Software Development for D-VLBI Scheduling and Analysis of Spacecraft Observations

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Outline

Overview

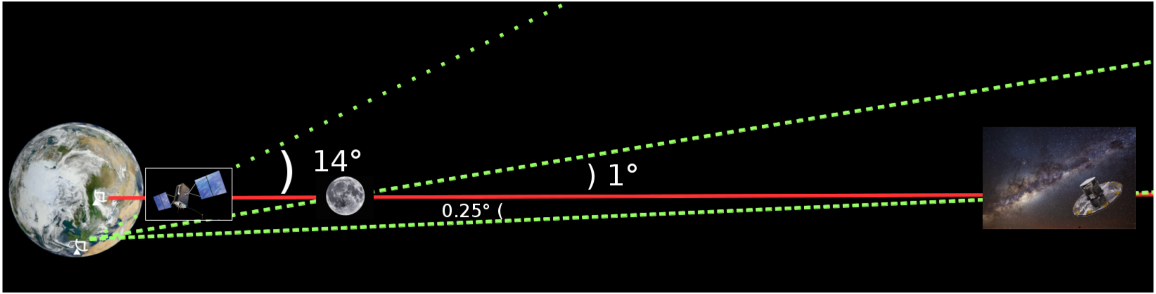
D-VLBI (differential VLBI)

- Known as *phase referencing* in the astronomical VLBI community for $\gtrsim$ 30 years
- 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
- Velocity accuracy can be far better, limited by SNR, atmospheric effects , and unmodeled source effects

Scientific Goals of this Study

- 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

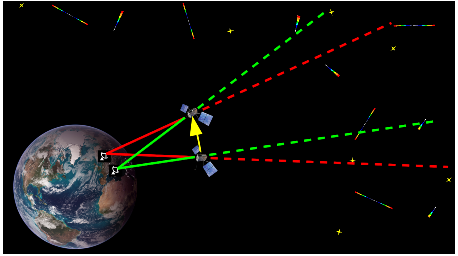
Geocentric Parallax

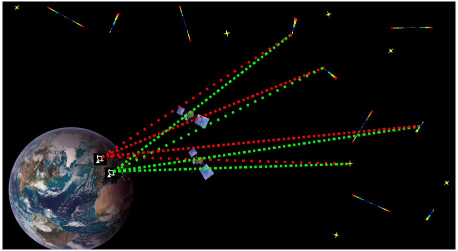


Credit: ESA/ATG medialab/ESO/S. Brunier (2004), NASA/Sean Smith (2008), Norman Kuring, NASA/GSFC/Suomi NPP (2012), and USAF (2010)

- 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

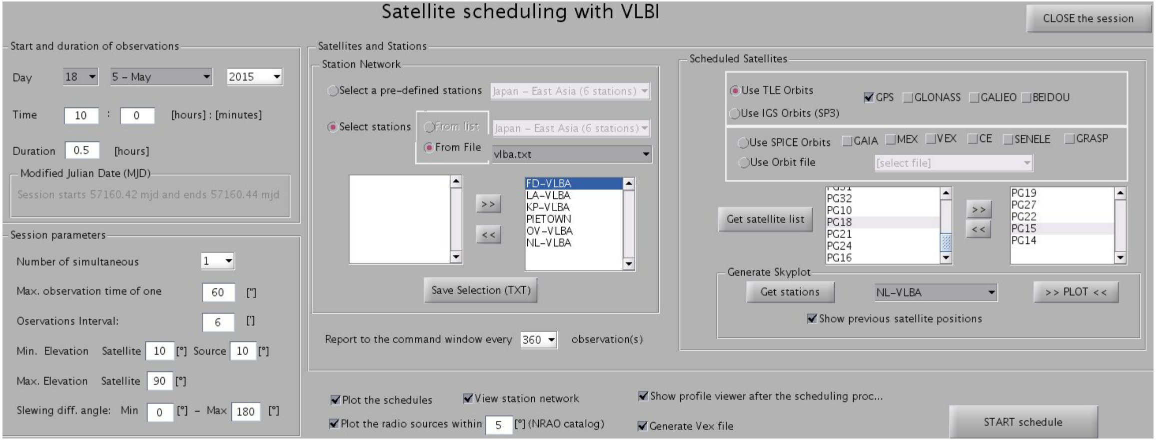
Moving Near-Field Targets and Phase Calibrators





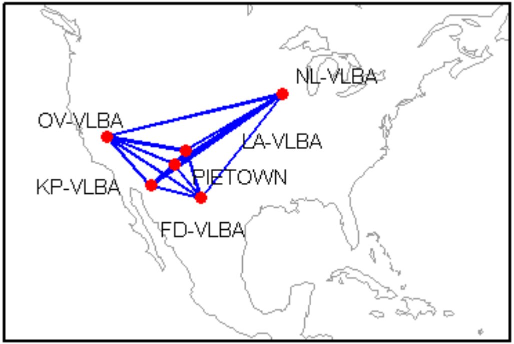
- Each station sees the target in a different direction (Geocentric parallax)
  - Result: different stations require different phase calibrators
  - Depends on projected baseline distance, distance to spacecraft, maximum allowed angular separation
- As the spacecraft moves, the stations must look in 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

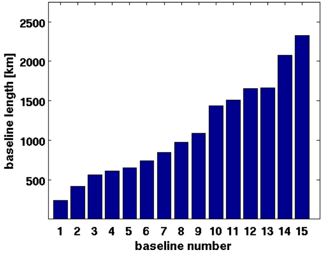
VieVS@GFZ Spacecraft Scheduling Software



- Based on earlier VieVS satellite scheduling software

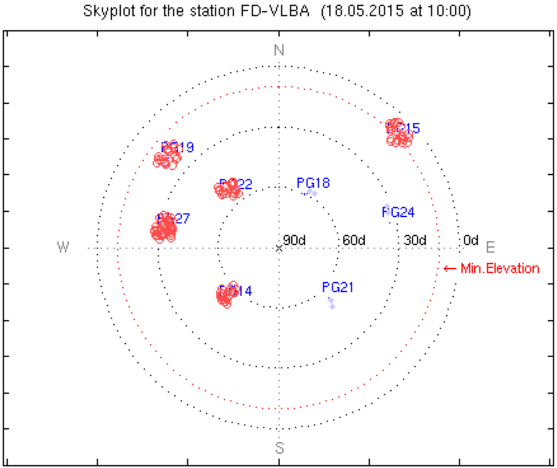
Example of a VLBA Subarray for GPS Observations



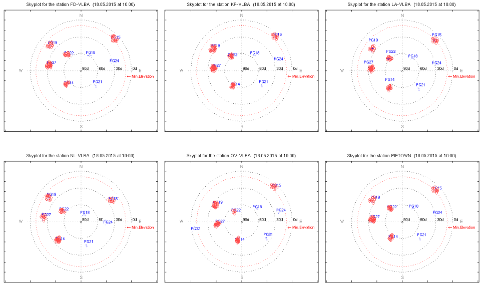


- Need L band receivers for GPS L1 and L2 signals
- Need short enough VLBI baselines for common satellite visibility
- Need high sensitivity for D-VLBI calibrator observations
- VLBA and EVN (European VLBI Network) arrays ideal for test cases

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

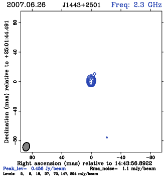


Calibrator Selection

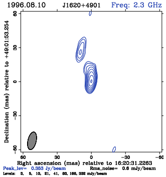
- Phase calibrator list includes sources from the VLBA Calibrator List (NRAO 2015) (as well as the Radio Fundamental Catalog, Petrov 2015)
- Selection Criteria
  - Angular distance between spacecraft and calibrator, Sun, horizon, . . .
  - Position accuracy
  - Absence of source structure
  - Flux density 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



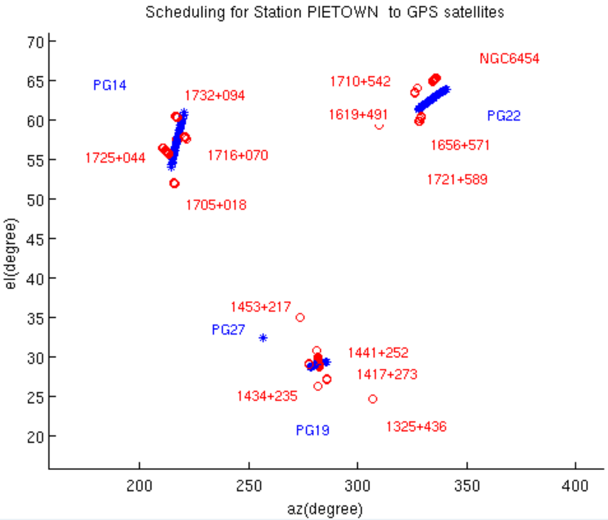
Good, little structure



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

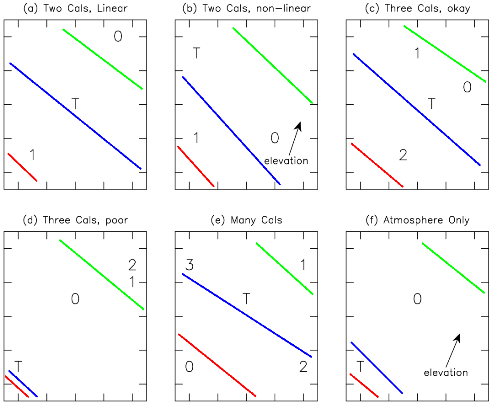
Scheduling Output

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. . .

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

The End

Thank you for your attention

Acknowledgments: The presented research was done within the project Ties between kinematic and dynamic reference frames (D-VLBI) (SCHU 1103/4-1) as part of the DFG Research Unit Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space funded by the German Research Foundation (FOR 1503).

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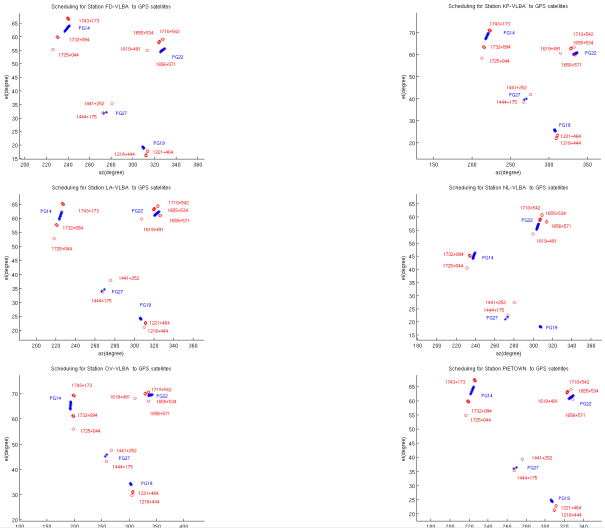
More Plots for Scheduling Results



- 30 minutes of observing time shown here
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- Allows visual inspection of target–calibrator geometries to verify software-based selections