiment with 6 stations, $\sim$ 25 calibrators and $\sim$ 100 scans will be used

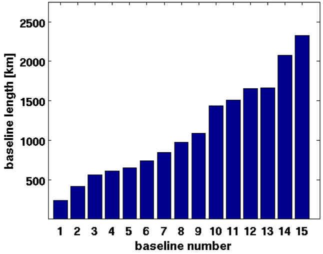
VieVS@GFZ Spacecraft Scheduling Software



- Based on earlier VieVS satellite scheduling software

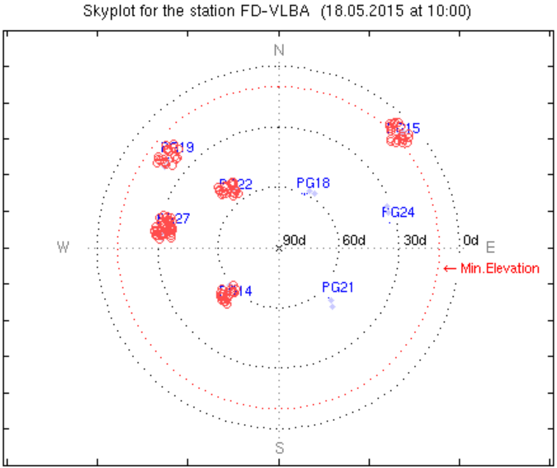
Example of a VLBA Subarray for GPS Observations



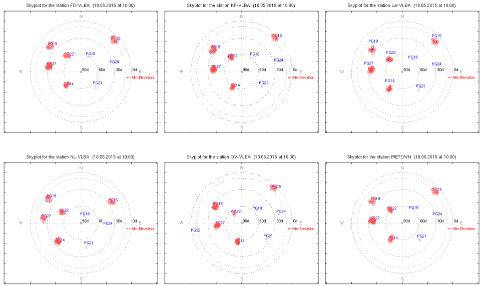


- Need L band receivers for GPS L1 and L2 signals
- Need short enough VLBI baselines for common satellite visibility
- Need high sensitivity for D-VLBI calibrator observations
- VLBA and EVN (European VLBI Network) arrays ideal for test cases

Sky Plots for the VLBA Network Example



- 12 minutes of schedule planning time shown
- Blue points: GPS satellites, plotted every 6 minutes
- Red points: all possible phase calibrator sources within angular separation cutoff

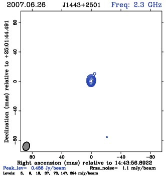


Calibrator Selection

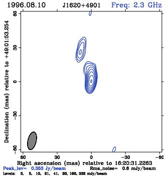
- Phase calibrator list includes sources from the VLBA Calibrator List (NRAO 2015b) (as well as the Radio Fundamental Catalog, Petrov 2015)
- Selection Criteria
  - Angular distance between spacecraft and calibrator, Sun, horizon, ...
  - Position accuracy
  - Absence of source structure
  - Flux density for appropriate baseline length, with spectral index correction to observing frequency
  - Station sensitivities and maximum phase-referencing cycle time (atmospheric coherence time for the target–calibrator separation) used to generate flux-density cutoff limit

Source	name	ra(hhmmss)	de(ddmmss)	rae	dee		flux_s	flux_l		flux_s	flux_l	
J1223+4611	1221+464	12h23m39.336605s	+46d11'18.60268"	0.37	0.46	S	0.37	0.31	C	0.14	-0.05	GSFC
J1221+4411	1218+444	12h21m27.044660s	+44d11'29.67162"	0.16	0.32	S	0.59	0.49	C	0.35	0.26	GSFC
J1443+2501	1441+252	14h43m56.892189s	+25d01'44.49069"	0.02	0.03	S	0.49	0.43	X	0.46	0.26	GSFC
J1620+4901	1619+491	16h20m31.225198s	+49d01'53.25688"	0.13	0.28	S	0.52	0.24	C	0.36	0.15	GSFC
J1656+5321	1655+534	16h56m39.624167s	+53d21'48.77142"	0.25	0.41	S	0.10	0.11	C	0.11	0.10	GSFC
J1711+5411	1710+542	17h11m40.504775s	+54d11'45.13465"	0.19	0.45	S	0.17	0.13	X	0.19	0.17	GSFC
J1657+5705	1656+571	16h57m20.708933s	+57d05'53.50370"	0.36	0.46	S	0.53	0.32	C	0.36	0.11	GSFC
J1728+0427	1725+044	17h28m24.952724s	+04d27'04.91390"	0.03	0.04	S	0.76	0.46	C	0.69	0.22	GSFC
J1734+0926	1732+094	17h34m58.376987s	+09d26'58.26005"	0.31	0.47	S	1.54	0.67	X	0.53	0.08	GSFC
J1745+1720	1743+173	17h45m35.208170s	+17d20'01.42369"	0.03	0.04	S	0.93	0.60	X	0.69	0.40	GSFC

- Links to calibrator images and data to be provided when run interactively



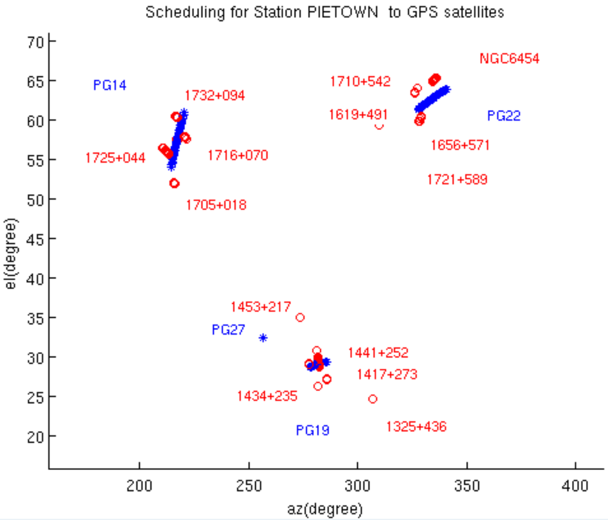
Good, little structure



Bad, structure affects snapshot measurement position

Plots taken from (Petrov 2015)

Plots for Scheduling Results



- 60 minutes of observing time shown here
- One plot per station, showing detailed target locations for each scan and the calibrators used for all stations
- Allows visual inspection of target–calibrator geometries to verify software-based selections

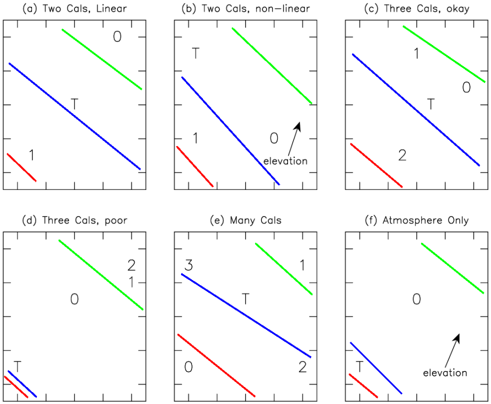
Scheduling Output

Scheduling file

```
2015   5 18 10  0  0.00 FD-VLBA   LA-VLBA  1221+464   qq
2015   5 18 10  0  0.00 FD-VLBA   KP-VLBA  1221+464   qq
2015   5 18 10  0  0.00 FD-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0  0.00 FD-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0  0.00 LA-VLBA   KP-VLBA  1221+464   qq
2015   5 18 10  0  0.00 LA-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0  0.00 LA-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0  0.00 KP-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0  0.00 KP-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0  0.00 PIETOWN   OV-VLBA  1221+464   qq
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 16.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 27.00 FD-VLBA   LA-VLBA  1221+464   qq
2015   5 18 10  0 27.00 FD-VLBA   KP-VLBA  1221+464   qq
2015   5 18 10  0 27.00 FD-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0 27.00 FD-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0 27.00 LA-VLBA   KP-VLBA  1221+464   qq
2015   5 18 10  0 27.00 LA-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0 27.00 LA-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0 27.00 KP-VLBA   PIETOWN  1221+464   qq
2015   5 18 10  0 27.00 KP-VLBA   OV-VLBA  1221+464   qq
2015   5 18 10  0 27.00 PIETOWN   OV-VLBA  1221+464   qq
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
2015   5 18 10  0 43.00 PIETOWN   OV-VLBA      PG19   sc
```

- Currently outputs .SKD and internal format files
- Will also develop output to keyin files for NRAO SCHED
  - Supports VLBA non-sidereal tracking
  - Support for SPICE data for scheduling non-sidereal tracking
  - VEX and .v2d support
  - Support for multiple phase centers
    - For times when in-beam calibration can be applied
    - GNSS in-beam calibration opportunity about once per hour per station for a 25 m diameter station and reasonable selection criteria

D-VLBI Processing Software Modifications: ATMCA



Based on Figure 1 of Fomalont & Kogan (2005). T indicates the target, and numbers indicate calibrator sources.

Different panels show different relative source orientations.

- For nearby spacecraft, multiple calibrators are necessary for D-VLBI because of Geocentric parallax and spacecraft motion
- ATMCA is an AIPS task to calculate and apply phase referencing calibration from multiple calibrators (see AIPS Memo 111, Fomalont & Kogan 2005)
- Colored lines have been overlaid to simulate spacecraft tracks viewed by three different stations
- Calibrator–target orientation categories can be different for different stations and change with time

ATMCA Modifications for Nearby/Moving Spacecraft

- Target direction different for each station
  - Target position must be calculated from satellite ephemerides rather taking the fixed (α, δ) coordinates in the AIPS SU (source) table.
- Target moves as a function of time
  - Calibration gradient on sky results in different calibration values at different locations
  - Phase calibration no longer constant for each scan
- Calibration algorithm (linear interpolation, 2-D gradient, assume only elevation gradient present, . . .) may be different for each station, and may change with time
  - Original software has user select a single algorithm to use for all stations and times
- Different calibrator groups used for different directions in the sky — the software should automatically select the appropriate calibrators to use from all available observations
- Development still in progress. . .

Gaia

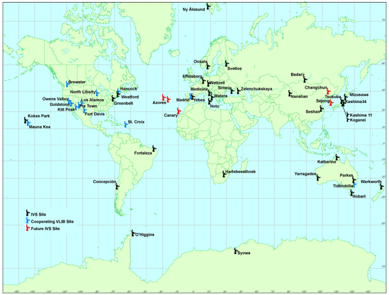
Why Is FOR1503 Interested in Gaia?

- Provides a different type of spacecraft orbit to test how well we can perform D-VLBI and link the spacecraft to the ICRF
- Gaia's signal strength is only a factor of 2000 times our typical source flux density, so most telescopes can see the spacecraft and calibrators without modifications (GNSS a factor of 10^7)
- Signal frequency at 8465 MHz is within the standard X band receiver at VLBI stations (GNSS signals are below 2 GHz and cannot be observed at most geodetic VLBI stations)
- Spacecraft motion on the sky is fast enough to be interesting, but slow enough to allow sidereal tracking to be used (GNSS stations move very rapidly through the station beam)
- Gaia only somewhat stresses the VLBI near-field delay model (GNSS spacecraft are far closer, and most correlator delay models are not yet correct)
- See how well D-VLBI can measure the 3-D orbit at this distance
- Astrometric community interested in how well the radio and Gaia celestial frames will tie

But Gaia Already Has

- Gaia's Ground Based Optical Tracking (GBOT)
- Some amount of ΔDOR observations by ESA
- Planetary Radio Interferometry and Doppler Experiment (PRIDE) Gurvits et al. (2012) has been used for some Gaia tests

What Can We Provide for Gaia?



Credit: IVS (2013)

- We are at the proof-of-concept stage to demonstrate how well things can be done — not at an operational stage at this time
- Measurement accuracies depend on the VLBI array used and observing time allocated. The VLBA should be able to provide transverse positions and velocities accurate to 6 m and 0.2 mm s^{-1}, respectively, (one hour of observation time, 0.1 Jy calibrator). The IVS could provide something at a factor of ~ 3 larger residuals.
- An intertechnique comparison for Gaia on the Gaia orbit side of the equations, not just the source side

What Do We Need From Gaia?

- Gaia to be transmitting at 8465 MHz (data transmissions, tone signals, or just noise are all fine)
- Schedule of transmission times several months in advance for the IVS array — the VLBA can accommodate shorter-term scheduling notices
- Gaia state vector models (the most important criteria is smoothness, absolute accuracy to a few arcseconds is acceptable)
- Interest from the Gaia community to have such measurements be made

The End

Thank you for your attention

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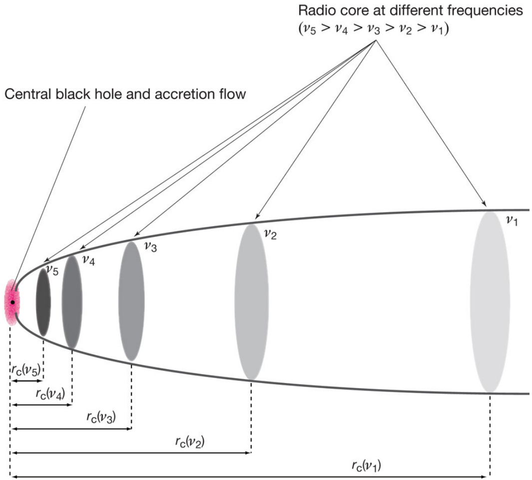
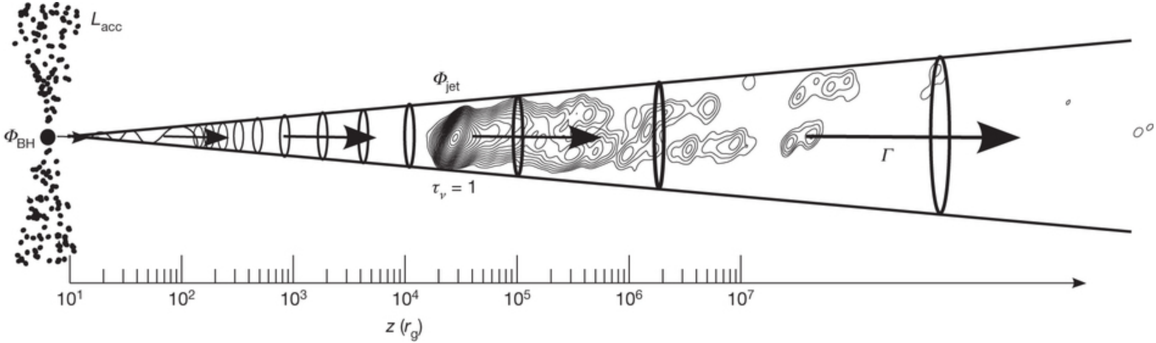
Jet Core Shift



Credit: Hada et al. (2011)

- D-VLBI does not generally use group delay measurements, so core shift affects the positions of the calibrators
- At 8.5 GHz the expected core shift is 100–200 µas (Kovalev et al. 2008)

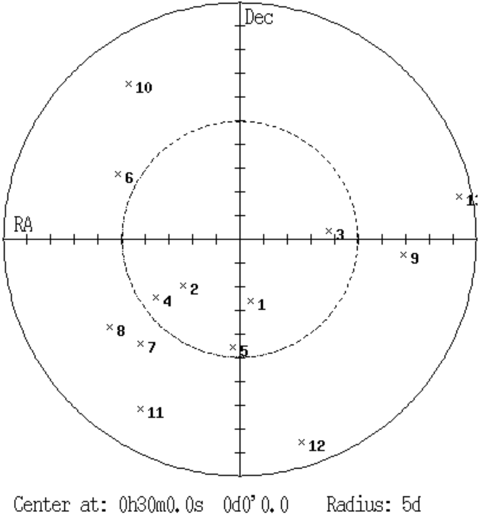
Jet Structure



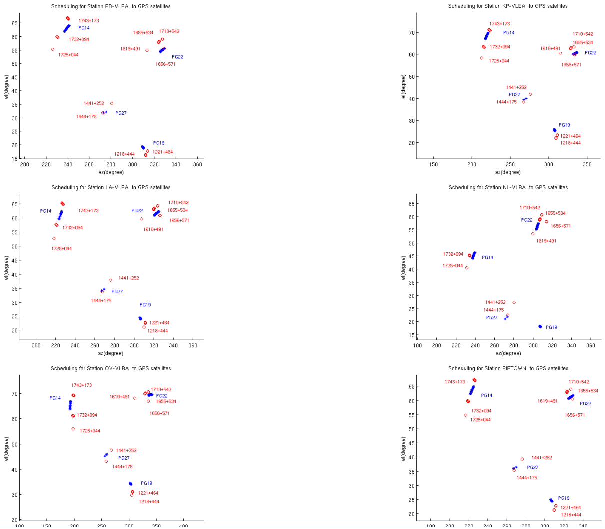
Credit: Zamaninasab et al. (2014)

- Jet structure affects measurement positions
- Need many different baseline lengths and baseline orientations to average out source structure

Calibrator Selection



More Plots for Scheduling Results



- 30 minutes of observing time shown here
- One plot per station showing detailed target locations for each scan and the calibrators used
- Allows visual inspection of target–calibrator geometries to verify software-based selections

Future Plans

- Finish initial development and debugging
- Schedule, observe, process, and analyze test observations
  - Test D-VLBI and our software's performance for different spacecraft orbit types and observing frequencies
  - GNSS for nearby spacecraft
  - RadioAstron for distances out to roughly the Lunar orbit
  - Gaia for the L2 orbits
- Software tweaking
  - Improve calibrator selection criteria weighting
  - Add checks for in-beam opportunities
  - Add tuning option for maximizing velocity measurement accuracy (different calibrator selection, satellite repetition frequency)
- Extend automated VLBI processing scripts from the astronomical community for spacecraft D-VLBI