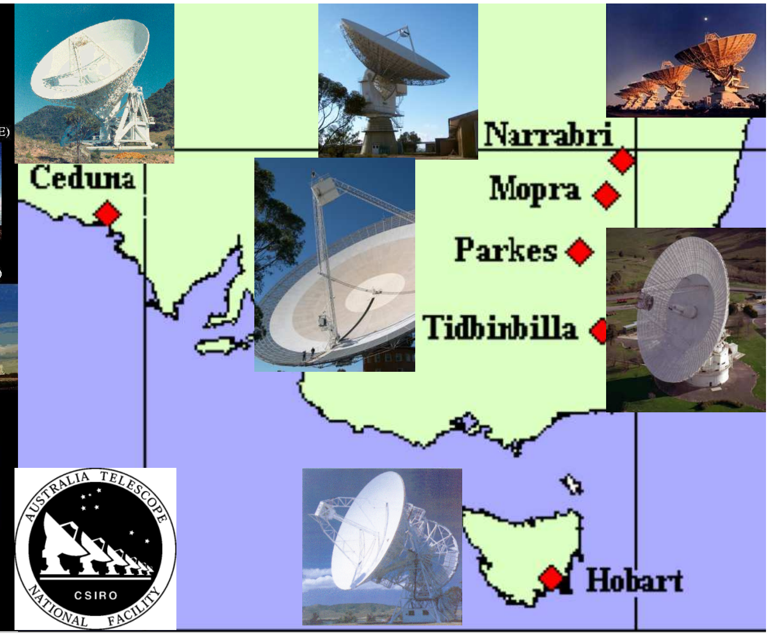


EUROPEAN vlbi NETWORK

NRAO

Very Long Baseline Interferometry

Adam Deller

12th NRAO Synthesis Imaging Workshop

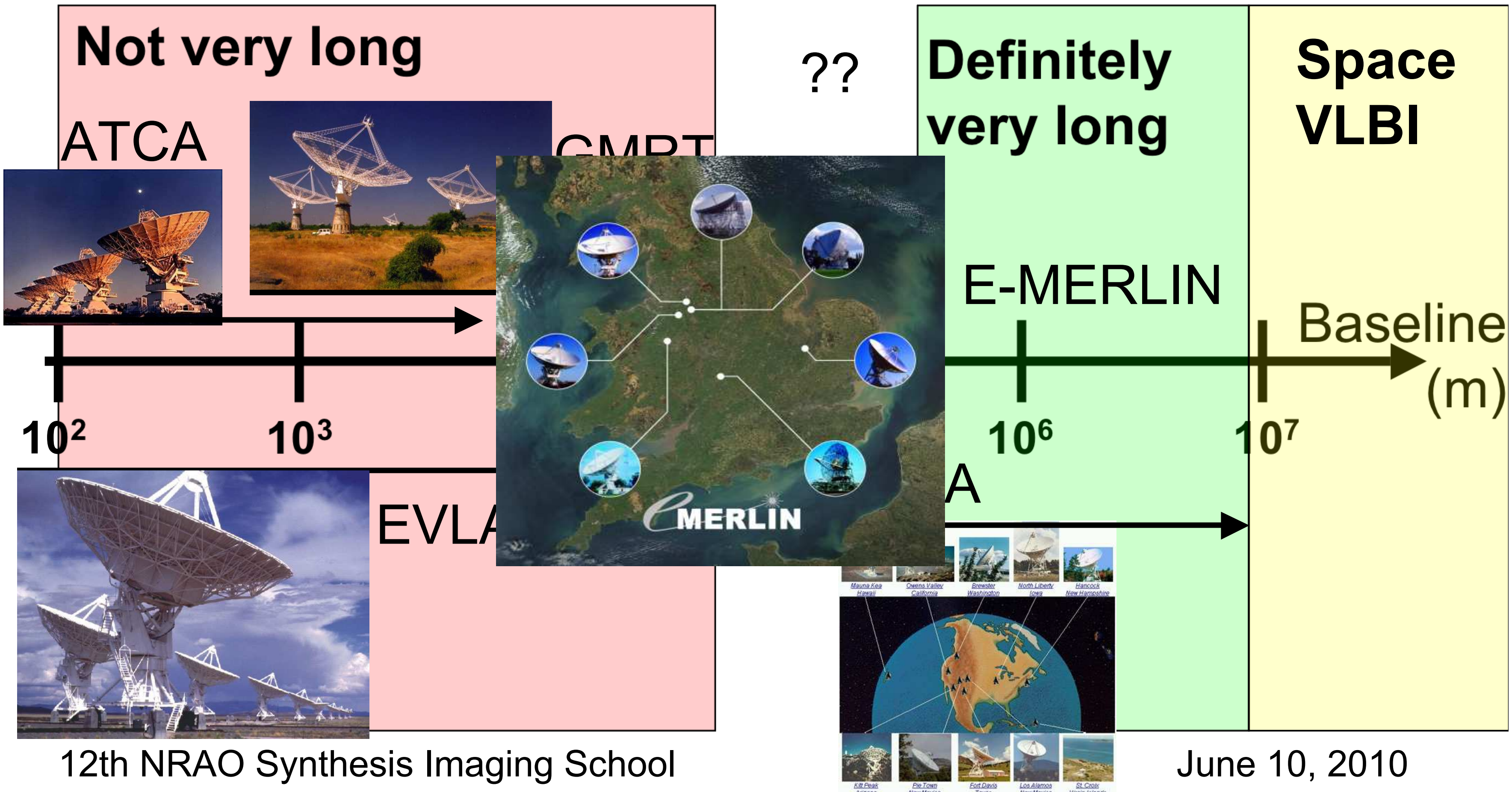
June 10 2010

Outline

- What is VLBI?
- Capabilities of modern VLBI
- Science applications of VLBI
- 7 (*mostly* bogus) reasons why VLBI is "hard"
- How you "do" VLBI: scheduling and data reduction
- New VLBI capabilities and techniques
- The future of VLBI

VLBI in context

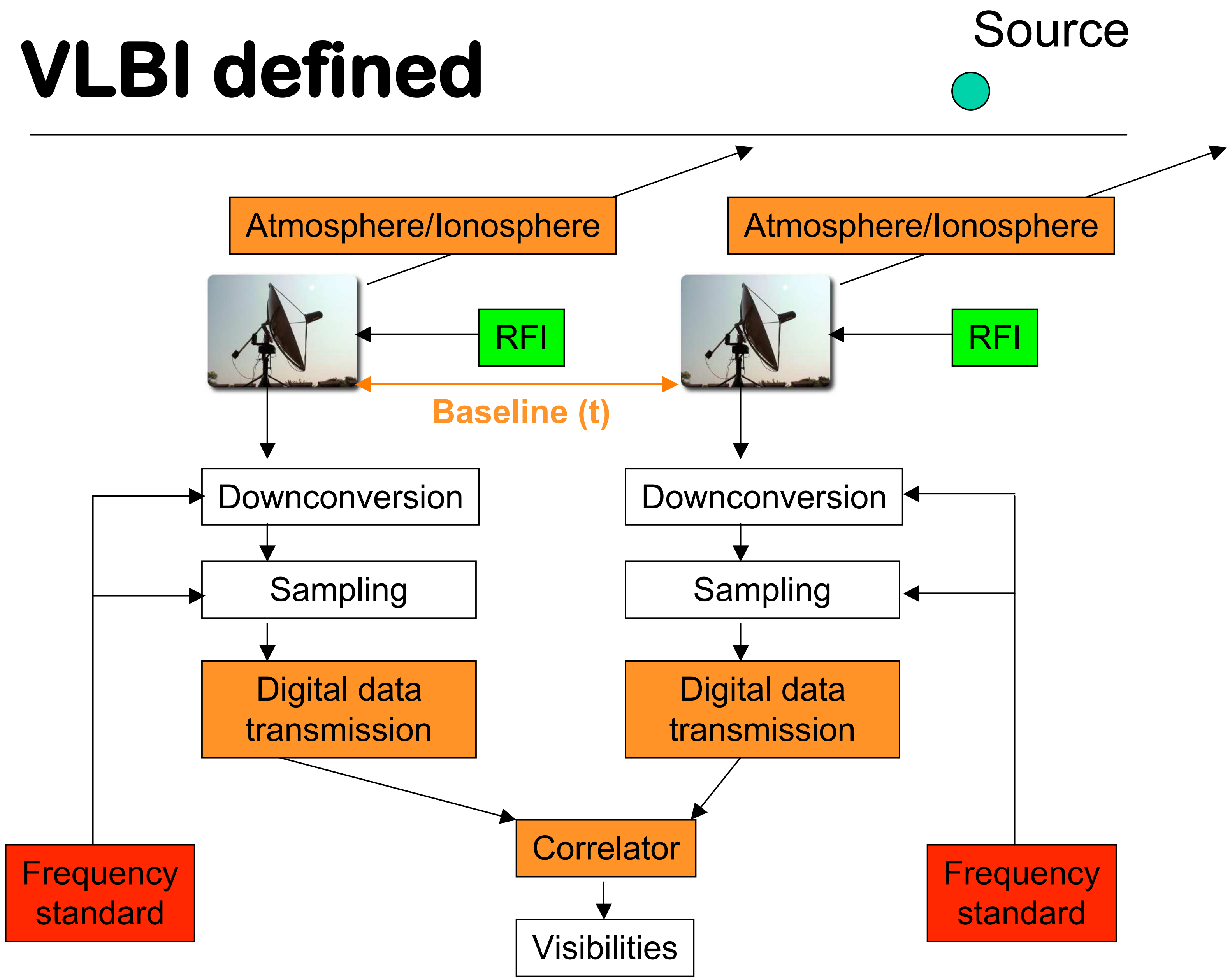
- How long is "Very Long"?



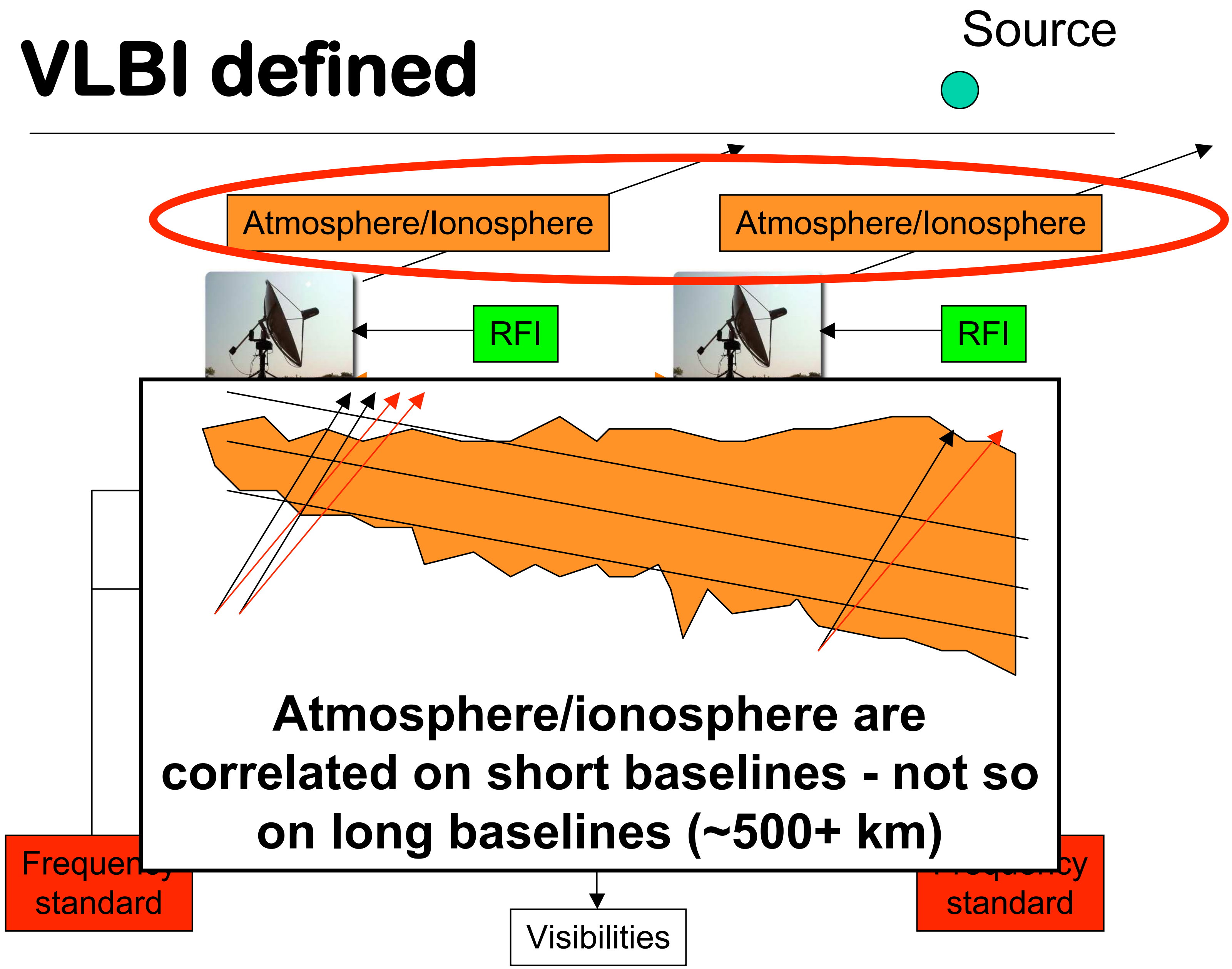
VLBI in context

- Clearly its not just about the baseline length…
- What constitutes VLBI is actually a little hard to pin down (its more like a “syndrome” than a “disease”!)
  - This is because there’s really **nothing** fundamentally different between VLBI and regular interferometry - only technology, convenience and convention
  - For now, take the defining characteristic to be independent antenna electronics; i.e., anything that’s not “connected element”

VLBI defined

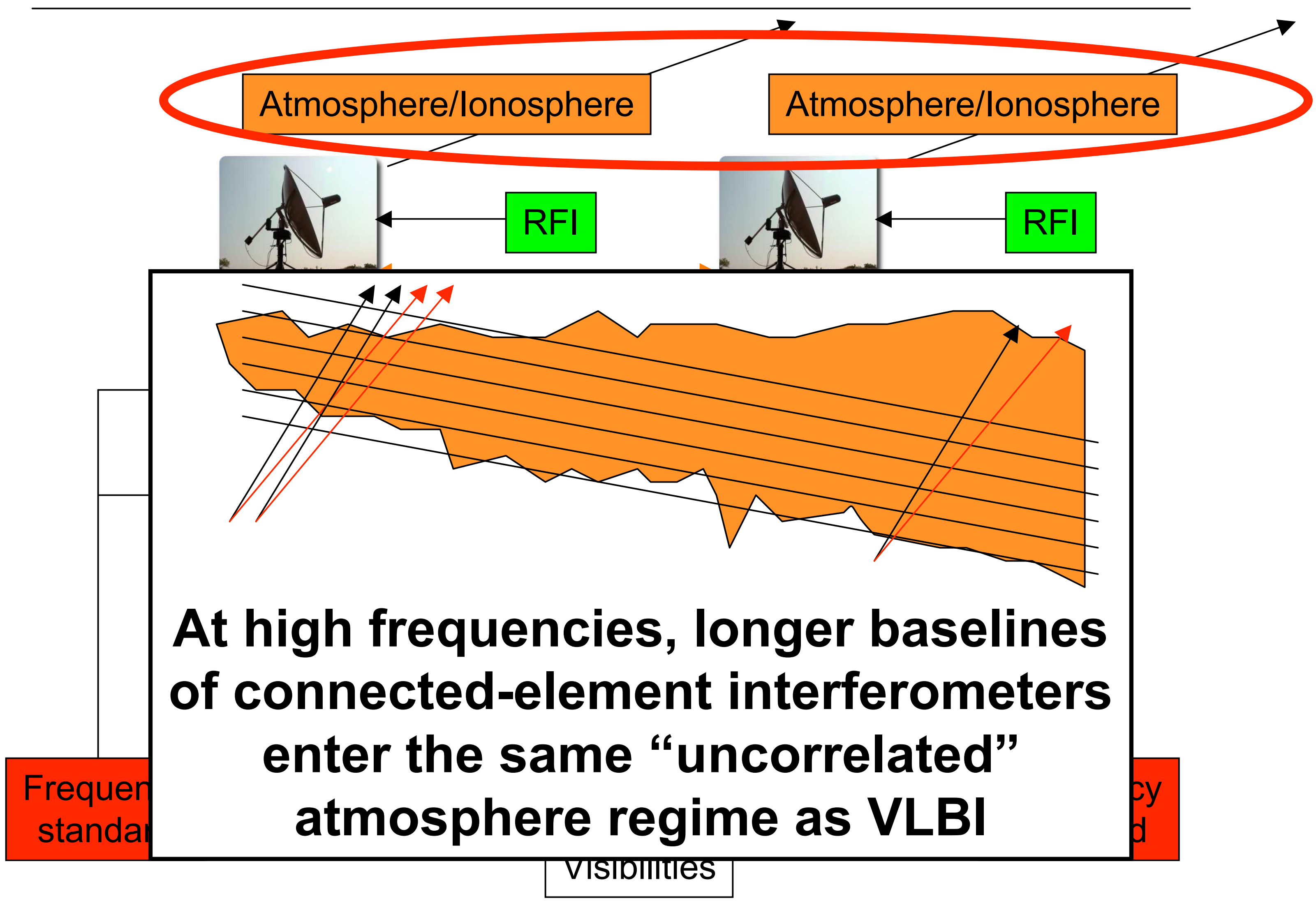


VLBI defined

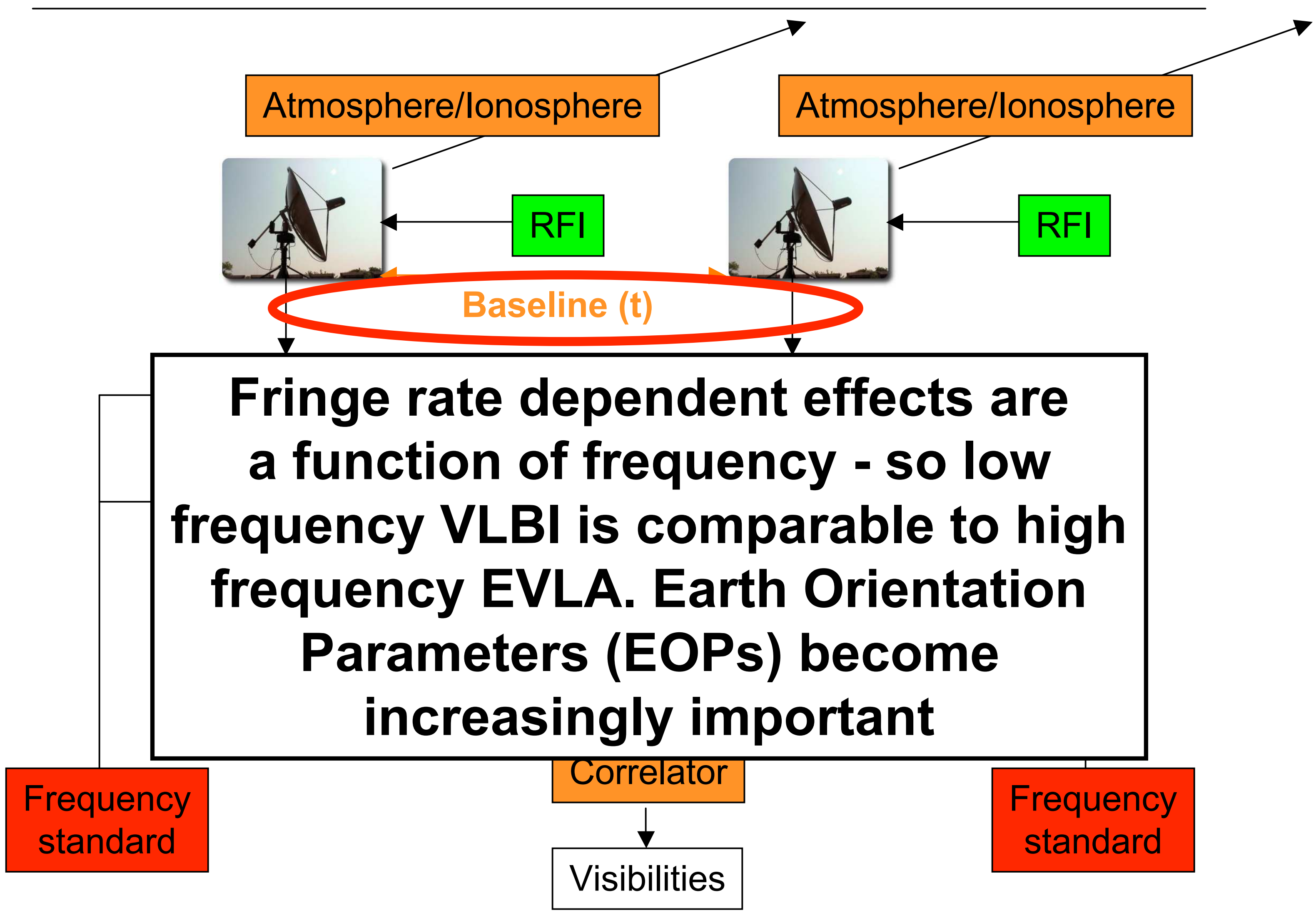


VLBI defined

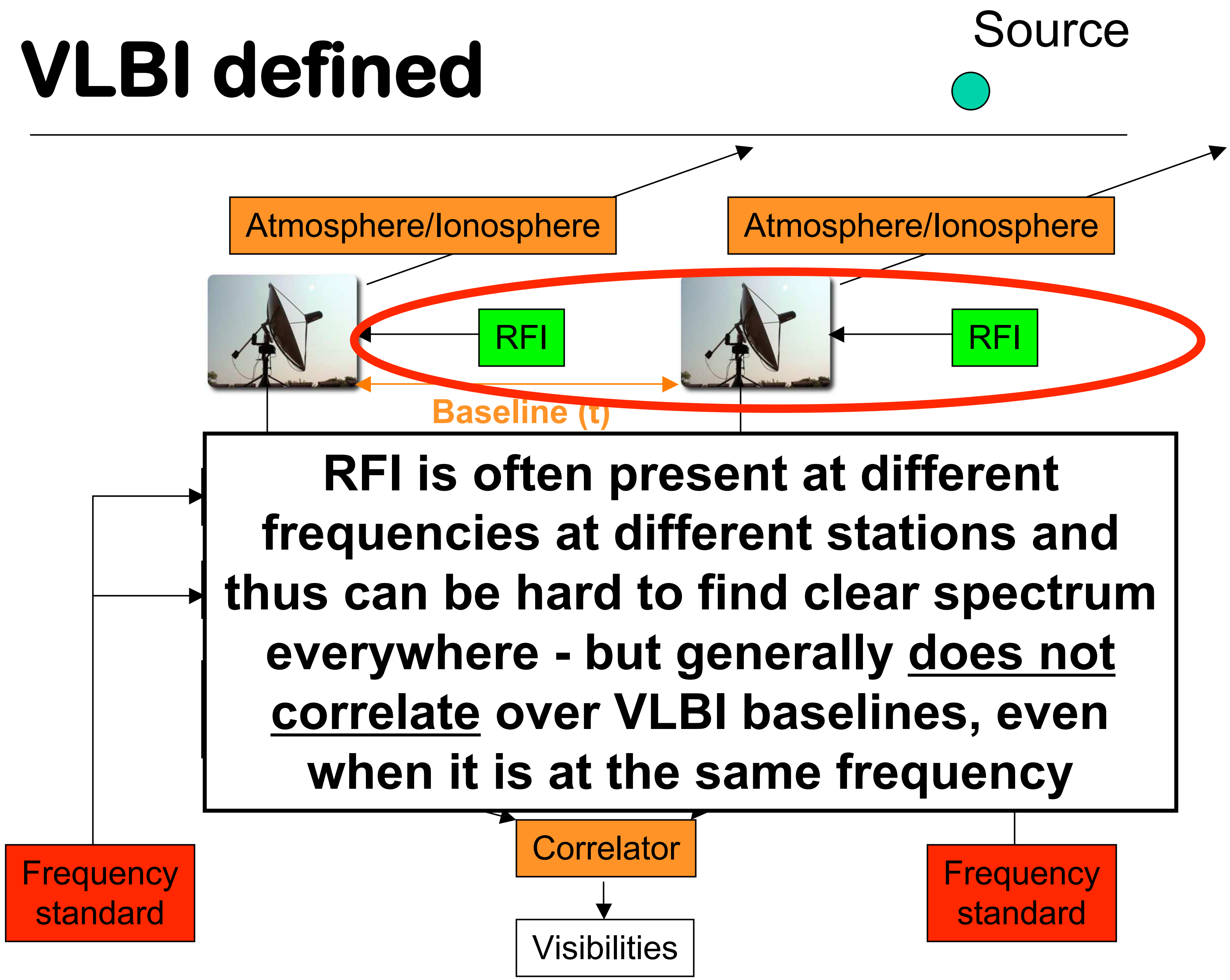
Source



VLBI defined



VLBI defined



RFI is often present at different frequencies at different stations and thus can be hard to find clear spectrum everywhere - but generally <u>does not correlate</u> over VLBI baselines, even when it is at the same frequency

VLBI defined

Source

Atmosphere/Ionosphere

Atmosphere/Ionosphere

The data transmission is where VLBI differs most obviously.

more logistical

k w

aff

Correlator

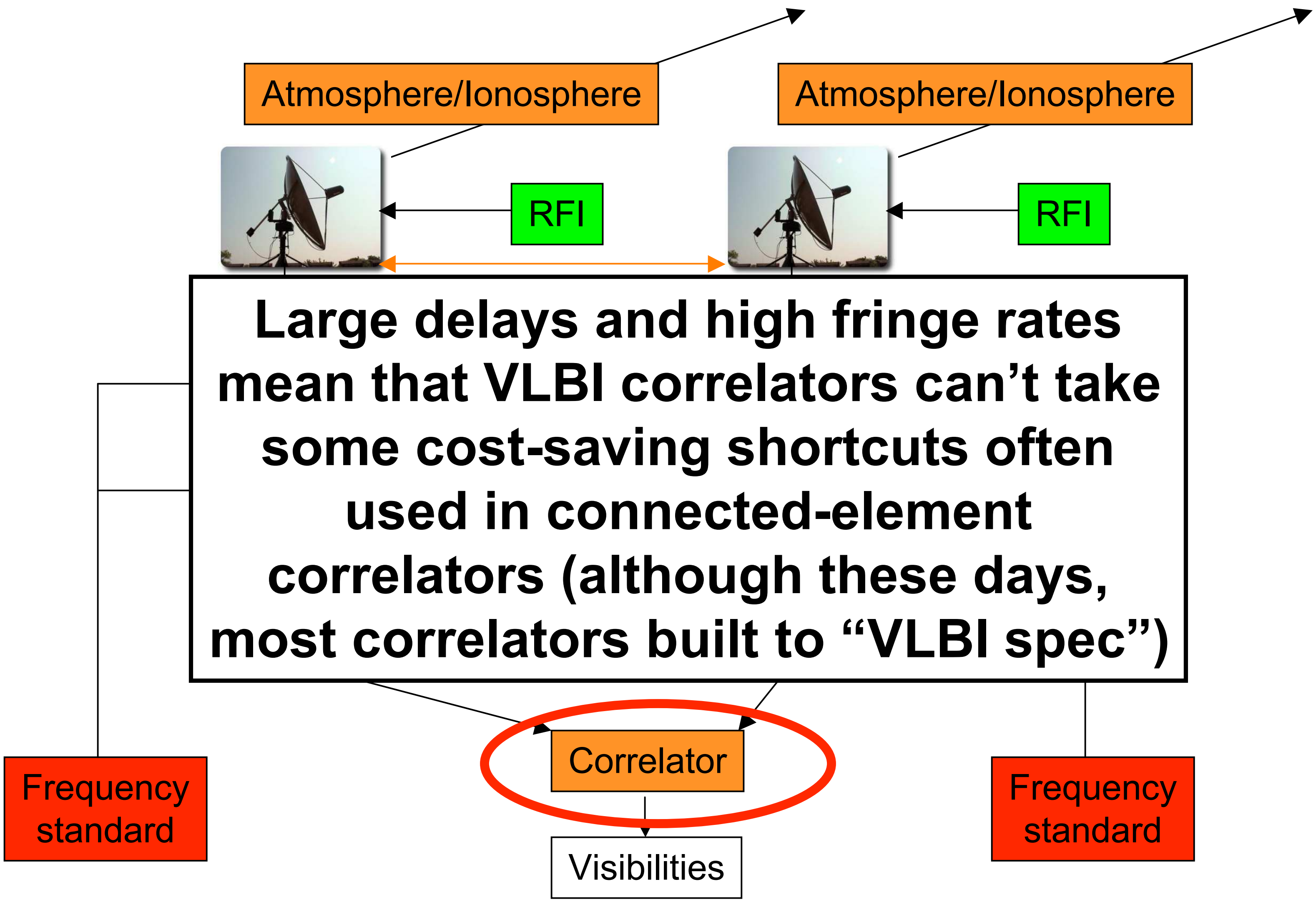
Frequency standard

Frequency standard

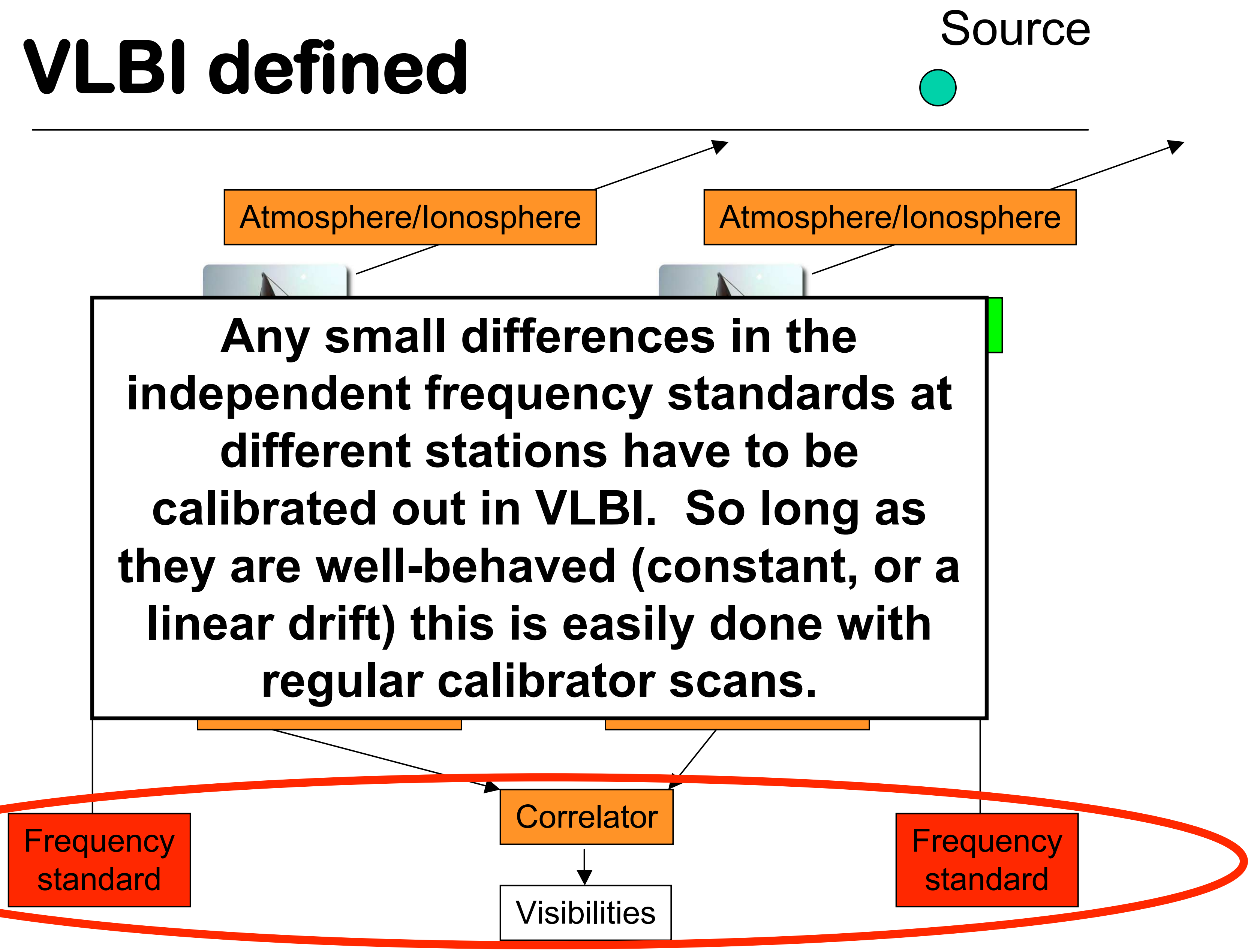
Visibilities

VLBI defined

Source



VLBI defined



Any small differences in the independent frequency standards at different stations have to be calibrated out in VLBI. So long as they are well-behaved (constant, or a linear drift) this is easily done with regular calibrator scans.

Current VLBI arrays

■ The Very Long Baseline Array (VLBA)

- 10 x 25m antennas
- 0.3 - 86 GHz
- maximum baseline ~8,000 km
- full time operation

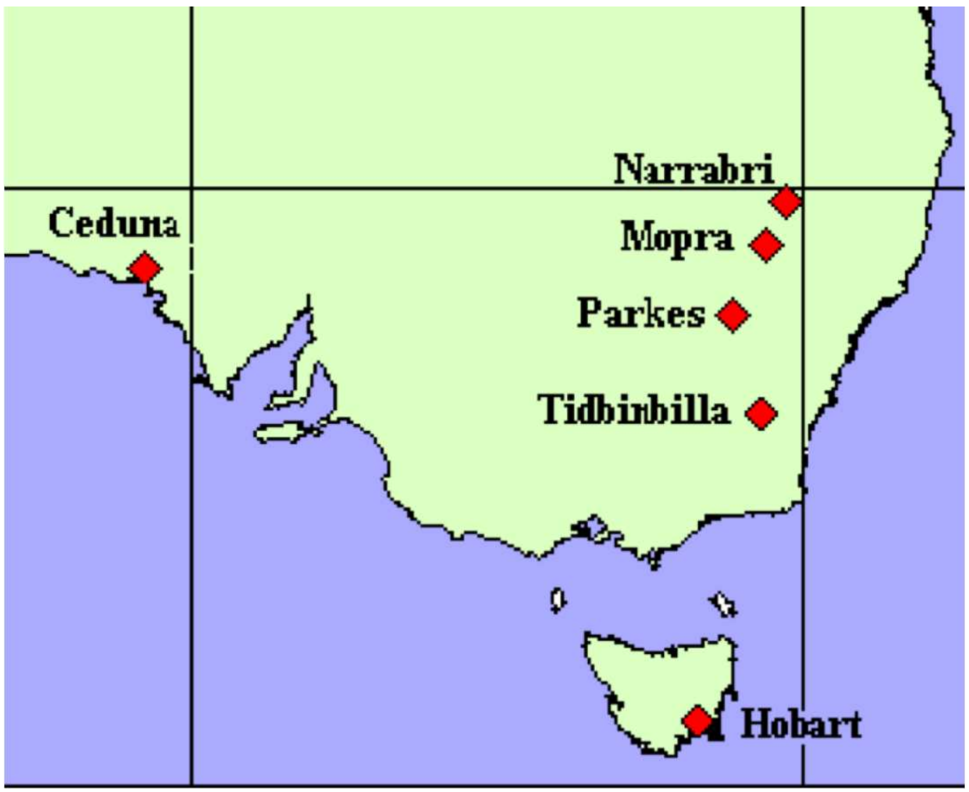
Current VLBI arrays

- The European VLBI Network (EVN)

- 18 antennas, 10m -> 100m
- 0.3 - 86 GHz
- maximum baseline ~8,000 km
- operates ~3 months/year

Current VLBI arrays

- The Long Baseline Array (LBA)



- 6 antennas, 22m -> 70m
- 1.3 - 22 GHz
- maximum baseline ~1,700 km
- operates ~3 weeks/year
- only Southern Hemisphere instrument

Current VLBI arrays

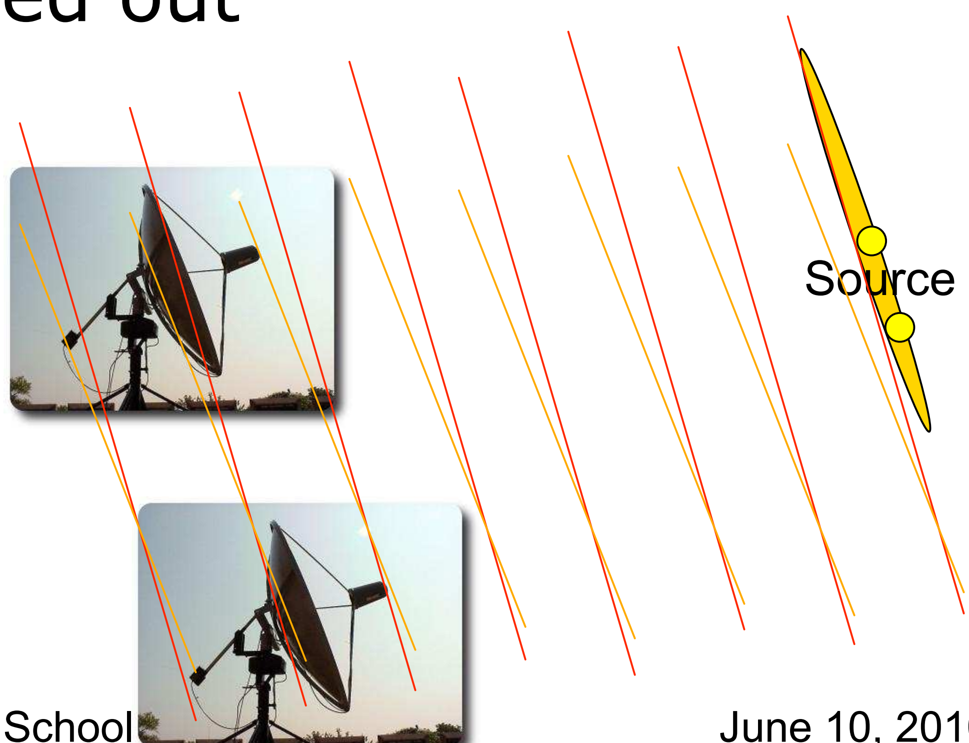
- Other active arrays which are not open-access:
  - Japanese VLBI network (JVN)
  - VLBI Exploration of Radio Astrometry (VERA)
  - Korean VLBI network (KVN)
  - The Event Horizon Telescope (EHT)
- Plus various ad-hoc combinations of the previous arrays with extra dishes (e.g., High Sensitivity Array = VLBA + phased (E)VLA + GBT + Effelsberg + Arecibo)

What VLBI gives you

- From the fundamentals of interferometry, you immediately know that the resolution will be very high:
  - At 1.4 GHz (21cm), an array of maximum baseline 8,000 km will have a resolution of $1.22\lambda/D$ ~= 7 milli-arcseconds!
  - At 43 GHz (7 mm), the same array will have a resolution of 200 microarcseconds!
- The collecting area can also be very large so point source sensitivity can be excellent (think Arecibo + GBT + …)

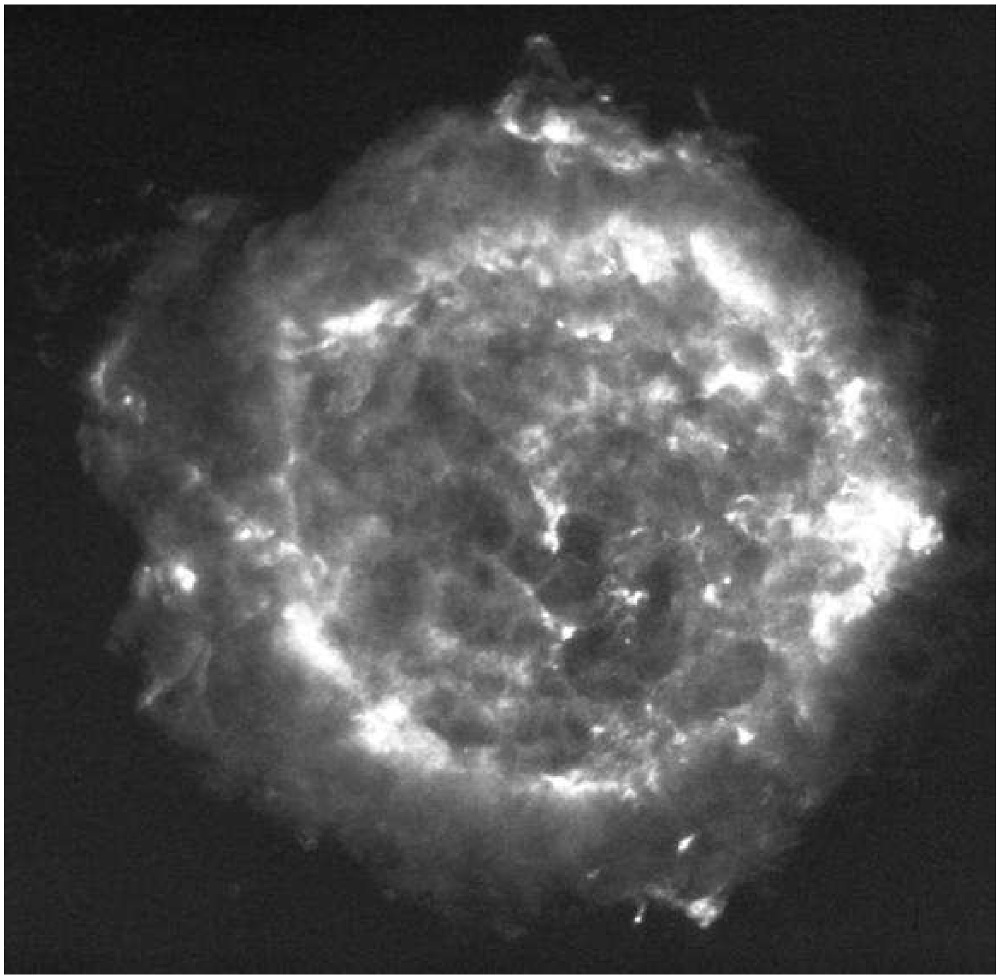
… but there's always a catch

- The curse of resolution; if the object is larger than your synthesized beam, emission from different regions will interfere destructively and the source will be "resolved out"
- The surface brightness sensitivity is very low (array filling factor is low)



… but there’s always a catch

6’



VLA beam

VLBA beam has 2×10^{-7} of the area of the VLA beam

The Cas A supernova remnant, VLA C array, 6cm

Science applications of VLBI

- VLBI provides a tool to study mas-level structure in radio sources - what sources are this compact?
  - Thermal sources are not bright enough for current VLBI arrays, thus entirely non-thermal
  - Active Galactic Nuclei (AGN)
  - Pulsars
  - Masers
  - Supernova remnants
  - Magnetically active stars

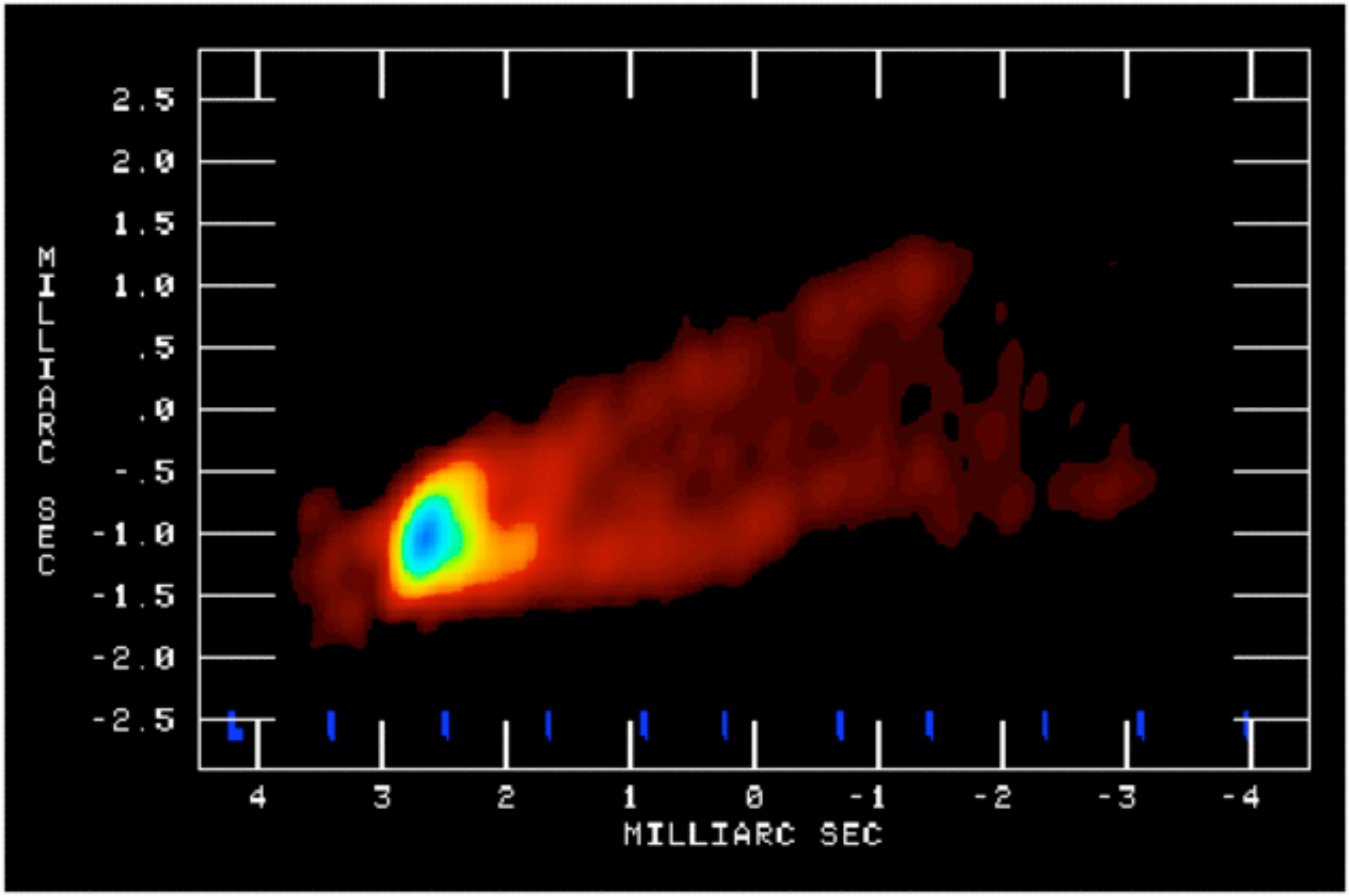
Science applications of VLBI

- For these sources, we typically want one of four things:
  - Compact flux? [Is anything there at all?]
  - Determine (very) small scale structure [e.g., what do the base of jets in AGN look like, how do supernova remnants evolve?]
  - Their precise location, to obtain source kinematics or distance [astrometry]
  - A “test source” to model the propagation through the ISM/atmosphere/ionosphere or the location of the receiving telescopes [geodesy]

Hallo? Any (compact) body there?

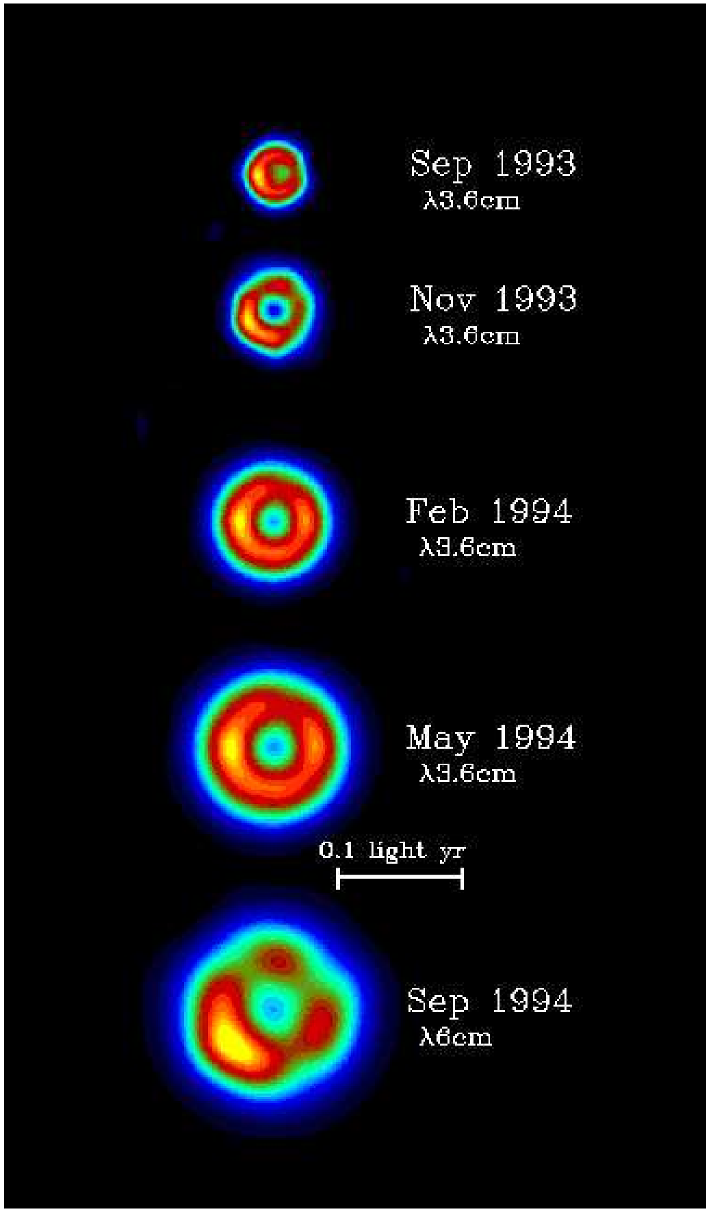
- A VLBI detection instantly identifies a compact non-thermal source
- In the local Universe, that might be a supernova [remnant], pulsar, shock…
- In the high redshift Universe, it **must** be a (radio loud) AGN
- VLBI is thus a brilliant tool for discriminating between potential sources of radio flux at high redshift (AGN feedback in the high-z Universe; more on this later)

High resolution imaging



The M87 jet as seen by the VLBA: C. Walker et al.

High resolution imaging

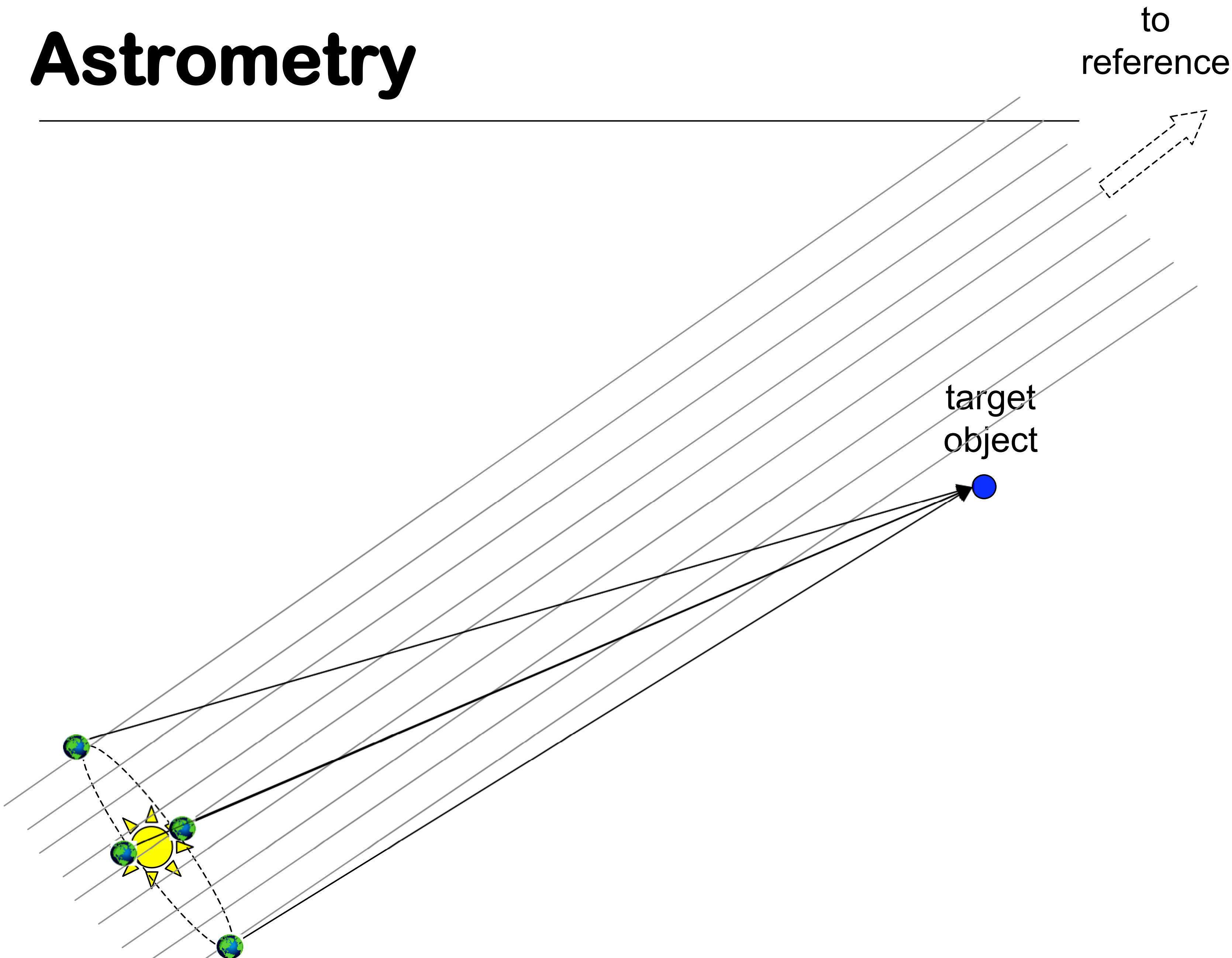


The expansion of SN1993J: Global VLBI observations, J. Marcaide et al.

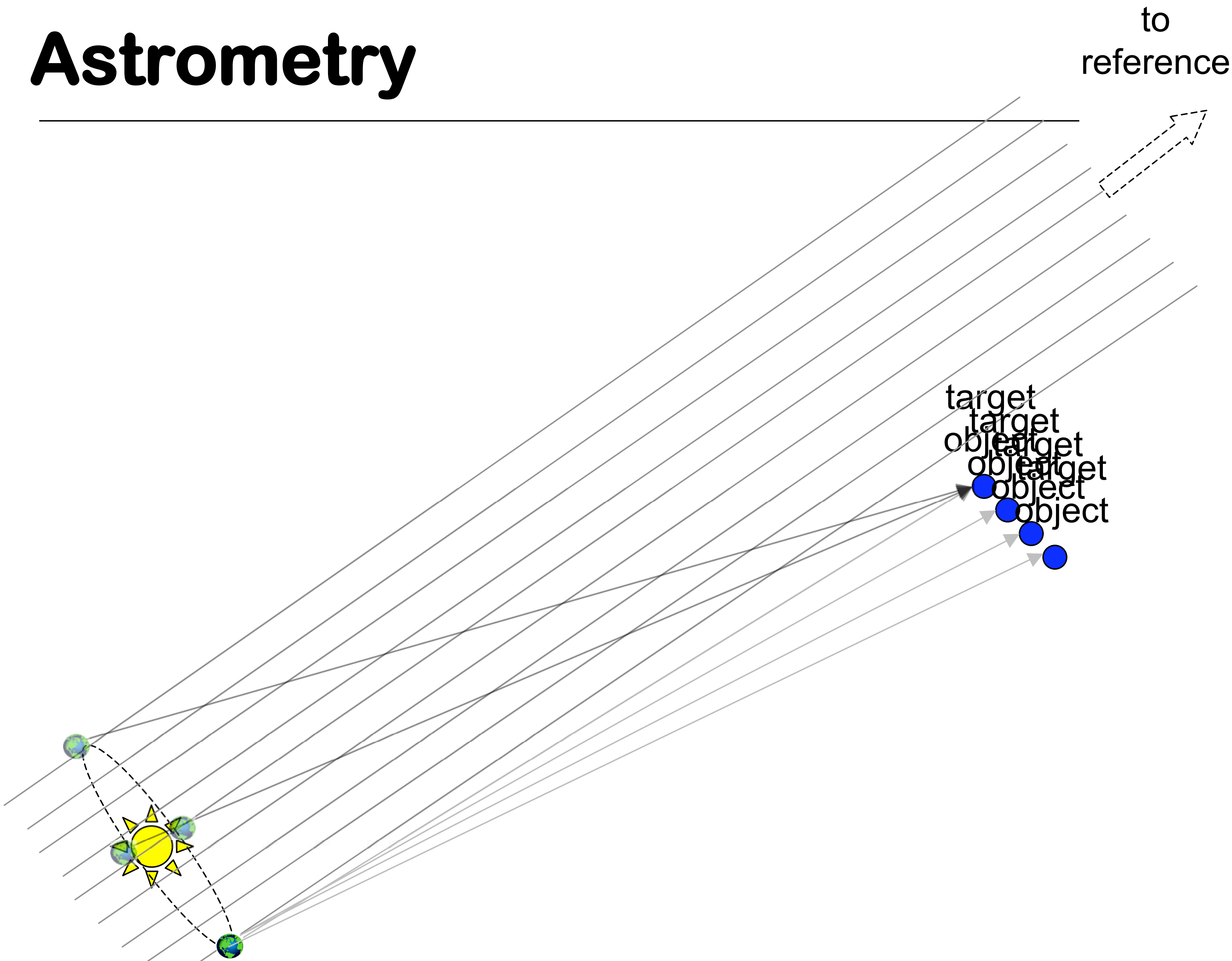
Astrometry

- With VLBI we can centroid an object's location to the ~0.01mas level
- Ideally unchanging point sources!
- Can be relative or absolute (next lecture) - VLBA in particular has excelled in relative astrometry recently
- Proper motions and parallaxes of objects across the Galaxy can be discerned

Astrometry

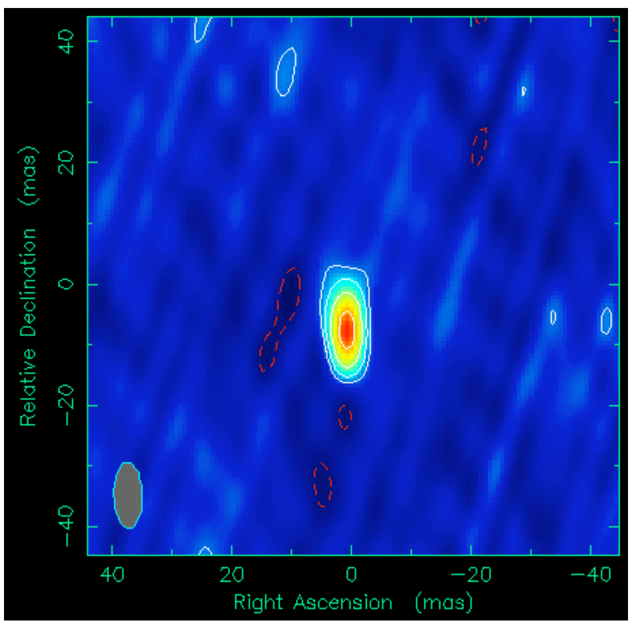


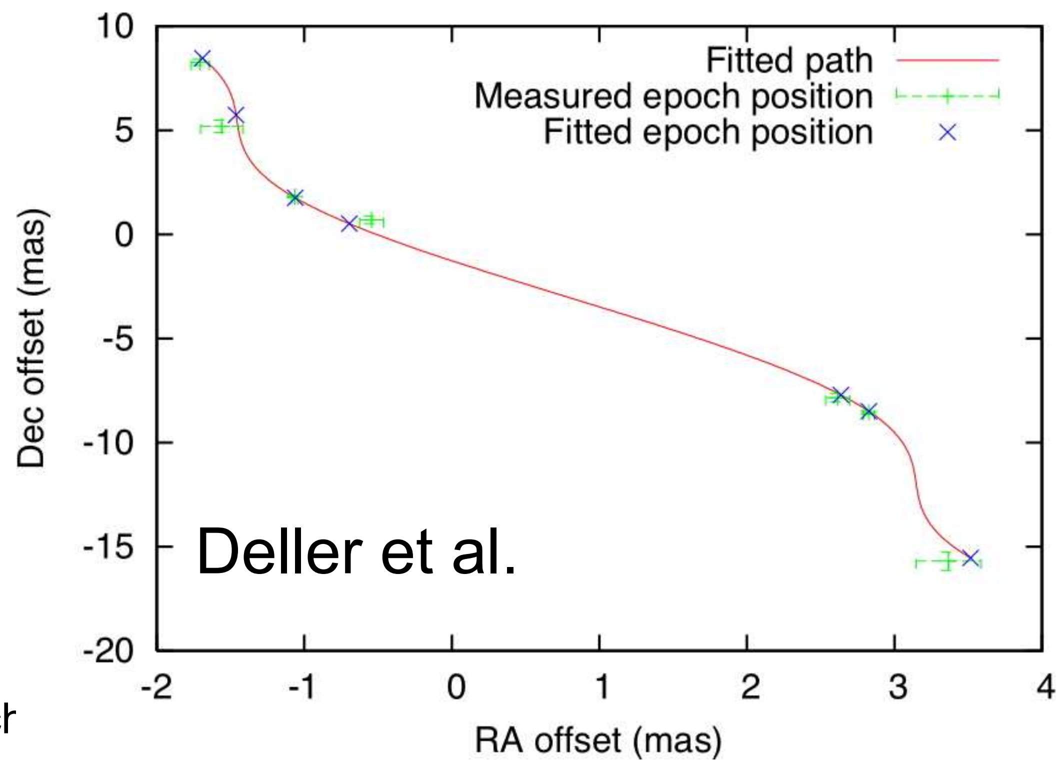
Astrometry



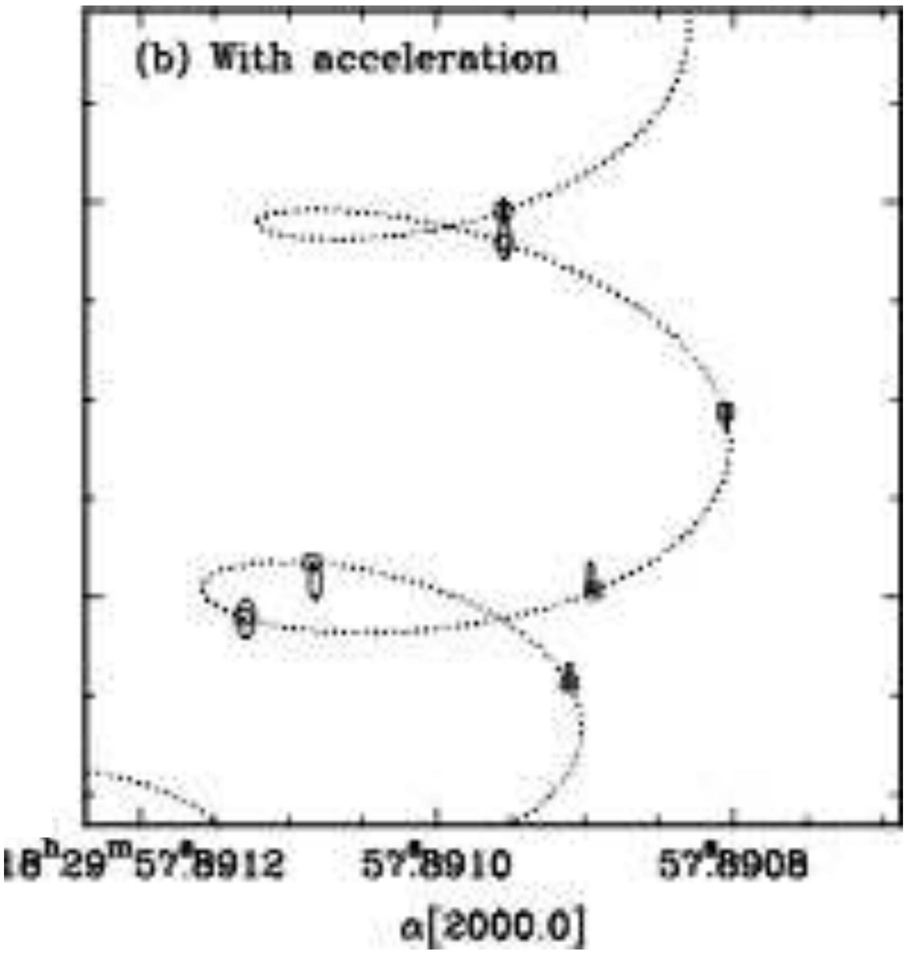
Astrometry highlights

- In-progress astrometry of a faint (~2 mJy) binary millisecond pulsar with the VLBA yields a distance of 1410 ± 40 pc, velocity 120 ± 5 km/s, mass to 10%





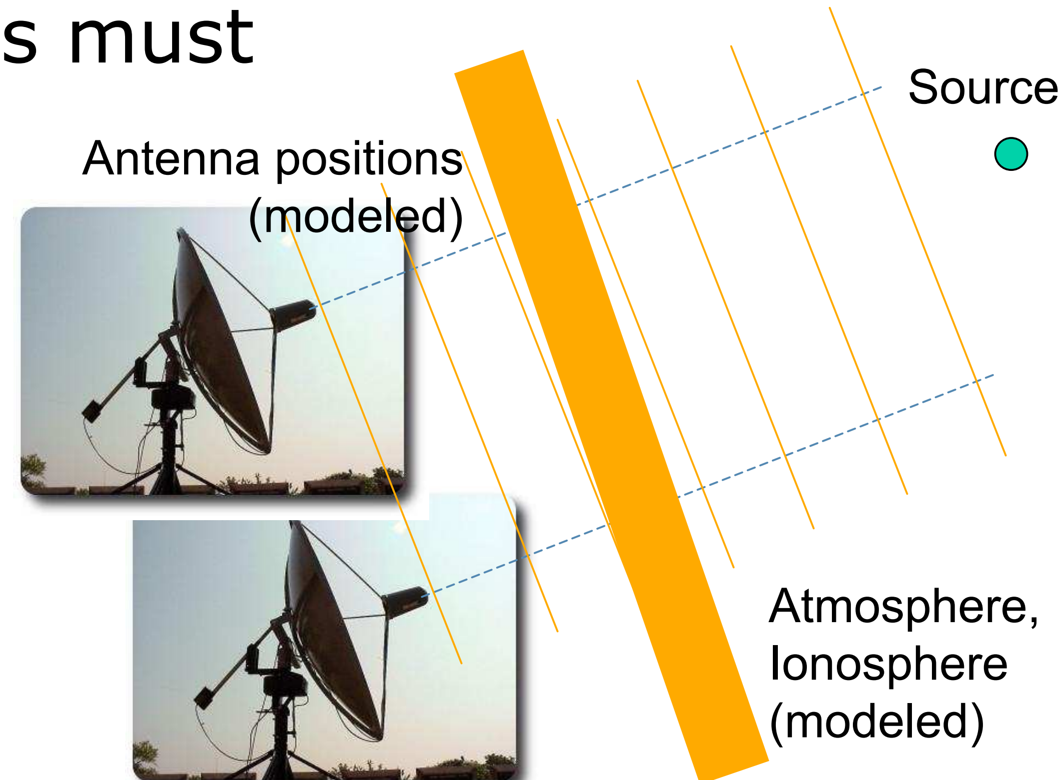
Astrometry highlights



Parallax of low-mass stars in the Serpens star-forming region; accuracy 20μas.
The distance to this region was revised upwards by a factor of almost 2.
Dzib et al. (2010)

Propagation effects & geodesy

- If you know the location of a source very precisely (e.g. an ICRF source) then any misalignment of the signal at two antennas must come from unmodeled propagation effects or antenna position errors



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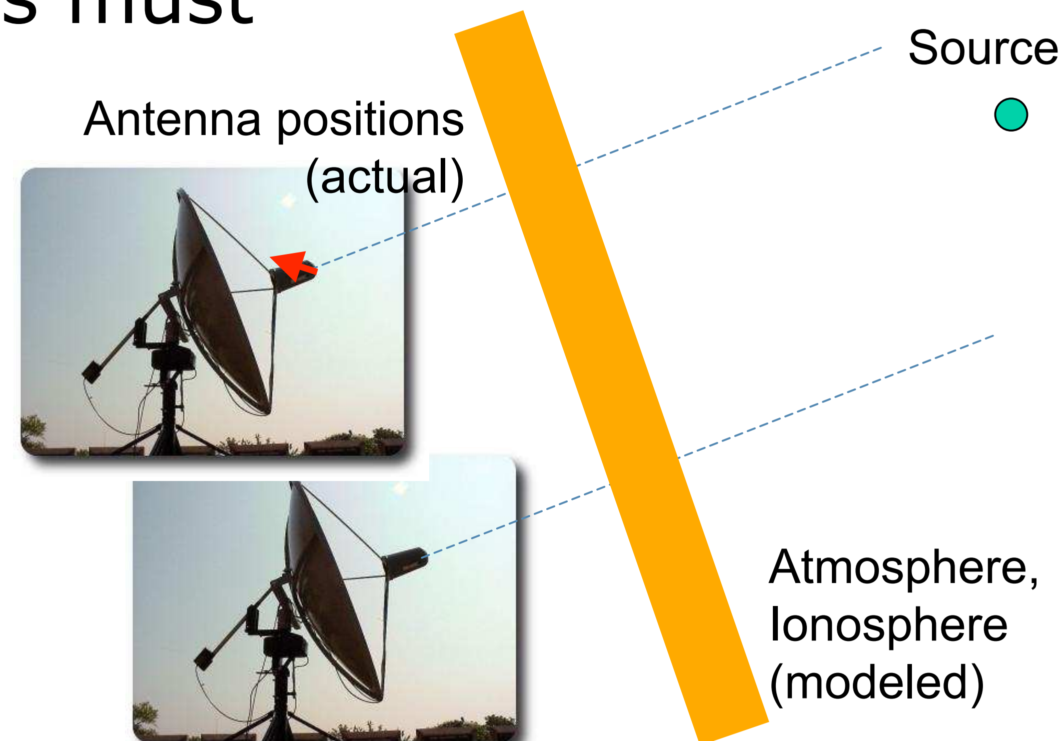

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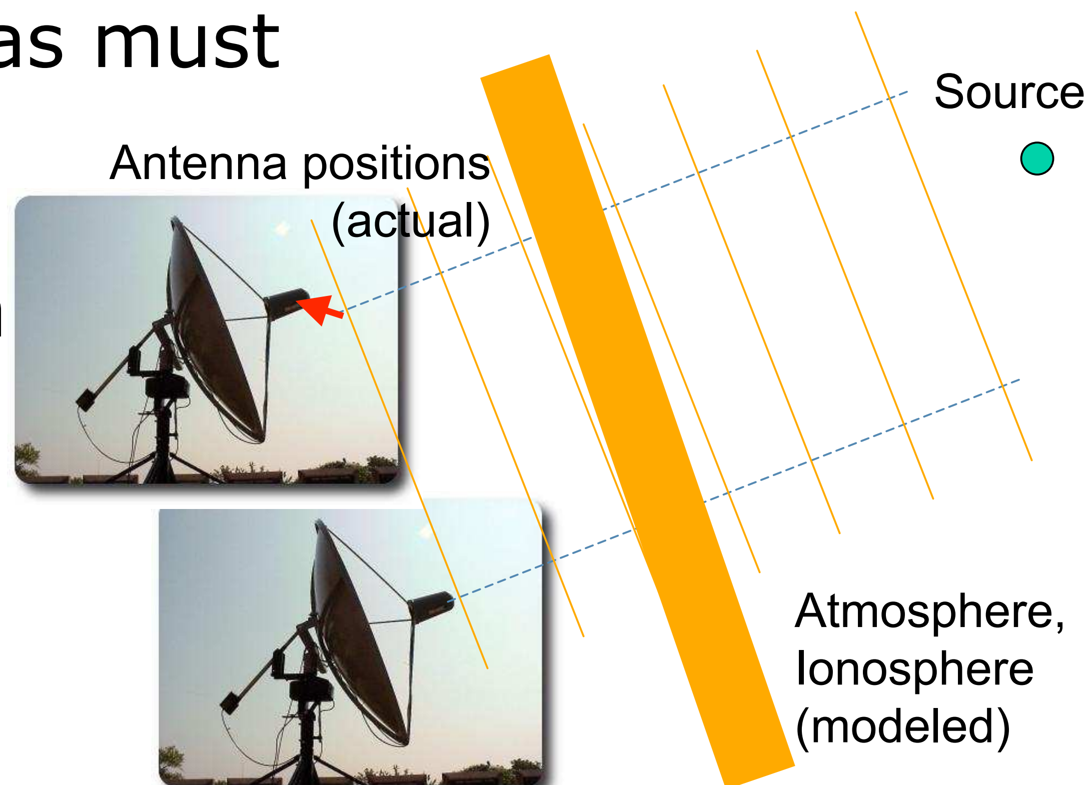

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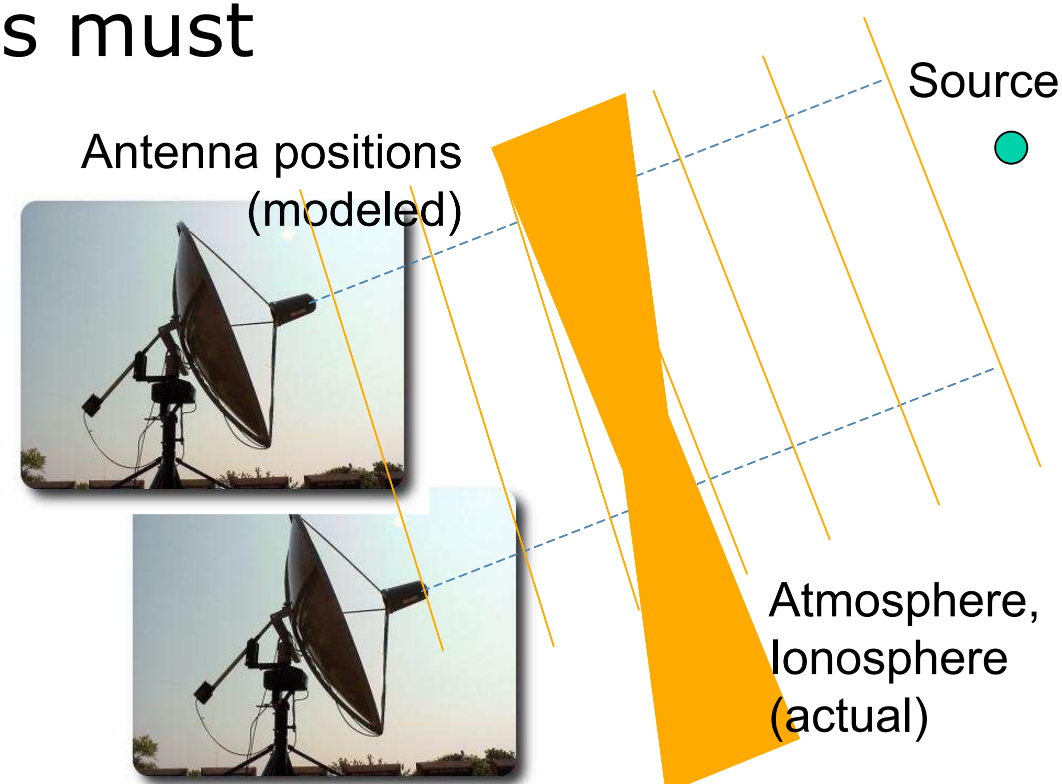


Geodetic results

- Global geodesy measures the Earth's rotation phase (UT1-UTC) to a precision of ~4 microseconds every day
- The VLBA station positions are known to a precision of several mm
- After the recent earthquake in Chile, the position of the Concepion antenna was measured to have moved by ~2m

(Mostly) bogus VLBI complaints

- There are some observational realities (set by the physics) which sometimes get blown out of proportion
- These misconceptions lead to some people excusing themselves from trying VLBI observing because it's "too hard" or "too unreliable"
- Here I'll list the common VLBI concerns, debunk some myths, and highlight the remaining "gotchas" compared to connected-element interferometers

Myth #1: Unstable systems

- Some grain of truth; VLBI antennas have completely independent electronics as mentioned, [illegible] ise in the time standard w[illegible] ut”
- But moder[illegible] ydrogen masers, digi[illegible] ers) are stable on tim[illegible] of many hours
- Future all-digital backends (more later) will improve further on this

Bogus rating: 7/10

Myth #2: Unstable conditions

- Again, partially true - the atmosphere above each antenna is generally completely uncorrelated
- But this is not a [illegible]ted to VLBI - the same [illegible]n observing with mod[illegible]es (EVLA, ALMA)
- Dea[illegible]ith it in the same way - switch between a nearby calibrator and source at a sufficiently rapid interval

Bogus rating: 3/10

Myth #3: Unreliable imaging

- This might have been true in the early days of VLBI, when instrumental phase and amplitude stability was p[illegible]r
- Nowadays, set up v[illegible]tions right (sufficien[illegible]) and getting dynami[illegible],000 is easy
- Sti[illegible]aining problems:
  - O[illegible]ten fewer antennas (10 VLBA / 27 EVLA)
  - Layout is often not optimal (antenna placement determined by geography, infrastructure)

Bogus rating: 5/10

Myth #4: Dodgy flux scale

- There are no constant-flux VLBI sources
  - Anything compact enough is always variable - quasars eject bl[illegible] material, pulsars scintillate..
  - Thus cann[illegible]tude calibrator”
- Ho[illegible] largely negated by ext[illegible]ort put in to the *a priori* flux calibration (switched noise calibration)
- Absolute scale of VLBI flux is probably only valid to ~10% - usually no big deal

Bogus rating: 8/10

Myth #5: Voodoo data reduction

- "Because of all these nasty effects, you have to wade through tonnes of extra stuff in AIPS to get anythin[illegible]"
- Absolute rubbish!
- The pat[illegible], just like for high-fre[illegible] data
- If y[illegible] set up your observations right, VLBA data pipelines wonderfully well

Bogus rating: 10/10

Myth #6: No sensitivity

- Another blast from the (distant) past, when VLBI used 2 Mbps reel-to-reel tapes to record bandwidth... MHz
- The need to recor... generally limited VLBI... bandwidths
- Th... SA is completing an upg... (more later) to 4 Gbps (1 GHz) - will better the EVLA continuum point source sensitivity at 1.4 GHz
- Surface brightness sensitivity not great!

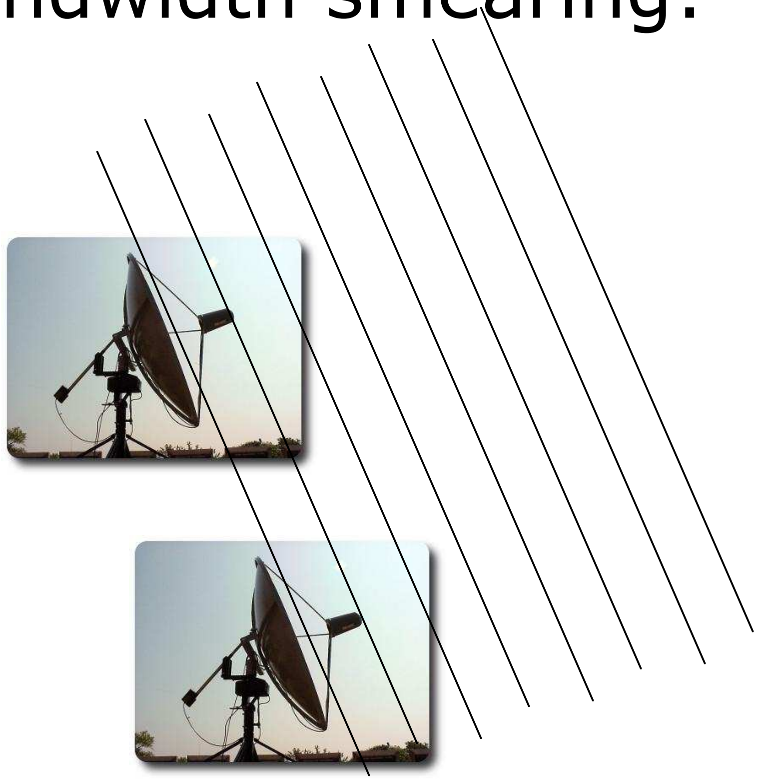
Bogus rating: 7/10

Myth #7: No field of view

- Until very recently, this was a fair accusation - correlator limitations compressed the attainable FOV to ~arcseconds for most VLBI observations

Myth #7: No field of view

- Bandwidth smearing:



At the phase centre, all frequencies have zero phase, all the time

For 8,000km baselines @ 1.6 GHz, 0.5 MHz channels limit the FOV to <10″

Myth #7: No field of view

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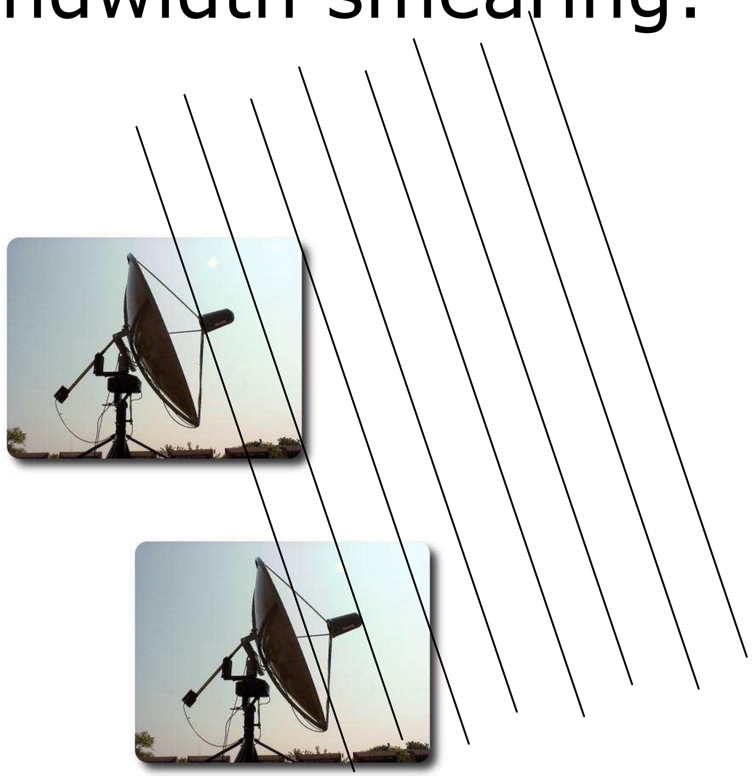

Off the phase centre, phase varies as a function of frequency, so if you average you get decorrelation

For 8,000km baselines @ 1.6 GHz, 0.5 MHz channels limit the FOV to <10″

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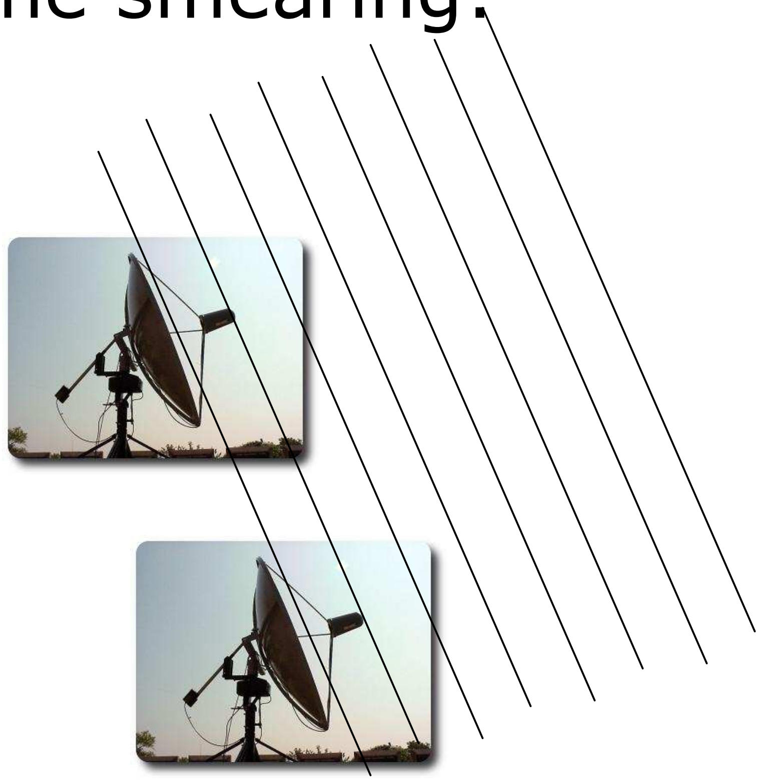
- Time smearing:



At the phase centre, all frequencies have zero phase, all the time

For 8,000km baselines @ 1.6 GHz, 2 sec averaging limits the FOV to <20″

Myth #7: No field of view

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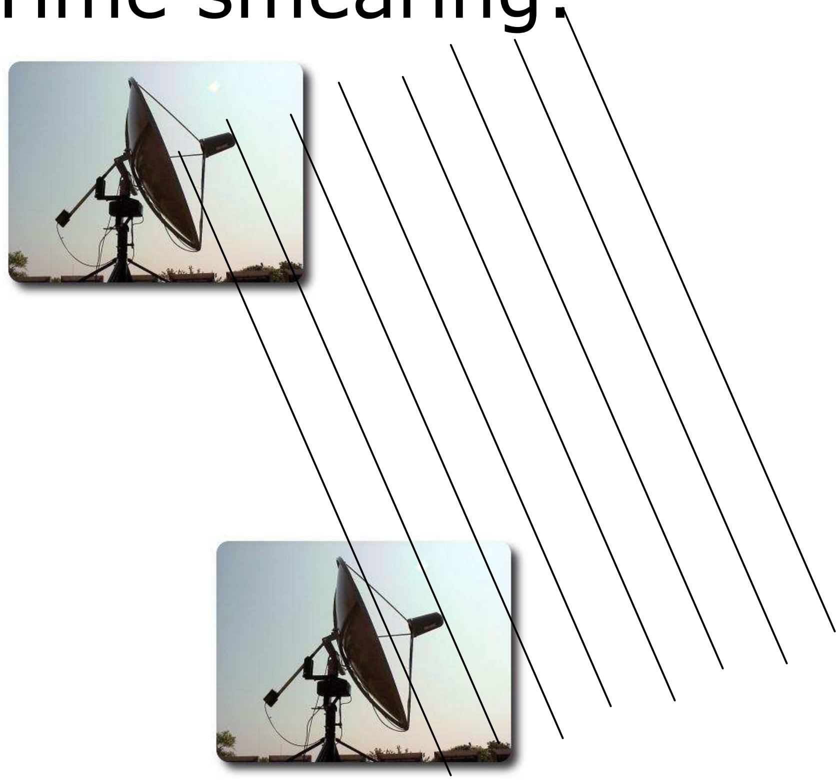

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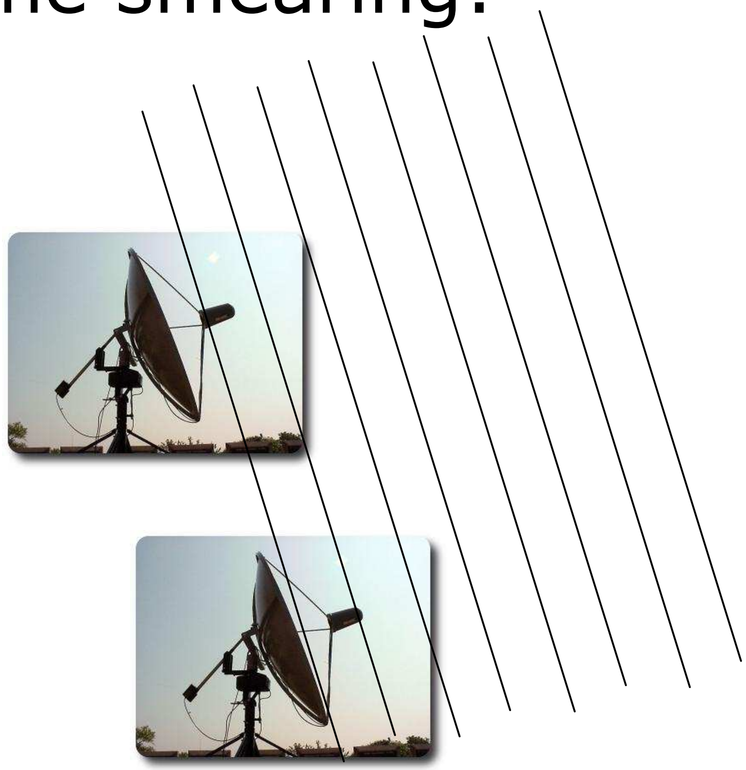

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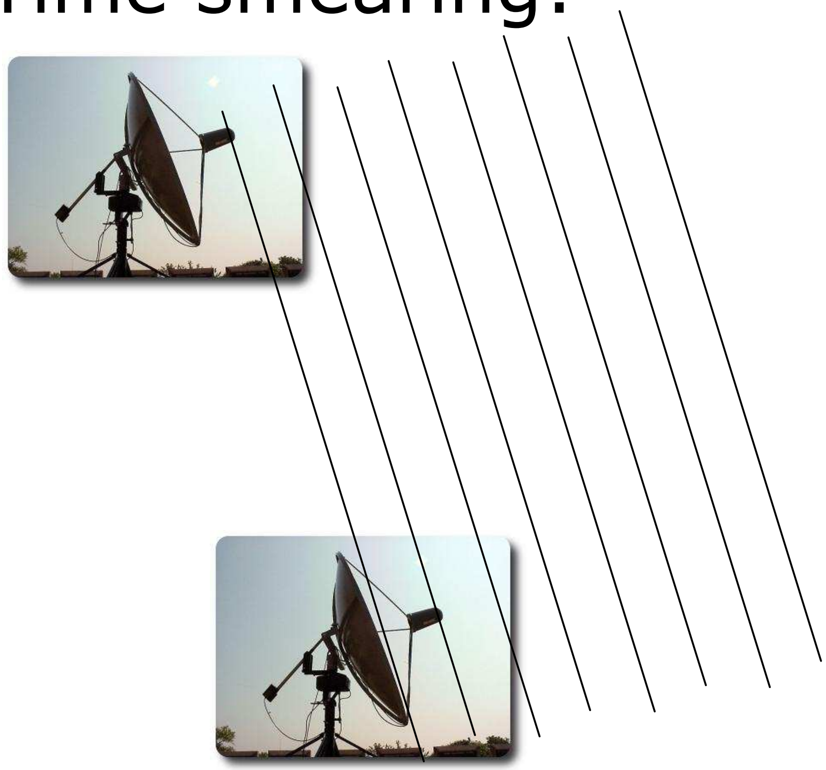


Off the phase centre, phase varies as a function of time, so if you average you get decorrelation

For 8,000km baselines @ 1.6 GHz, 2 sec averaging limits the FOV to <20″

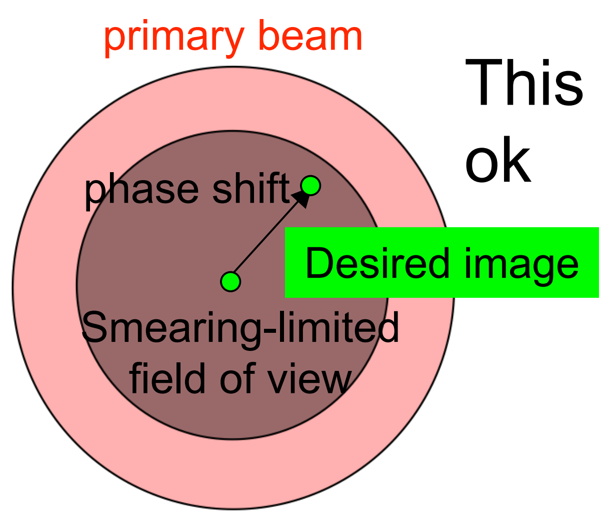
Myth #7: No field of view

- Even if high time and frequency resolution was possible (and has been for some time with newer correlators) the data volumes get immense - >10TB data to image the full primary beam…
- BUT: New work to mitigate the data volume problem just becoming available

Bogus rating: 3/10

New stuff: multiple field centers

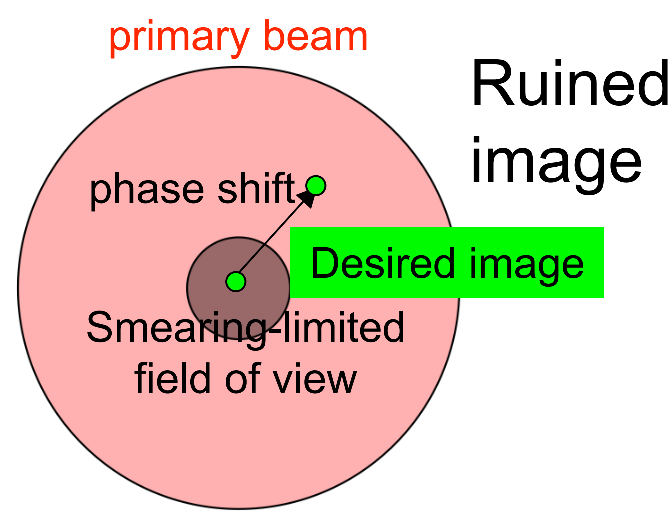
- "Pointing" a correlator involves appropriate delay and phase corrections
- "Re-pointing" correlated visibilities requires the appropriate differential phase change (fn of baseline/freq/time)



This is ok

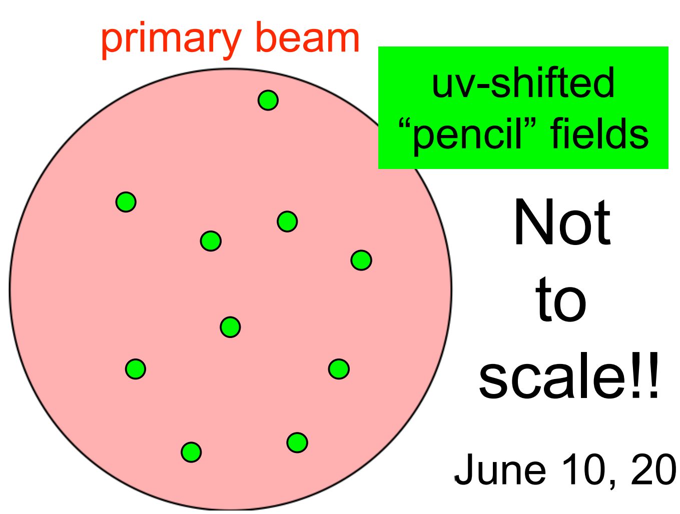
New stuff: multiple field centers

- "Pointing" a correlator involves appropriate delay and phase corrections
- "Re-pointing" correlated visibilities requires the appropriate differential phase change (fn of baseline/freq/time)
- But if the data already averaged too heavily in frequency and time, smearing is too severe



New stuff: multiple field centers

- Writing out sufficiently high resolution visibilities suffers from the same data volume problem as imaging, but…
- The DiFX software correlator used at the VLBA and LBA now allows the shift to be done inside the correlator; visibilities then averaged down to normal resolution
- Large number of phase centres possible; AGN surveying!



Not to scale!!

New stuff: multiple field centers

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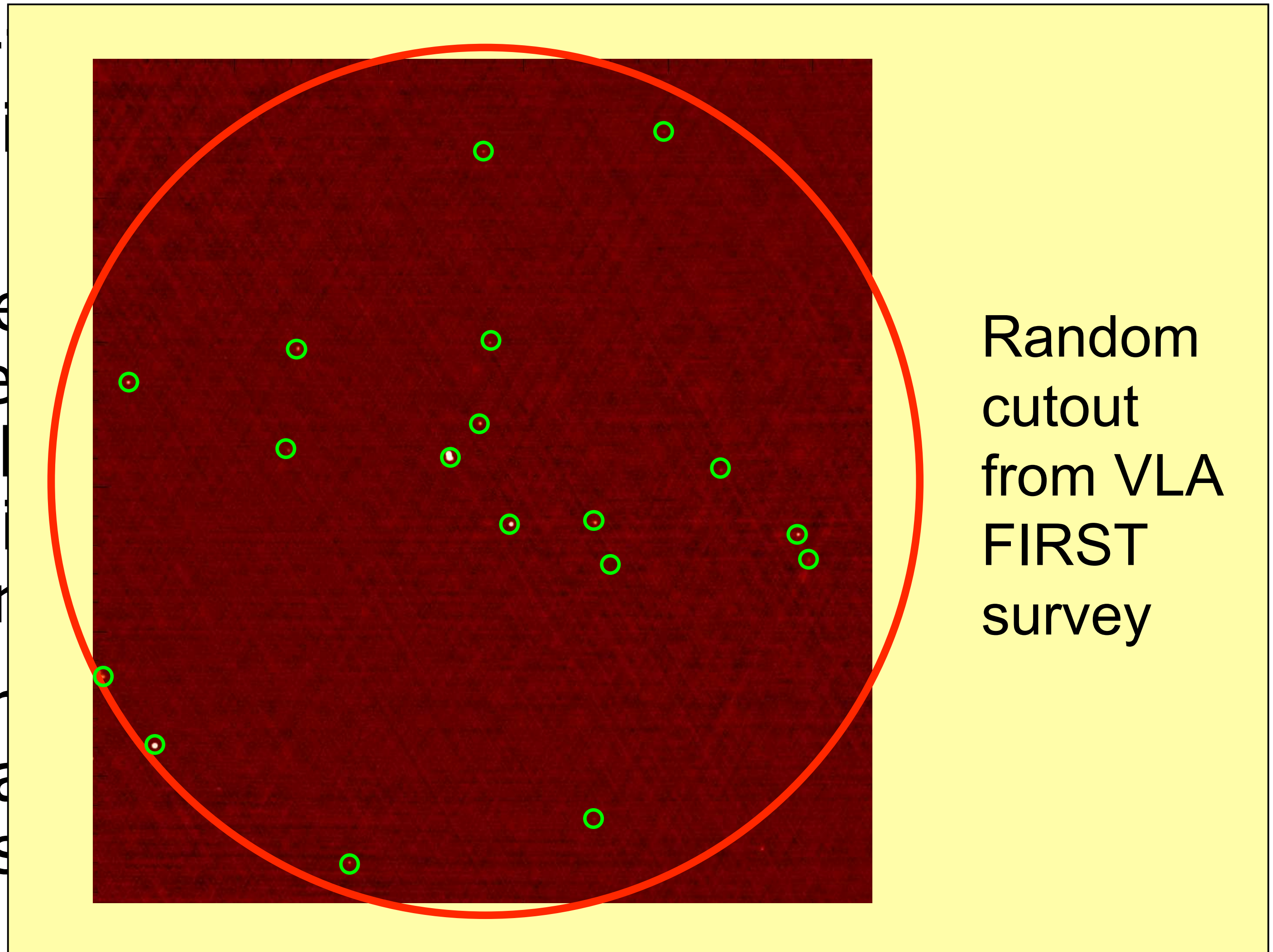

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- BUT: New [illegible]itigate the data volume[illegible] just becoming available
- Since [illegible] sensitivity, lower resolution radio [illegible]ata is easy to come by…

Bogus rating: 8/10

The practicalities of VLBI

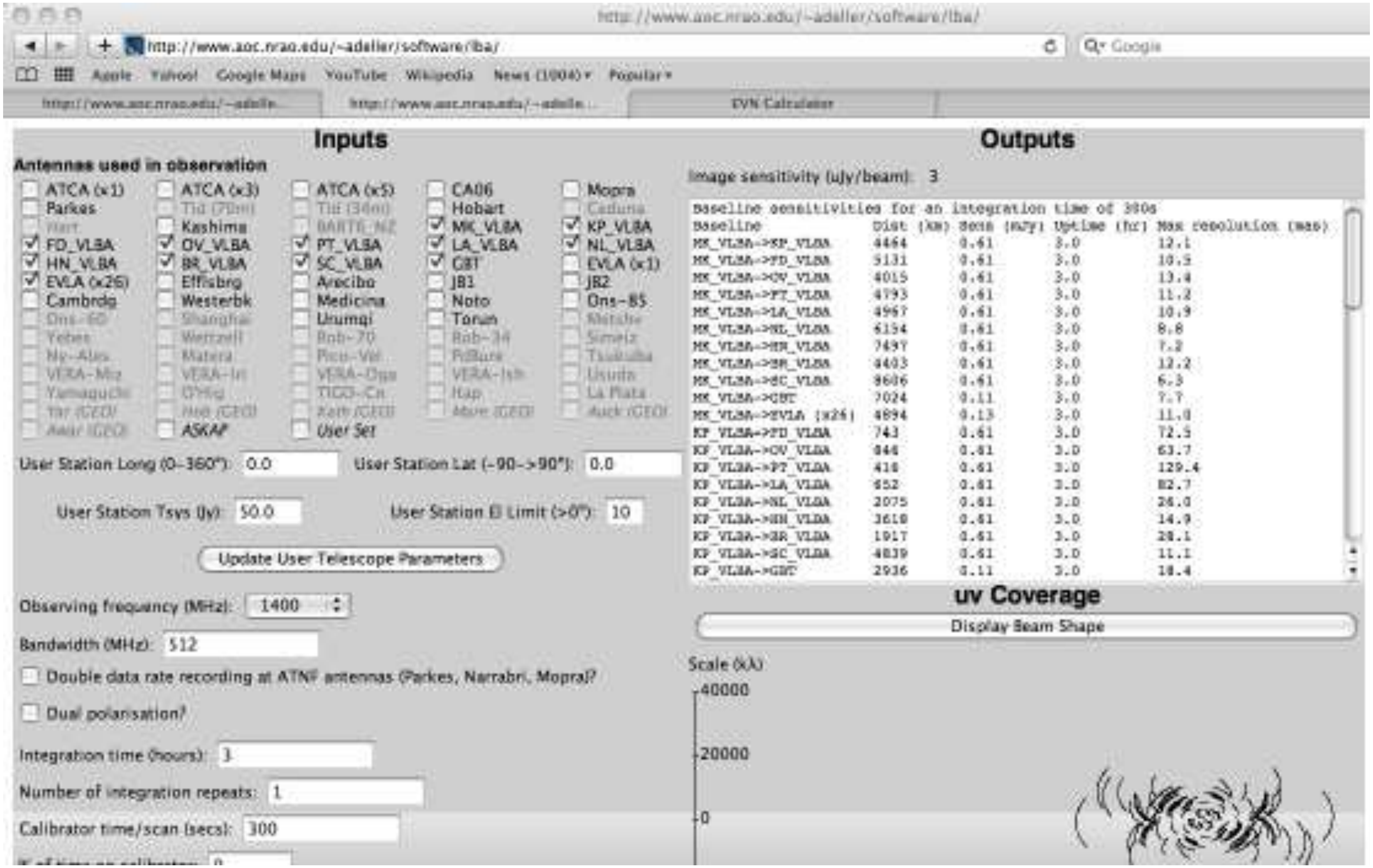
- So you have some target, which you would like to image at mas resolution. What do you actually do?

1. Plan
2. Propose
3. Schedule
4. Observe
5. Calibrate and image
6. Publish, get promoted, bask in glory…

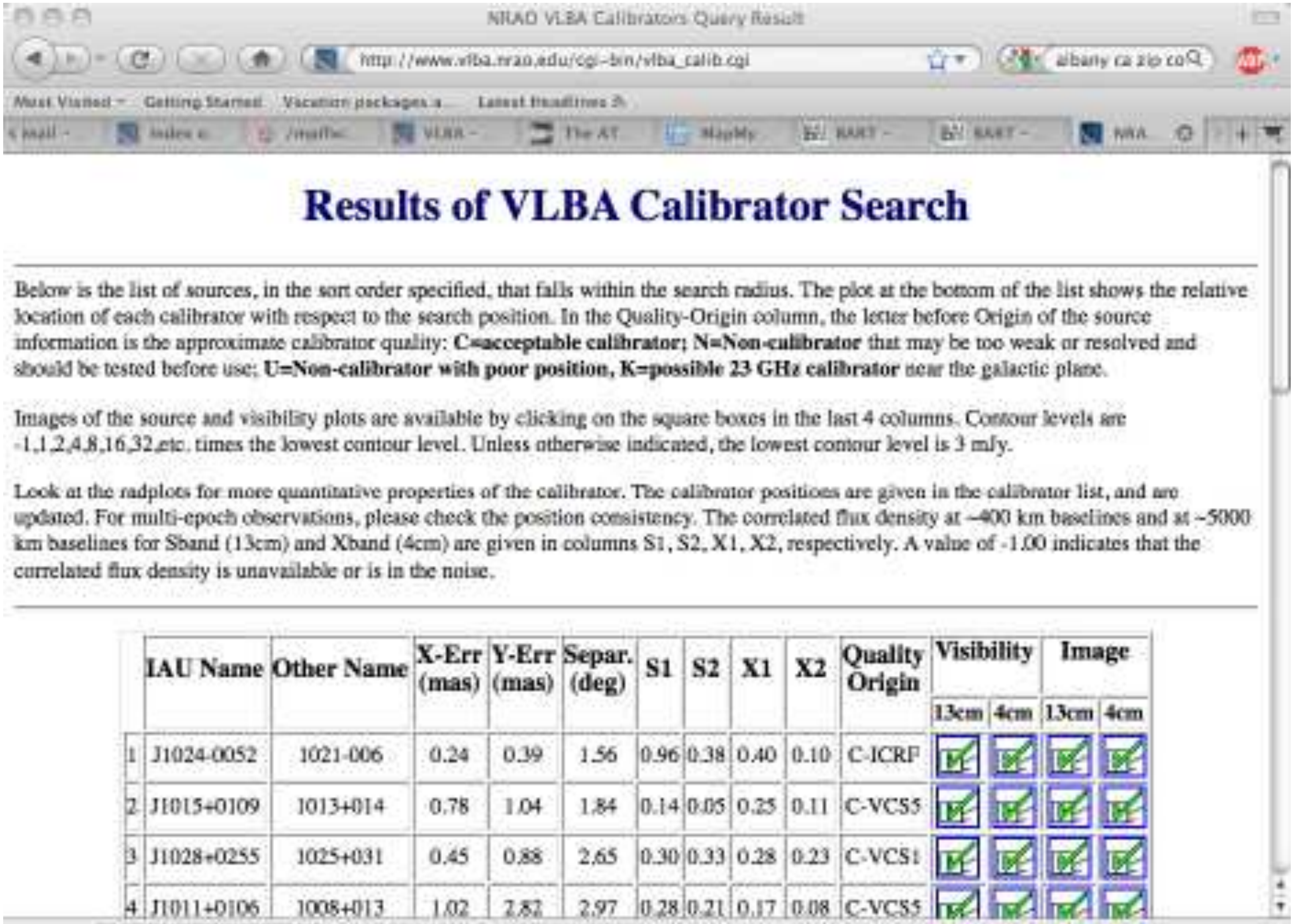
Plan

- You need to consider your target (size, flux density, location), the array parameters (resolution, frequency, sensitivity) and calibration strategy
  - Object declination and size determine what array(s) are feasible, at what frequency
  - http://www.aoc.nrao.edu/~adeller/software/lba/ has a tool for calculating uptime, sensitivity and resolution
  - Calibrator search tools available at http://www.vlba.nrao.edu/astro/calib/ (North) or http://astrogeo.org/calib/search.html (all sky)

Plan


http://www.aoc.nrao.edu/~adeller/software/lba/
EVN Calculator
Inputs
Antennas used in observation
ATCA (x1)
Parkes
FD_VLBA
HN_VLBA
EVLA (x26)
Cambrdg
ATCA (x3)
Kashima
OV_VLBA
BR_VLBA
Efflsbrg
Westerbk
ASKAP
ATCA (x5)
PT_VLBA
SC_VLBA
Arecibo
Medicina
Urumqi
User Set
CA06
Hobart
MK_VLBA
LA_VLBA
GBT
JB1
Noto
Torun
Mopra
KP_VLBA
NL_VLBA
EVLA (x1)
JB2
Ons-85
User Station Long (0–360°): 0.0
User Station Lat (-90->90°): 0.0
User Station Tsys (Jy): 50.0
User Station El Limit (>0°): 10
Update User Telescope Parameters
Observing frequency (MHz): 1400
Bandwidth (MHz): 512
Double data rate recording at ATNF antennas (Parkes, Narrabri, Mopra)?
Dual polarisation?
Integration time (hours): 3
Number of integration repeats: 1
Calibrator time/scan (secs): 300
Outputs
Image sensitivity (uJy/beam): 3
uv Coverage
Display Beam Shape
Scale (kλ)
40000
20000
0

Plan



NRAO VLBA Calibrators Query Result

http://www.vlba.nrao.edu/cgi-bin/vlba_calib.cgi

Results of VLBA Calibrator Search

Below is the list of sources, in the sort order specified, that falls within the search radius. The plot at the bottom of the list shows the relative location of each calibrator with respect to the search position. In the Quality-Origin column, the letter before Origin of the source information is the approximate calibrator quality: **C=acceptable calibrator; N=Non-calibrator** that may be too weak or resolved and should be tested before use; **U=Non-calibrator with poor position, K=possible 23 GHz calibrator** near the galactic plane.

Images of the source and visibility plots 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.

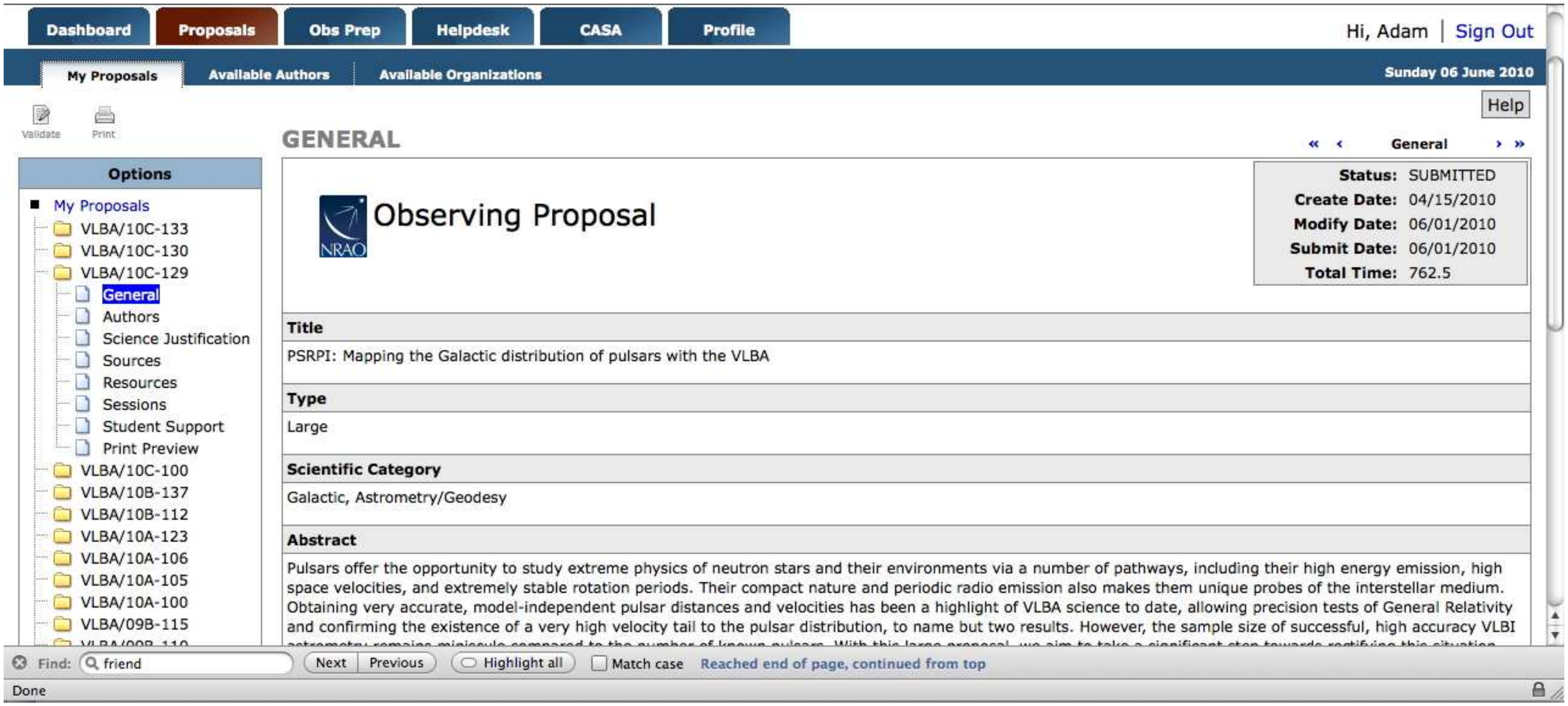
Look at the radplots for more quantitative properties of the calibrator. The calibrator positions are given in the calibrator list, and are updated. For multi-epoch observations, please check the position consistency. The correlated flux density at ~400 km baselines and at ~5000 km baselines for Sband (13cm) and Xband (4cm) are given in columns S1, S2, X1, X2, respectively. A value of -1.00 indicates that the correlated flux density is unavailable or is in the noise.

	IAU Name	Other Name	X-Err (mas)	Y-Err (mas)	Separ. (deg)	S1	S2	X1	X2	Quality Origin	Visibility		Image	
											13cm	4cm	13cm	4cm
1	J1024-0052	1021-006	0.24	0.39	1.56	0.96	0.38	0.40	0.10	C-ICRF				
2	J1015+0109	1013+014	0.78	1.04	1.84	0.14	0.05	0.25	0.11	C-VCS5				
3	J1028+0255	1025+031	0.45	0.88	2.65	0.30	0.33	0.28	0.23	C-VCS1				
4	J1011+0106	1008+013	1.02	2.82	2.97	0.28	0.21	0.17	0.08	C-VCS5				

VLBI proposals

- Different arrays have different deadlines
- NRAO currently 3x yearly (Feb 1, June 1, October 1)
- EVN is synchronized with these dates
- LBA 2x year, June 15 and December 15
- Generally similar to other radio proposals - nowadays generally using the same proposal submission tool

VLBI proposals



Scheduling

- The program SCHED (C. Walker, NRAO) is used to schedule VLBI experiments
- You provide a list of stations and sources, the observing frequency and bandwidth, and a list of scans
- General recipe:
  - Observe target as often as you can
  - Scans on phase reference as necessary (cycle ~6 min @ 1.6 GHz, ~30s @ 43 GHz)
  - Include very bright calibrator ~few hours, other special calibration as necessary

Observing

- Depends on array:
  - EVN and VLBA: provide schedule file, wait to receive the correlated data by ftp
  - LBA: provide schedule file, and go to one of the stations to assist with observations (a great way to learn interferometry!)

Data reduction (calibration)

- AIPS is the predominant package for VLBI calibration; presently a few important steps can **only** be carried out in AIPS
- Calibration includes flagging, **amp. calibration** (from switched power), EOP correction, ionosphere correction, **delay**, bandpass, and phase solutions
- I find the ParselTongue* package (a python interface to AIPS) to be very convenient for scripting

***http://www.jive.nl/dokuwiki/doku.php?id=parseltongue:parseltongue**

Data reduction (imaging)

- A calibrated VLBI visibility dataset looks just like any other interferometer - so you can pick your imaging software:
  - AIPS
  - CASA
  - difmap
- Wide-field imaging is computationally intensive (time/bandwidth smearing)
- Limited uv coverage means you need to be careful with deconvolution

New/ongoing VLBI innovation

- Increased bandwidth for sensitivity (target and calibrator)
  - EVN/LBA already upgraded to 1 Gbps
  - VLBA[HSA] 4 Gbps , 25[2] μJy 1σ rms (1 hr)
- New processing techniques
  - Software correlators; high time/freq resolution, multiple fields
  - Improved astrometric analysis
- Real-time correlation ("eVLBI")
  - Mostly EVN (some LBA), offers potentially higher data rates (plus data sooner!)

The future of VLBI

- The next few years are an exciting time for km-scale interferometers:
  - mm: ALMA
  - cm: EVLA, ASKAP, MEERKAT
  - m: LOFAR, MWA
- VLBI, on the other hand, has no new instruments in the pipeline (until SKA)
- Advances will come from still more bandwidth (Astro2010: 32 Gbps for VLBA) and innovations like in-beam calibrators and multiple fields

Conclusions

- VLBI offers a **unique** capability; the highest angular resolution imaging in astronomy
- Gives the ability to probe smallest size scales and do **very** precise astrometry
- However, it has limitations (determined by physics) that can't be avoided; you can't see everything that's visible at lower resolution
- VLBI is not a "black art" - it is no harder than high frequency EVLA observing

Questions?

New/ongoing VLBI innovation

- Three major trends over last few years:
  - Wider bandwidths via disk-based recording
  - Flexible processing via software correlators
  - Real-time correlation (eVLBI)
- The EVN and LBA have had 1 Gbps capability for several years
- The VLBA is currently completing an upgrade from 512 Mbps to 4 Gbps
- This corresponds to a factor of almost 3 in continuum sensitivity

Continuum sensitivity

- At 4 Gbps, the VLBA alone reaches a 1σ rms of 25 μJy in 1 hour on-source
- With the HSA, down to 2 μJy!
- Very faint sources are within reach in a realistic timescale
- The limiting sensitivity for calibrators is also excellent, meaning you can find a calilbrator close to your target - important for fast switching and for astrometric accuracy

"Software" correlators

- As data rates stagnated from the late 1990s, commodity-based computing power continued to grow
- You no longer need custom hardware to correlate a VLBI-sized array - a (small) rack of Linux servers has enough power
- So we code the correlation algorithm in C++ (rather than stamping out boards) which gives us the flexibility to explore lots of new correlator functionality

“Software” correlators

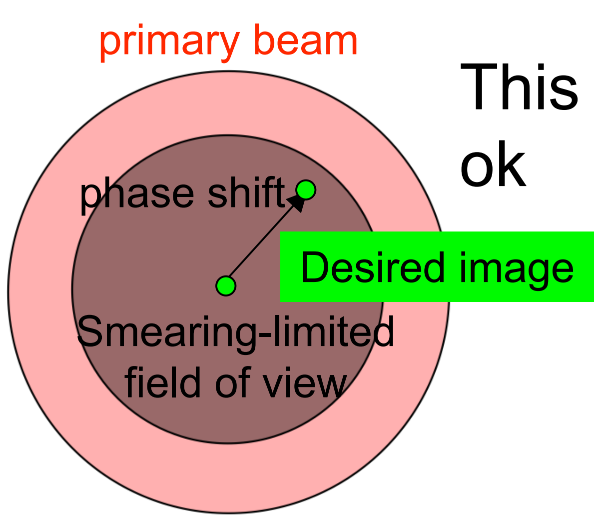
The now-defunct VLBA hardware correlator

“Software” correlators

The servers hosting the new VLBA software correlator

New stuff: multiple field centers

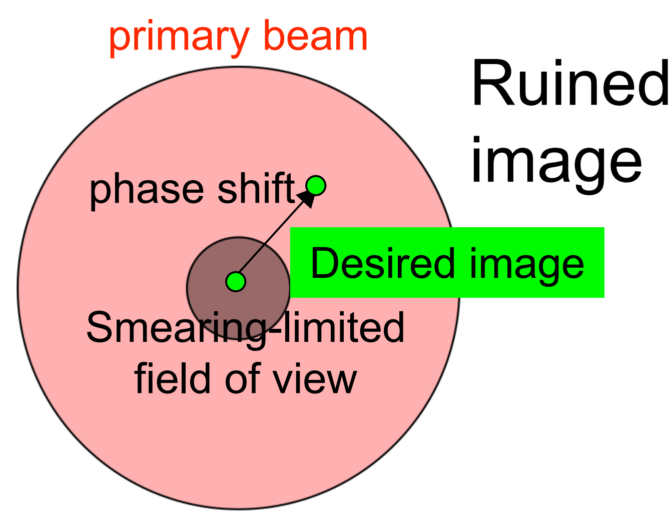
- "Pointing" a correlator involves appropriate delay and phase corrections
- "Re-pointing" correlated visibilities requires the appropriate differential phase change (fn of baseline/freq/time)



This is ok

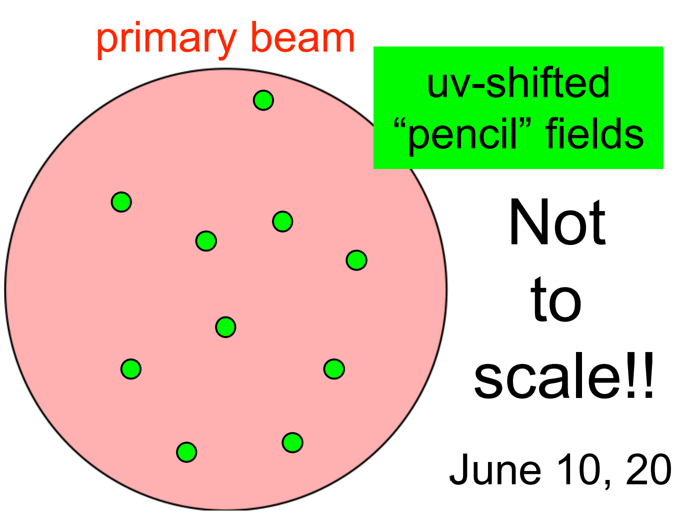
New stuff: multiple field centers

- "Pointing" a correlator involves appropriate delay and phase corrections
- "Re-pointing" correlated visibilities requires the appropriate differential phase change (fn of baseline/freq/time)
- But if the data already averaged too heavily in frequency and time, smearing is too severe



New stuff: multiple field centers

- Writing out sufficiently high resolution visibilities suffers from the same data volume problem as imaging, but…
- The DiFX software correlator used at the VLBA and LBA now allows the shift to be done inside the correlator; visibilities then averaged down to normal resolution
- Large number of phase centres possible; AGN surveying!



Not to scale!!

New stuff: multiple field centers

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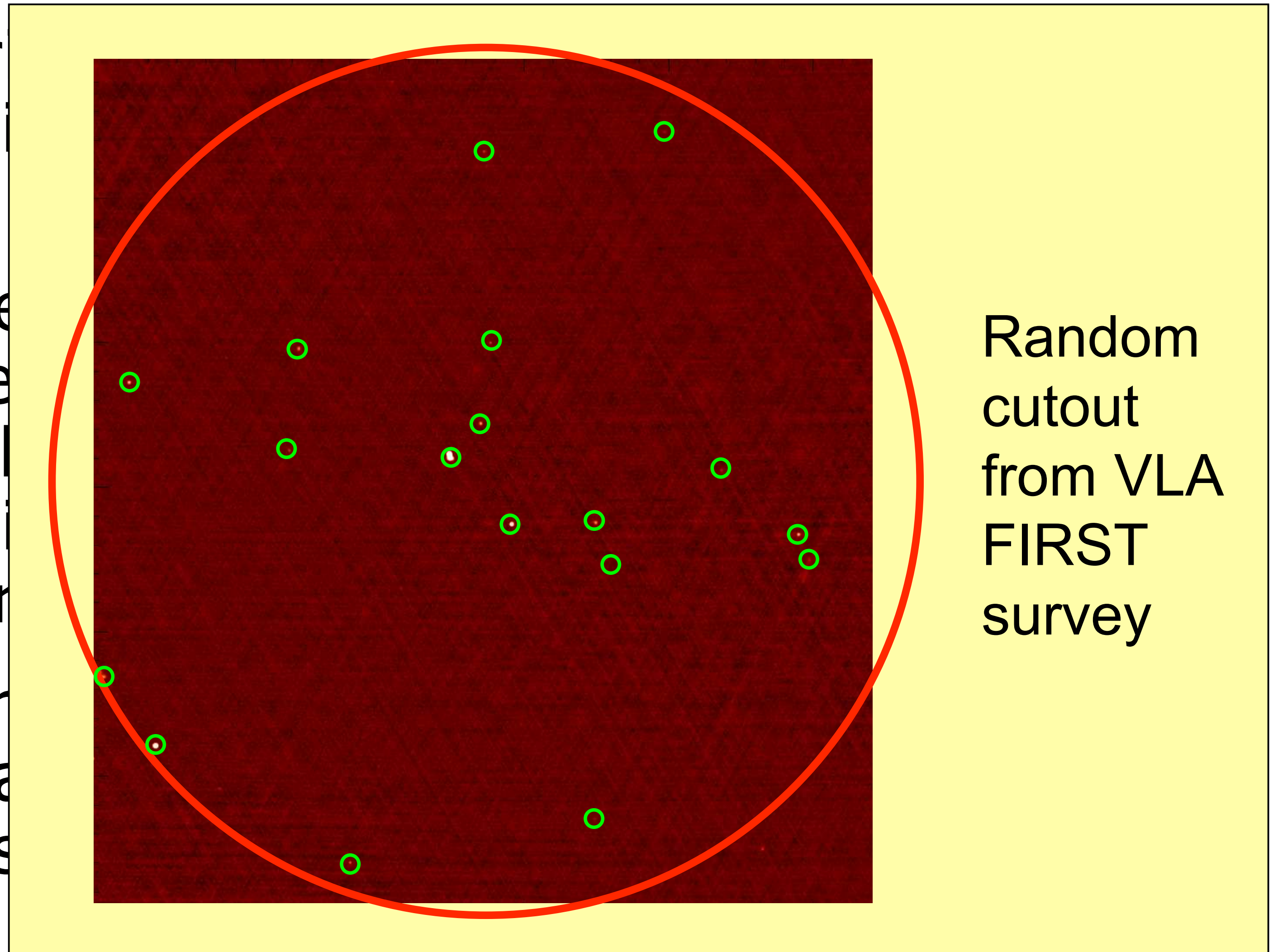

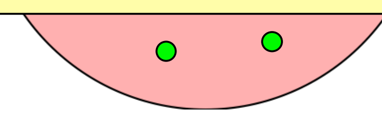

eVLBI

- Riding the telecommunications wave to real-time processing of VLBI data has been hot news for the last ~5 years
- Further reduce "VLBI" distinction
- Two main reasons:
  - Reduced wait time for results
  - Potential for even higher data rates (no longer limited by disk speed/capacity)
- Spearheaded by the EVN (advantage of better network connectivity in Europe)