Scheduling, Correlating, and Analyzing VLBI Phase-Referencing Observations of Earth-Orbiting Satellites

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VLBI Observations of Near-field Targets
Bonn
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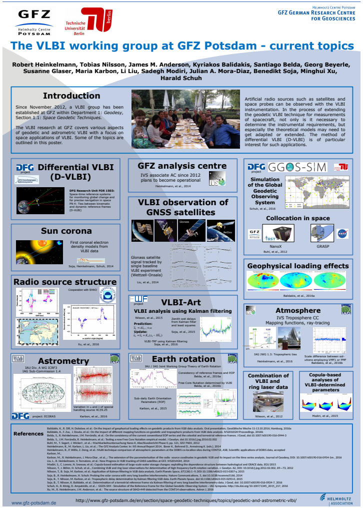
Outline

Why Would You Want to Phase Reference?

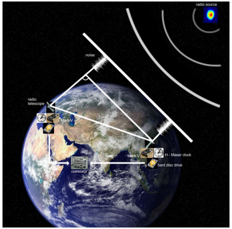
- Phase referencing is orders of magnitude more precise than “standard geodetic” VLBI
- Phase referencing is orders of magnitude more accurate (relative sense) than “standard geodetic” VLBI
- So the question you really should be asking yourself is, “Do I have a fundamentally valid reason why NOT to phase reference?”

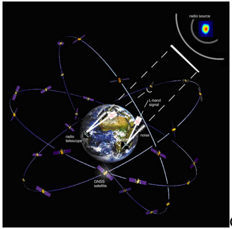
Background: Our Institute and Our Research

VLBI at the GFZ



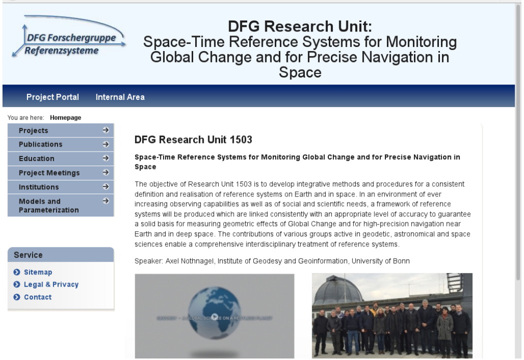
- The Geodetic and Astrometric VLBI Group is part of the Space Geodetic Techniques Section within the Geodesy Department at the German Research Centre for Geosciences
- Other groups in section: GNSS Atmosphere Sounding, GNSS Reflectometry, and GNSS Analysis Centres and Services
- Other sections in department: Global Geomonitoring and Gravity Field, Earth System Modelling, Remote Sensing, and Geoinformatics





GFZ (2016a)

DFG FOR1503



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

FOR 1503 & Federal Agency for Cartography and Geodesy (BKG) (2015)

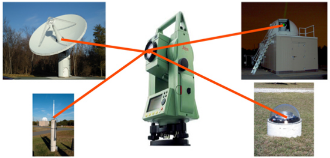
- Funded by the German Research Foundation (DFG), along with its Austrian and Swiss counterparts
- We are involved in project “PN4: Ties between kinematic and dynamic reference frames (D-VLBI)” of this research unit
- Anderson came into the project in 2014 following Lucia Plank’s departure after completing her degree
- A note on nomenclature: **D-VLBI**, or **differential-VLBI**, is known as **phase referencing** in the astronomical community, and I will use the terms interchangeably in this talk

Standard Frame Connection: Local Ties

Site with multiple instruments

Bundesamt für Kartographie und Geodäsie (2013)

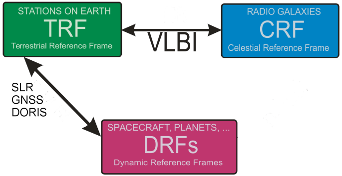
Use a total station to measure position vectors



NASA (2013)

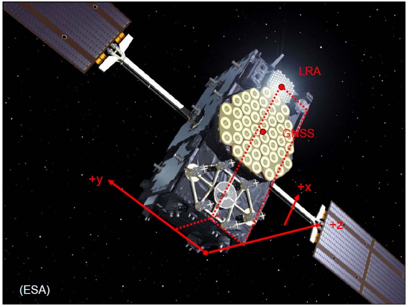
- Difficult to do well — residuals typically at level of up to centimeters

Long chain of measurements connect spacecraft frames to celestial frame



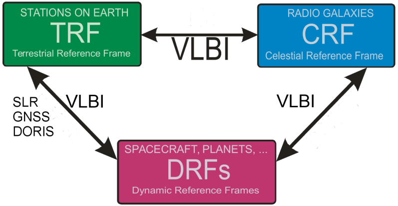
Additional Option for Frame Connections: Space Ties

Multi-technique spacecraft



ESA (2015)

Tie spacecraft directly to celestial frame



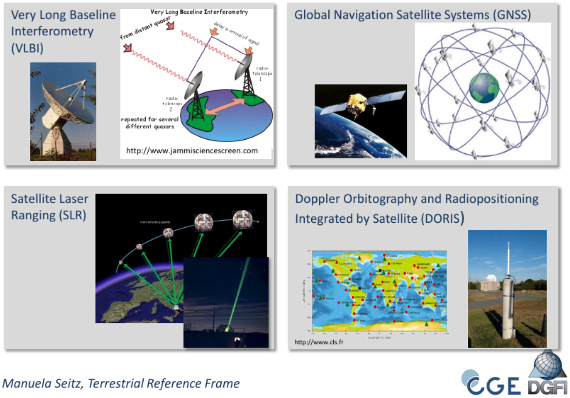
Satellites provide technique ties

- See other presentations at this workshop
- Greatly increases the number of tie points between frames

- GNSS, SLR, and DORIS space ties already exist — VLBI needs to be added

Background: Where is the Geodetic Community Heading?

Space Geodetic Techniques and Measured Parameters



Seitz (2013)

	Earth Orientation Parameters (EOP)					Indirect parameters: datum parameters	
	Station coordinates	Terrestrial pole	ΔUT1	Length of day (LOD)	Nutation parameters	Origin	Scale
VLBI	x	x	x	x	x		x
SLR	x	x		x		x	x
GNSS	x	x		x			
DORIS	x	x		x			

Seitz (2013)

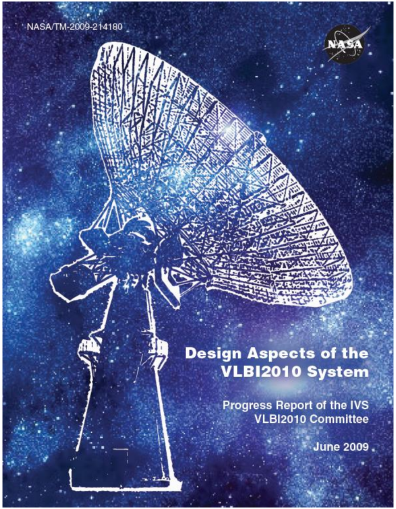
- No single space geodetic technique is sensitive to all of the necessary geodetic parameters
- Only VLBI connects to celestial frame
- Only SLR determines origin

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: IVS VLBI2010 Committee (2009)

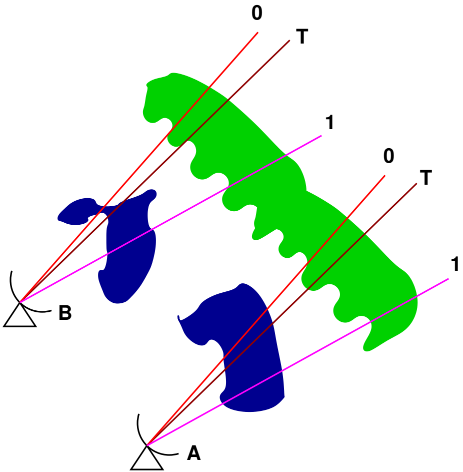
- Within the International VLBI Service for Geodesy and Astrometry (IVS)
- VLBI portion of GGOS improvements
- See, for example, Petrachenko et al. (2013) or IVS (2014)
- General goals include
  - ITRF positionally accurate to 1 mm
    - Each individual error term should be kept below 0.1 mm (∼0.3 ps)
  - Frame velocity 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

General Phase Referencing Concept

Phase Referencing Review Material

- VLBI Phase-Referencing (Beasley & Conway 1995)
- Very Long Baseline Interferometry (Walker 1999)
- Strategies for Phase Referencing with the VLBA (Wrobel et al. 2000)
- Interferometry and Synthesis in Radio Astronomy (Thompson et al. 2001)
- ATMCA: Phase Referencing using more than one Calibrator (Fomalont & Kogan 2005)
- Strategy for Removing Tropospheric and Clock Errors using DELZN Version 2.0 (Mioduszewski & Kogan 2009)
- Microarcsecond Radio Astrometry (Reid & Honma 2014)
- THE SCHED USER MANUAL (Walker 2015)
- AIPS COOKBOOK (The National Radio Astronomy Observatory 2016) 

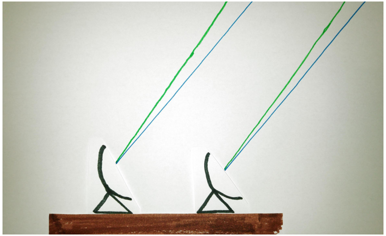
Standard D-VLBI / Phase Referencing



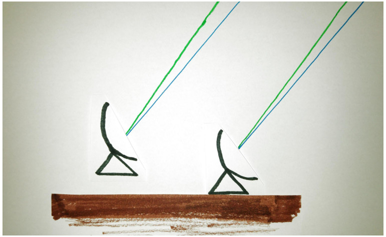
- Errors in VLBI measurements are strongly spatially and temporally correlated
- Remove these errors using measurements of calibrator sources (0, 1, ...) angularly nearby and nearby in time to a target source (T) — interpolation
  - For a single calibrator, do 0–T–0–T–0–...
  - For multiple calibrators do something like 0–T–1–T–0–T–1–...
- The closer the calibrators are to the target in direction and time, 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

Phase Referencing Corrects Errors in. . .

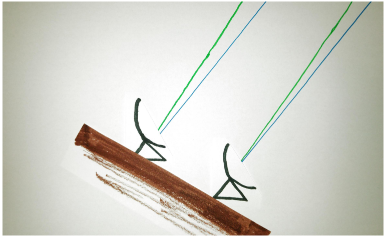
Ideal Case



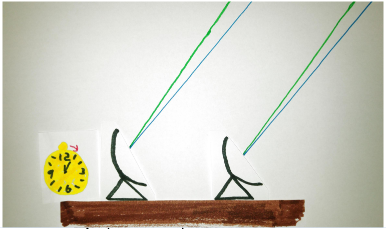
Station Position Error



EOP Error

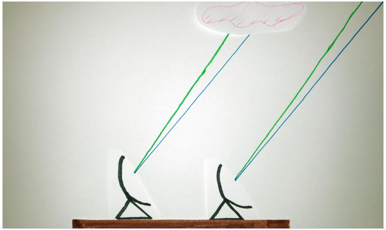


Clock/Cable Error



Tropospheric Delay Error

Ionospheric Delay Error



Phase Referencing Basics: Phase

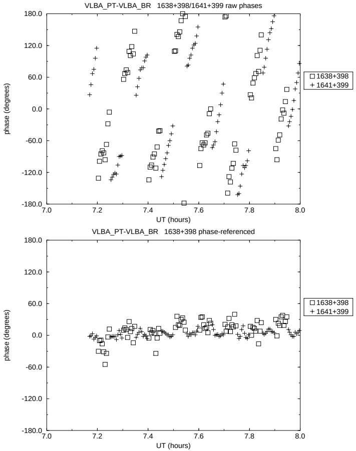


Figure 17.1: VLBA phase-referencing observation. *(a, top)* shows the raw phases on the sources 1638+398/1641+399; *(b, bottom)* shows the calibrated phases after fringe-fitting 1641+399 and phase-referencing the 1638+398 data.

Beasley & Conway (1995)

- Before calibration
  - Both calibrator and target show large phase rates
  - Both calibrator and target have unknown phase ambiguity
- After calibration
  - Target phase known to better than a few tens of degrees, possibly much better depending on angular offset, time offset, atmospheric gradients, frequency
  - After imaging with a sufficient number of baselines, the phase $2n\pi$ ambiguities are known — can use phase delay

Phase Referencing Basics: Angular Separation

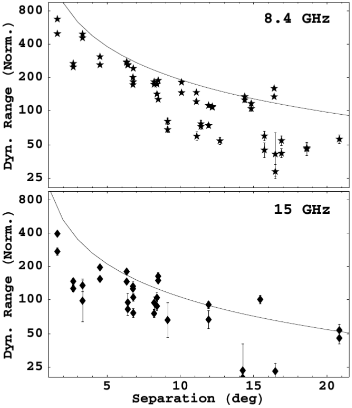


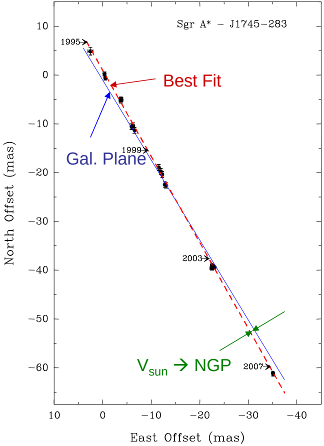
Fig. 1. Dynamic ranges (normalized to an observing time of 10 h) of the phase-referenced images as a function of distance to the calibrators. The error bars are proportional to the flux densities of the calibrators. Lines represent a model of the maximum achievable dynamic range (Eq. (2)).

Martí-Vidal et al. (2010)

- Results of Martí-Vidal et al. (2010) nicely demonstrate improvements in calibration accuracy (related to dynamic range here) with shorter angular separations between targets and calibrators
- Dynamic range shows the EFFECTIVE SNR one can achieve — there is a dramatic improvement at low angular separations (note log scale)
- Not shown: calibration improvement with shorter phase referencing cycle times
- In-beam calibration provides even better results (see, for example Radcliffe et al. 2016)

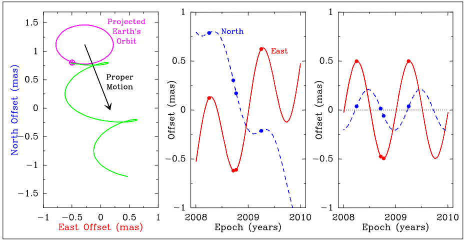
Standard Phase Referencing Applications

Proper Motion



Reid (2008)

Parallax



Reid (2008)

- 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 errors at centimeter wavelengths of ∼10 µas have become routine (Reid & Honma 2014) — equivalent to 0.5 mm error on a 10 000 km baseline at X band

Comparison of VLBI and D-VLBI

“Standard” Geodetic VLBI

- Primarily used to determine absolute station positions, Earth orientation parameters, absolute directions of many (strong) sources
- Measurements possible:
  - Group delay
    - Precision depends on frequency spacing
  - Phase delay
    - Rarely possible as it is difficult to eliminate $2n\pi$ ambiguities
    - Future VGOS measurements might aim for this
  - Phase rate
- Note: a continuous emission spectrum for target objects is not required by the technique

“Standard” D-VLBI Astrometry

- Primarily used for relative astrometry of a small number of sources per experiment, target sources are often weak
- Measurements possible:
  - Group delay
    - Almost never used, as phase delay is orders of magnitude more precise, but available in principle
  - Phase delay
    - $2n\pi$ ambiguities are solved by imaging, or or by having the a priori coordinates known sufficiently accurately
  - Phase rate
- Astronomers are frequently interested in targets that only have line emission, so astronomical software can deal with line emission in addition to continuous spectra

Comparison of VLBI and D-VLBI, Continued

“Standard” Geodetic VLBI

- Differential one-way ranging (DOR) can be used if the target emission contains a modulated signal
  - Used by the spacecraft industry, but quasar signals are apparently not modulated in a way useful for geodesy
- Spectral lines, or known signal modulations, can be used to determine Doppler shifts
  - Not used in geodesy
- Small N_{st} subarrays common

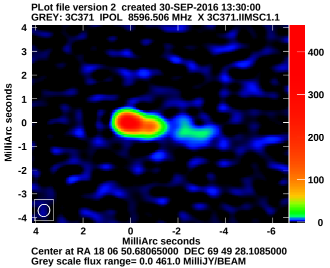
“Standard” D-VLBI Astrometry

- Delta-differential one-way ranging (ΔDOR) is used to improve results over DOR
- Spectral lines, or known signal modulations, can be used to determine Doppler shifts
  - Measured routinely by astronomers and the spacecraft industry for their targets
- Accuracy/precision increase exponentially as a function of N_{st}, so always observe with as many stations as possible
  - Beyond the straightforward SNR improvement on the target, more stations enables a weaker, but CLOSER calibrator and/or a SHORTER cycle time to be used, dramatically improving results

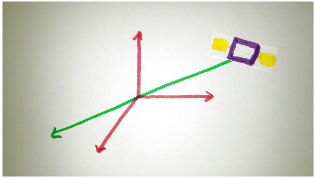
VLBI Changes From Infinity to Near Field

Number of Parameters to Solve

Target at infinity:
2 parameters
(1 **direction** = 2 **angles**)



Target near Earth:
6+ parameters
(3 **position** plus 3 **velocity** plus more if gravity field and other terms must be solved)



- Within one observing block/session, standard VLBI only needs to determine a **direction**
- An Earth-orbiting satellite needs to have **position** and **velocity** (= state vector) determined — alternatively, the orbital elements must be determined
- Many more measurements needed to determine all parameters well
- Angular velocities are so large that phase **rate** becomes crucial

Comparison of Infinite- and Finite-Distance VLBI

Infinite Distance

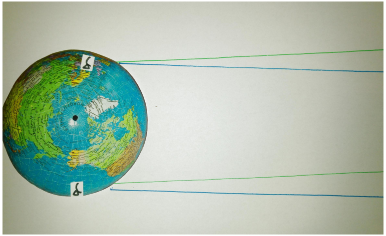
- Translation-invariant baseline measurements
- All stations see the same source intensity, correcting for atmospheric absorption and astronomical effects that are not the point of this workshop
- Source looks the same to all antennas
- All stations point at the same direction in the ICRF
- No source motion in ICRF

Finite Distance

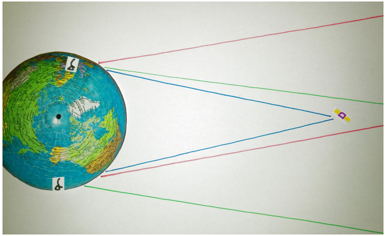
- 3-D baseline location and orientation with respect to emission source
- r^2 variations cause large amplitude differences among stations — need to account for this in imaging and other analysis
- Source viewed from different directions; sources generally have different emission properties as a function of viewing angle
- Each station points in a different direction
- Sources move on various timescales, from annual scales for Galactic objects, to stopwatch timescales for satellites

Visualizing The Effects

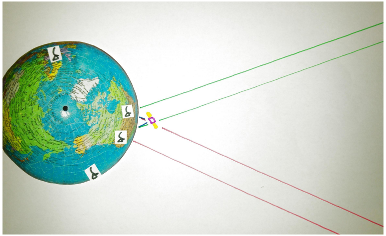
Infinite Distance



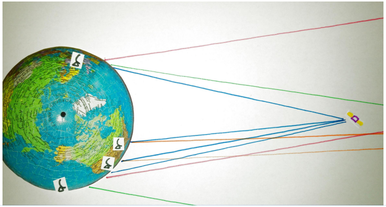
GNSS Satellite



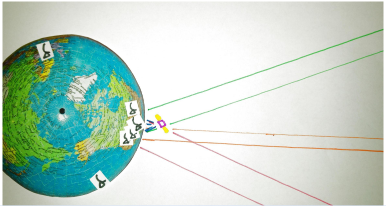
(E-)GRASP



Shorter Baselines Needed



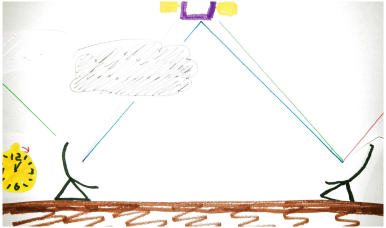
Shorter Baselines Needed



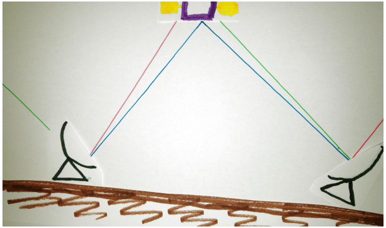
Phase Referencing No Longer Fixes Everything

Ideal Case

First Order Corrections Atmospheric/Clock Errors



Limited Correction Position/EOP Errors



Comparison of VLBI and D-VLBI

Geodetic VLBI

- Small spacecraft frequency separations can limit group delay precision
- All stations that can see the spacecraft can participate
  - Long baselines typically can make few observations because of limited common viewing time, in contrast to standard geodesy where one can pick a source from the entire sky to find a common visibility
  - Short baselines end up contributing more to satellite measurements
  - Difficult for geodecists to put into their mental framework, because they are so used to thinking that longer baselines are always better

D-VLBI

- Phase delay is always more precise
- Only stations with baselines SHORT enough that D-VLBI can be done can participate
  - Large geocentric parallaxes make D-VLBI useless — spend too much time slewing antennas, lose temporal coherence
  - Really short baselines with common calibrators for most/all antennas provide the best results
  - Because D-VLBI can outperform VLBI by orders of magnitude, short baseline arrays can outperform long baseline arrays
  - Example: A VLA, with baselines of 10s of km, that could do satellites would outperform the VLBA for low orbits
  - Difficult to get used to this result

Satellite VLBI Problems

- Baseline-based errors
  - Such as polarization leakage differences
  - Astronomers are not used to thinking so much about this, but many stations that are only used for geodetic VLBI have huge leakage problems (by astronomical standards) (see, for example, "A Bertarini" Roy 2010)
  - Even for receivers with "good" polarization properties, if the received frequency is at the edge of the band, the polarization leakage is usually high
  - For highly polarized emissions (usual case for spacecraft), leakage errors could be 10s to 100s or more picoseconds
  - Polarization calibration is necessary
- Bandpass calibration is essential to get accurate results (phase offsets of $\gtrsim 50^\circ$ are COMMON)
- Finding multiple VLBI antennas that can observe the satellite transmission frequencies
  - Other than the standard S/X DSN frequencies, VLBI has tended to try to avoid spacecraft transmission frequencies (see next slide)
  - Frequency setups untested, antenna LO chains unstable, passband cutoffs, . . .

Satellite VLBI Problems: Continued

- Satellites are too whopping bright!
  - Changes in the attenuation needed to receive/process a signal cause delay/phase jumps
    - Known to be a problem with the DBBC (G. Tucari, 2015, priv. comm., and see talks in this workshop)
    - Known to be a problem with the RDBE (Walker 2015)
    - Expected to happen for all receivers/backends — changing the electric circuit will change the delay
  - Automatic gain control is therefore BAD
  - This problem will generally only affect spacecraft, leading to systematic biases in spacecraft measurements
  - What about phase cal/pulse cal?
    - Difficult to correct automatic gain changes
    - Does the cal system work properly when observing a very bright target?
    - What about all of the stations where the cal system isn't working (broken, or corrupted by RFI/satellite signal)?
  - Nonlinear phase/delay response of receiver/backend at high signal strengths (see other talks this workshop, last night's dinner discussion)
  - In the opinion of the lead author, spacecraft engineers should design their transmitters intended for reception by VLBI stations to not significantly increase the power received by the stations above the level of standard geodetic quasars such that an attenuation change would be needed
    - Different power level for VLBI sessions?

Phase Referencing Problem: Core Shift

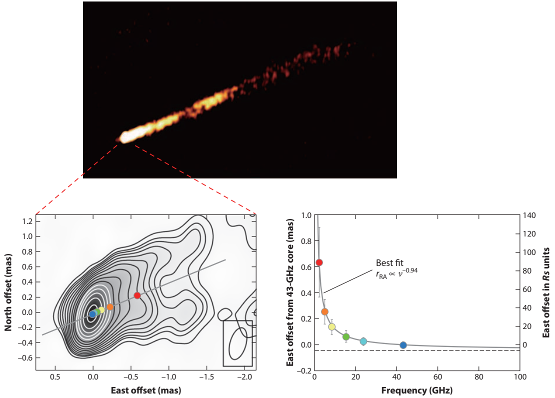


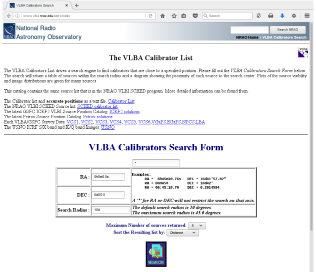
Figure 4

The apparent shift in the core of M87 as a function of observing frequency. This effect can be explained by frequency-dependent optical depths and allows the position of the supermassive black hole to be accurately located on the images. The bottom right panel gives offsets in angular units (mas) and in units of Schwarzschild radii (*Rs*). Abbreviation: RA, right ascension. Adapted from Hada et al. (2012) with permission.

Reid & Honma (2014)

- From Kovalev et al. (2008) and Sokolovsky et al. (2011), the median core shift for AGNs in their samples was about 1.5 mas GHz/ν, with individual sources having a scatter of a factor of a few
- This translates to a typical core shift of 1.1 mas at L band, 170 μas at X band, and 47 μas at Ka band
- Challenge for the scheduler is to figure out how to reuse the same calibrators again and again

Picking Calibrators: Traditional Phase Referencing


National Radio Astronomy Observatory

NRAO Home > VLBA Calibrators Search

The VLBA Calibrator List

The VLBA Calibrators List drives a search engine to find calibrators that are close to a specified position. Please fill out the *VLBA Calibrators Search Form* below. The search will return a table of sources within the search radius and a diagram showing the proximity of each source to the search center. Plots of the source visibility and image distributions are given for many sources.

This catalog contains the same source list that is in the NRAO VLBI SCHED program. More detailed information can be found from:

The Calibrator list and **accurate positions** as a text file: Calibrator List
The NRAO VLBI SCHED Source list: SCHED calibrator list
The latest GSFC ICRF2 VLBI Source Position Catalog: ICRF2 solutions
The latest Petrov Source Position Catalog: Petrov solutions
Each VLBA/GSFC Survey Data: VCS1, VCS2, VCS3, VCS4, VCS5, VCS6,VGaPS,EGaPS,NPCS,LBA
The USNO ICRF S/X band and K/Q band Images: USNO

VLBA Calibrators Search Form

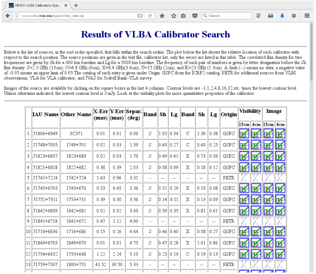
RA : 0h0m0.0s
DEC : 0d0'0.0
Search Radius : 10d

```
Examples:
      RA =  6h45m10.76s   DEC = 16d41'57.82"
      RA = 06H45M         DEC = 16d42'
      RA = 06:45:10.76    DEC = 0.2914594
```

A '' for RA or DEC will not restrict the search on that axis.*
The default search radius is 10 degrees.
The maximum search radius is 45.0 degrees.

Maximum Number of sources returned: 5
Sort the Resulting list by: Distance

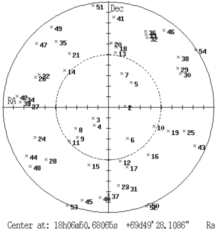
SEARCH


Results of VLBA Calibrator Search

Below is the list of sources, in the sort order specified, that falls within the search radius. The plot below the list shows the relative location of each calibrator with respect to the search position. The source positions are given in the text file, calibrator list; only the errors are listed in this table. The correlated flux density for two frequencies are given by Sh for a 400 km baseline and Lg for a 5000 km baseline. The frequency of each pair of numbers is given by letter designation before the Sh flux density: S=2.3 GHz (13cm), C=4.8 GHz (6cm), X=8.4 GHz(3.6cm), U=15 GHz (2cm), and K=23 GHz (1.3cm). A dash (--) means no data; a negative value of -0.05 means an upper limit of 0.05 The catalog of each entry is given under Origin: GSFC from the ICRF2 catalog; PETR for additional sources from VLBI observations; VLA for VLA calibrator; and JVAS for Jodrell Bank-VLA survey.

Images of the source are available by clicking on the square boxes in the last 4 columns. Contour levels are -1,1,2,4,8,16,32,etc. times the lowest contour level. Unless otherwise indicated, the lowest contour level is 3 mJy. Look at the visibility plots for more quantitative properties of the calibrator.

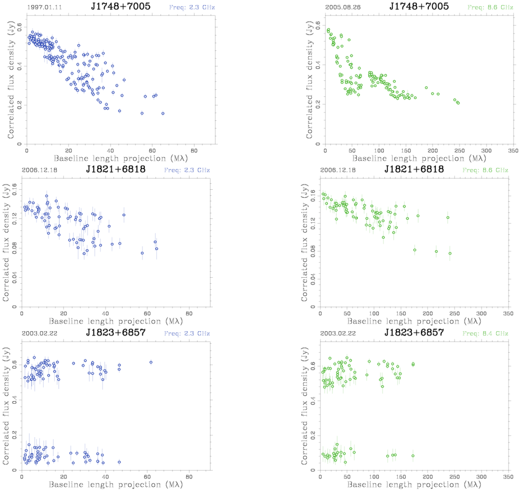
	IAU Name	Other Name	X-Err (mas)	Y-Err (mas)	Separ. (deg)	Band	Sh	Lg	Band	Sh	Lg	Origin	Visibility		Image	
													13cm	4cm	13cm	4cm
1	J1806+6949	3C371	0.01	0.01	0.00	S	1.05	0.54	C	1.30	0.38	GSFC				
2	J1748+7005	1749+701	0.02	0.03	1.59	S	0.60	0.27	C	0.60	0.25	GSFC				
3	J1823+6857	1823+689	0.02	0.03	1.70	S	0.49	0.41	X	0.73	0.59	GSFC				
4	J1821+6818	1822+682	0.38	0.39	2.03	S	0.08	0.09	X	0.18	0.12	GSFC				
5	J1741+7224	1742+724	1.43	0.96	3.31	-	--	--	-	--	--	PETR				
6	J1745+6703	1745+670	0.53	0.45	3.36	S	0.51	0.29	X	0.10	0.08	GSFC				
7	J1752+7311	1753+731	0.39	0.50	3.56	S	0.14	0.11	X	0.13	0.09	GSFC				
8	J1842+6809	1842+681	0.02	0.02	3.60	S	0.59	0.35	X	0.81	0.61	GSFC				
9	J1841+6718	1841+672	0.47	1.12	4.00	-	--	--	-	--	--	PETR				
10	J1716+6836	1716+686	0.15	0.26	4.64	S	0.46	0.40	X	0.58	0.27	GSFC				
11	J1849+6705	1849+670	0.01	0.01	4.75	S	0.47	0.28	X	1.01	0.86	GSFC				
12	J1754+6452	1753+648	1.22	2.24	5.10	S	0.23	0.19	C	0.19	0.13	GSFC				
13	J1759+7507	1800+751	41.52	30.50	5.33	-	--	--	-	--	--	PETR				

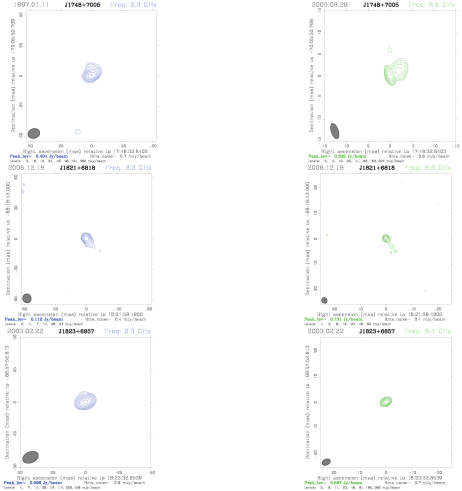


- Go to http://www.vlba.nrao.edu/astro/calib/
- Enter the coordinates of your target
- Study the available calibrators and their spatial relationship to your target

Images from NRAO (2016)

Picking Calibrators: Traditional Phase Referencing: 2

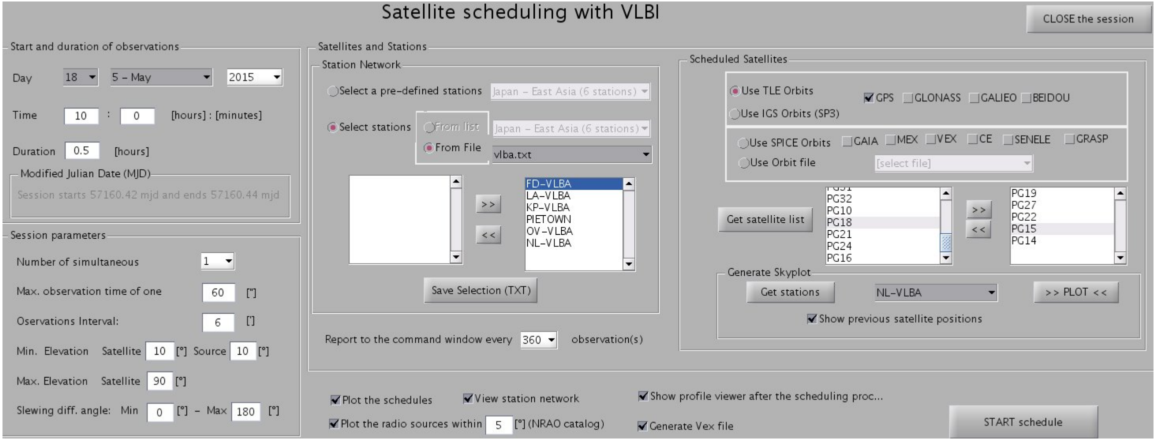




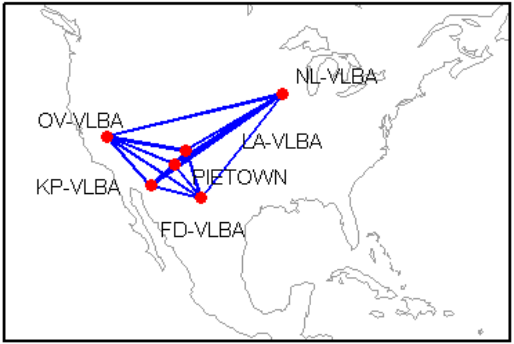
Images from NRAO (2016)

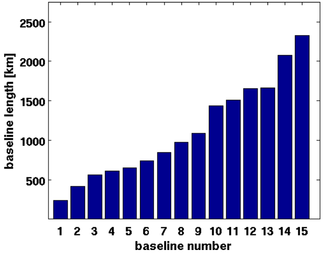
GFZ D-VLBI Activities

VieVS@GFZ Automated D-VLBI Scheduling Software



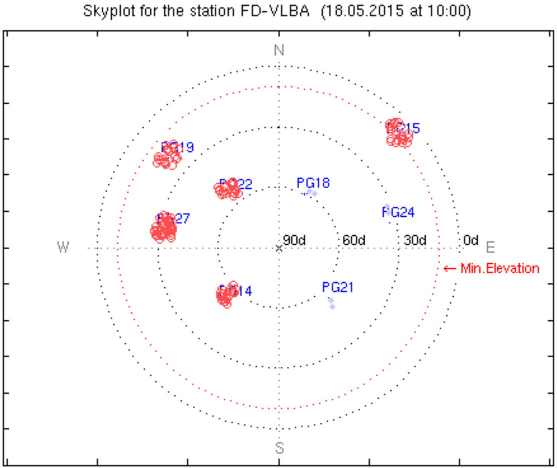
Example of a VLBA Subarray for GPS Observations



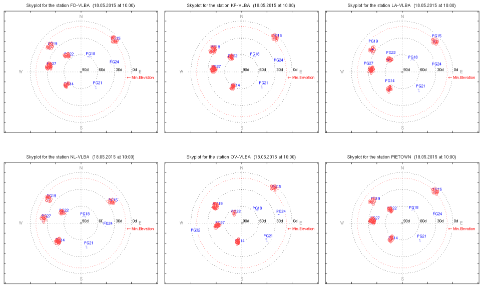


- Need L band receivers for GPS L1 and L2 signals
- Need short enough VLBI baselines for common satellite visibility
- Need high sensitivity for D-VLBI calibrator observations
- VLBA and EVN (European VLBI Network) arrays ideal for test cases

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

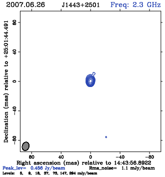


Calibrator Selection

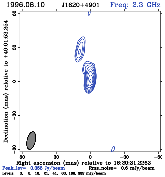
- Phase calibrator list includes sources from the VLBA Calibrator List (NRAO 2016) (as well as the Radio Fundamental Catalog, Petrov 2015)
- Selection Criteria
  - Angular distance between spacecraft and calibrator, Sun, horizon, . . .
  - Position accuracy
  - Absence of source structure
  - Flux density 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



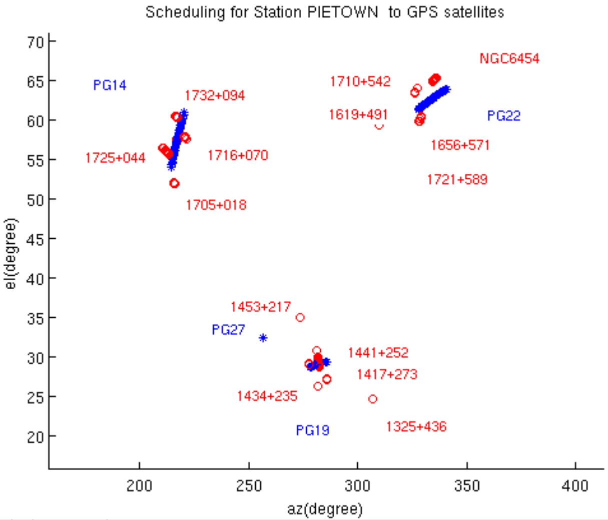
Good, little structure



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

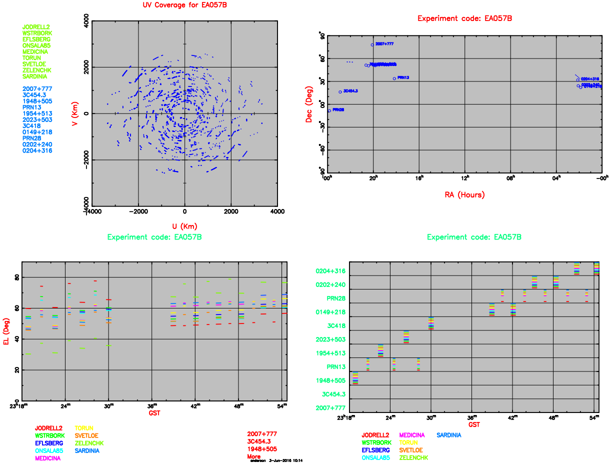
Scheduling Output

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
- Internal format converted to keyin file for NRAO SCHED (Walker 2015)
  - Has supported VLBA non-sidereal tracking for decades
  - Support for SPICE data for scheduling non-sidereal tracking
  - VEX and .v2d support — SPICE information for spacecraft can go directly into the .v2d file to minimize correlator staff effort
  - 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

NRAO SCHED



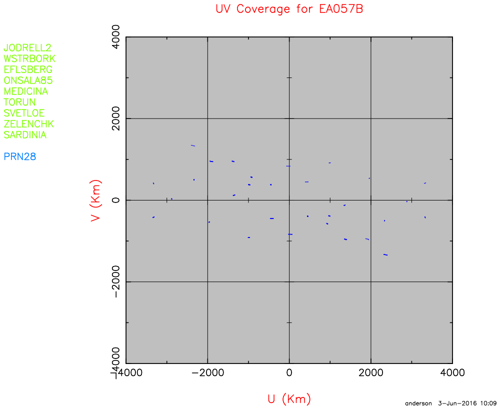
- Modified by us to support VEX output when observing spacecraft — needed for Field System driven stations
- Allowing stations to point at different RA,Dec coordinates for each scan to allow for geocentric parallax
- Workaround to deal with Field System not properly adhering to VEX standard

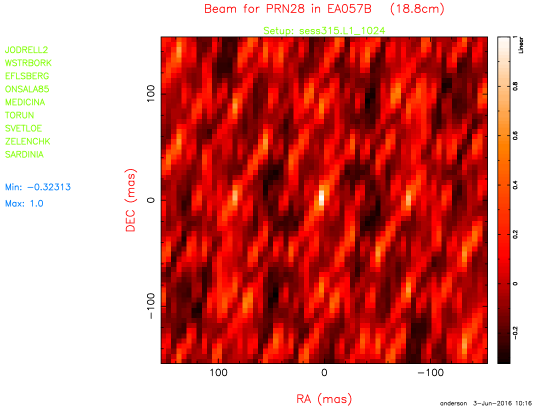
NRAO SCHED KEYIN File

```
File  Edit  Options  Buffers  Tools  Development  Help
source='1954+513'    dwell=00:00:40 setup='sess315.L1_1024'/


stations = JODRELL2,WSTRBORK,MEDICINA,ONSALA85,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='PRN13'       dwell=00:00:18 setup='sess315.L1_1024'/


stations = JODRELL2,WSTRBORK,EFLSBERG,MEDICINA,ONSALA85,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='2023+503'    dwell=00:00:40 setup='sess315.L1_1024'/


stations = JODRELL2,WSTRBORK,MEDICINA,ONSALA85,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='PRN13'       dwell=00:00:18 setup='sess315.L1_1024'/


stations = JODRELL2,WSTRBORK,EFLSBERG,MEDICINA,ONSALA85,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='3C418'       dwell=00:00:40 setup='sess315.L1_1024'/



stations = JODRELL2,WSTRBORK,EFLSBERG,MEDICINA,ONSALA85,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='0149+218'    dwell=00:00:40 setup='sess315.L1_1024'/


stations = JODRELL2,MEDICINA,
           TORUN,SVETLOE,ZELENCHK,SARDINIA
source='PRN28'       dwell=00:00:18 setup='sess315.L1_1024'/
-:LF---  Emacs: ea057b.key          90% (663,0)     (Fundamental SScr)
```

- Example keyin file from our latest EVN test session including GPS observations
- Gives scheduler complete control
- Familiarity/ease of use for the main D-VLBI scheduler at the GFZ (and non-justifiable bias trusting SCHED's slewing time predictions for phase referencing)

NRAO SCHED (u, v)-Coverage And Beam Predictions

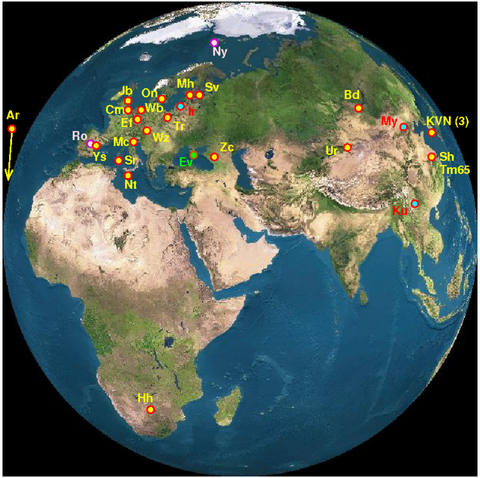




GFZ Test Observations

- EVN project EA057 to observe GPS satellites
  - Multiple frequency setups to try to get something to work within the constraints of the different EVN receiver/antenna limitations
  - EA057A (2015 Oct) failed because the frequency setups did not work — no fringes to fringe finders
  - EA057B (2016 Mar) Partial success — not all frequency setups failed!
  - Notified by JIVE in early September of the fringe finding status, JIVE to e-transfer satellite data to Bonn for correlation
  - Anderson in Bonn today to get access to data for correlation with DiFX
  - Initial findings hopefully presented at the upcoming EVGA meeting
  - If frequency setup tests are successful, EA057 will proceed to more GPS observation tests in upcoming EVN sessions
- Other Solar system test observations are underway, but are not covered in this talk

EA057B



Credit: for VLBI ERIC (2015)

- Stations included in experiment: JODRELL2 (Jb), WSTRBORK (Wb), EFLSBERG (Ef), ONSALA85 (On), MEDICINA (Mc), TORUN (Tr), SVETLOE (Sv), ZELENCHK (Zc), SARDINIA (Sr)
- Partial schedule shown in an earlier slide

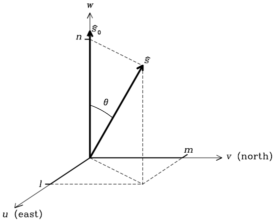
Correlation and Analysis Developments

Correlator Software Modifications

- Support for multiple near-field delay models to be used
  - We have implemented our own versions of delay models and are integrating them in DiFX
  - For testing frame ties, we want to be able to select whether or not the correlator internally performs frame transformations or not — delay models calculated in ICRF, GCRF, ITRF frames
- Support additional spacecraft orbit models
  - SPICE not currently suitable for satellite correlation/analysis — see later slide
- Support for additional partial derivative calculations to enable D-VLBI processing of near-field observations in AIPS and ParselTongue
  - In order to take full advantage of phase calibration, and to support narrow-band signals, want to use phase delay measurements
  - This means that the $2n\pi$ ambiguities need to be solved, and Fourier imaging is the best way to achieve that

Imaging Axes for Spacecraft

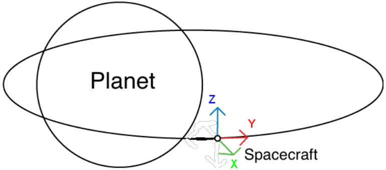
(l, m, n), $(\Delta\alpha, \Delta\delta, \Delta r)$



Credit: Condon (2016)

- 3-D generalization of standard astronomical imaging terms
- Pro: Keeps many parts similar to existing processing
- Con: Spacecraft offsets vary in direction with time

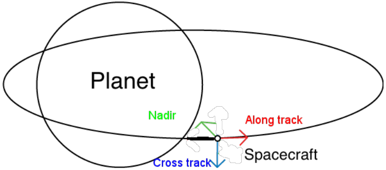
$(\Delta x, \Delta y, \Delta z)$



Credit: Maxpm (2014)

- Pro: Simple Euclidean coordinate system
- Con: (D-)VLBI error in radial direction far larger than in orthogonal directions, limiting implementation accuracy

$(\Delta A, \Delta C, \Delta N)$, $(\Delta$along track, Δcross track, Δnadir$)$



Credit: Maxpm (2014)

- Pro: For typical D-VLBI observations, spacecraft offsets remain fixed within the coordinate system
- Con: More complicated system as the spacecraft orientation changes continuously

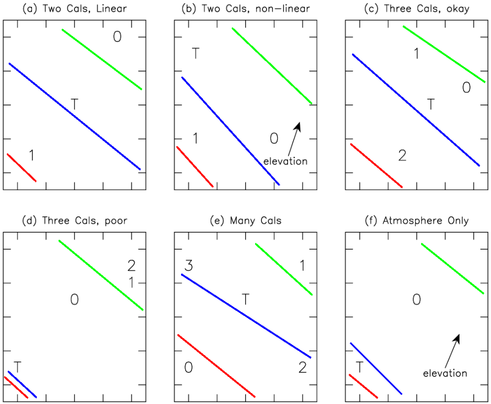
The Problem With SPICE

- SPICE is not suitable for sub-millimeter accuracy Earth-orbiting satellite use
- Quoting JPL, "While for general applications, SPICE is usually capable of much higher accuracy than required, for some specialized applications such as radio science, certain SPICE-based computations may not be sufficiently accurate." (NASA JPL 2016)
- One of the main problems is that the SPICE routines for time conversion are only "accurate to about 4.E-5 seconds"
  - Suspiciously close to the 47 μs accuracy provided by a Julian Date represented as an IEEE double
  - As typical Earth-orbiting satellites of interest have velocities of up to 7.8 km s^{-1}, a 47 μs error in the SPICE Ephemeris Time (ET) translates to a 370 mm **position error, orders of magnitude above the VGOS accuracy goal**
  - Difficult/impossible to know whether the ET timestamps in the SPICE kernels are accurate to better than 47 μs
  - Even the final double precision TDB (ET) times in the SPICE kernels "are not generally accurate to better than 1.E-7 second", for a position error of $\sim$1 mm in the best case

Analysis

- Software development to support 3-D and 6-D imaging within AIPS/ParselTongue
  - Allow for imaging in full position and position/velocity (state vector) spaces for D-VLBI measurements
  - Enables $2n\pi$ ambiguity resolution
  - Simulations suggest that rate (velocity) provides tighter constraints with D-VLBI than delay (position) for near-field targets, hence the plan to allow for 6-D imaging
  - Uses partial derivative information from the correlation stage to determine image scale factors
  - Analogous support for 3- and 6-D component models for CLEANing must be implemented as well
- Enable near-field support for D-VLBI atmospheric correction software.

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

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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