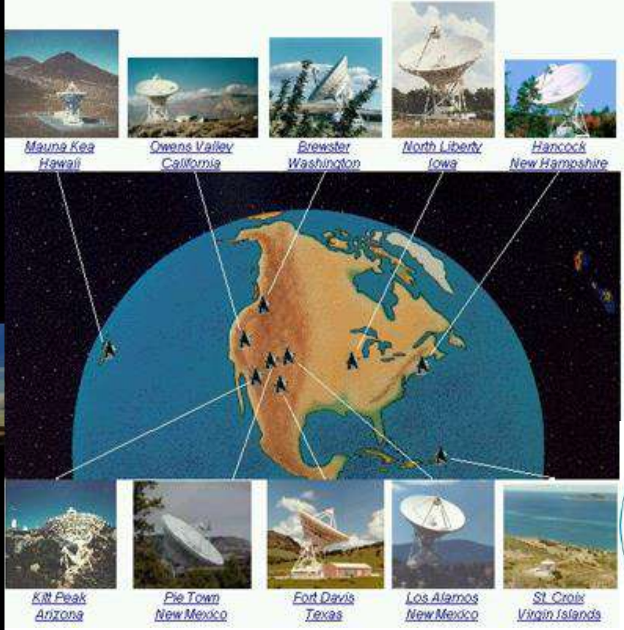
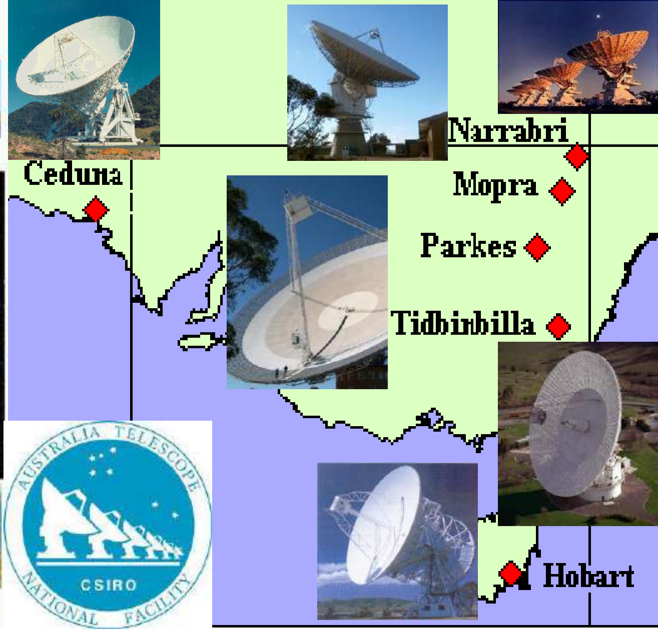
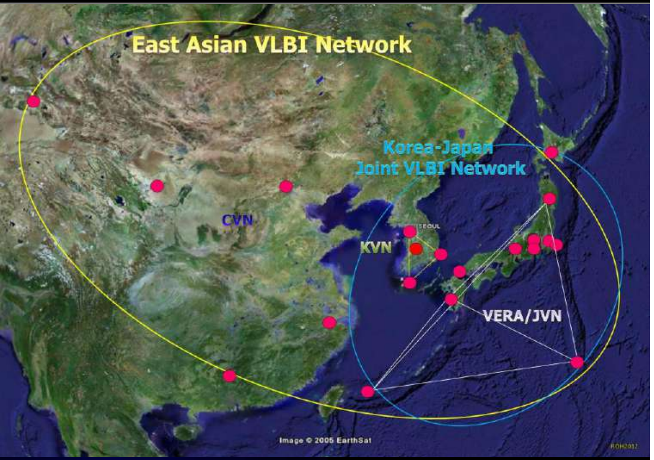






Very Long Baseline Interferometry

Adam Deller

14th NRAO Synthesis Imaging Workshop

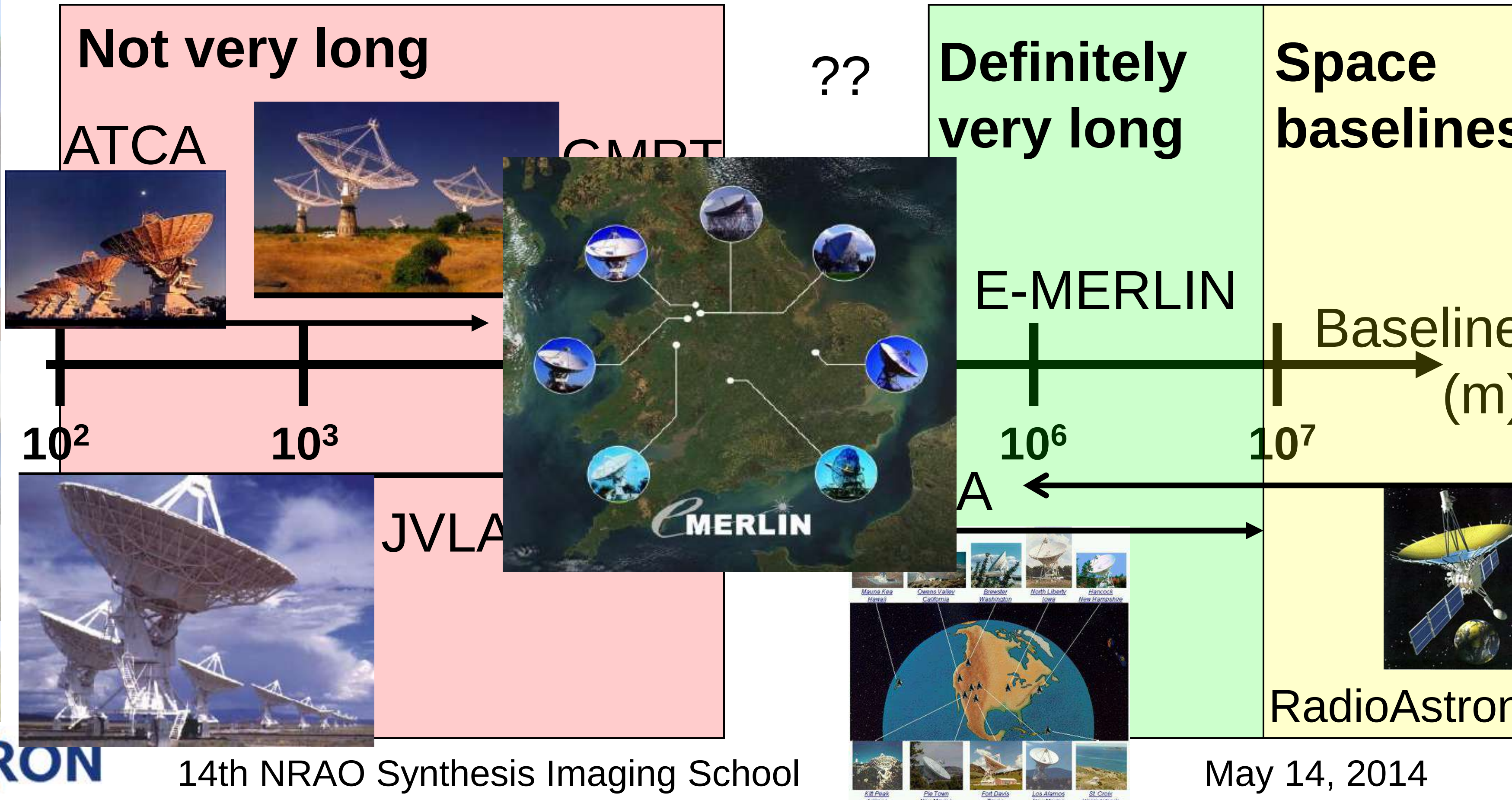
May 14, 2014

Outline

- What is VLBI and what does it give you?
- Science applications of VLBI
- A closer look at the differences with regular interferometry and how they have gotten smaller
- How to“do” VLBI: scheduling and data reduction
- New capabilities & the future of VLBI

VLBI in context

- How long is “Very Long”?



VLBI in context

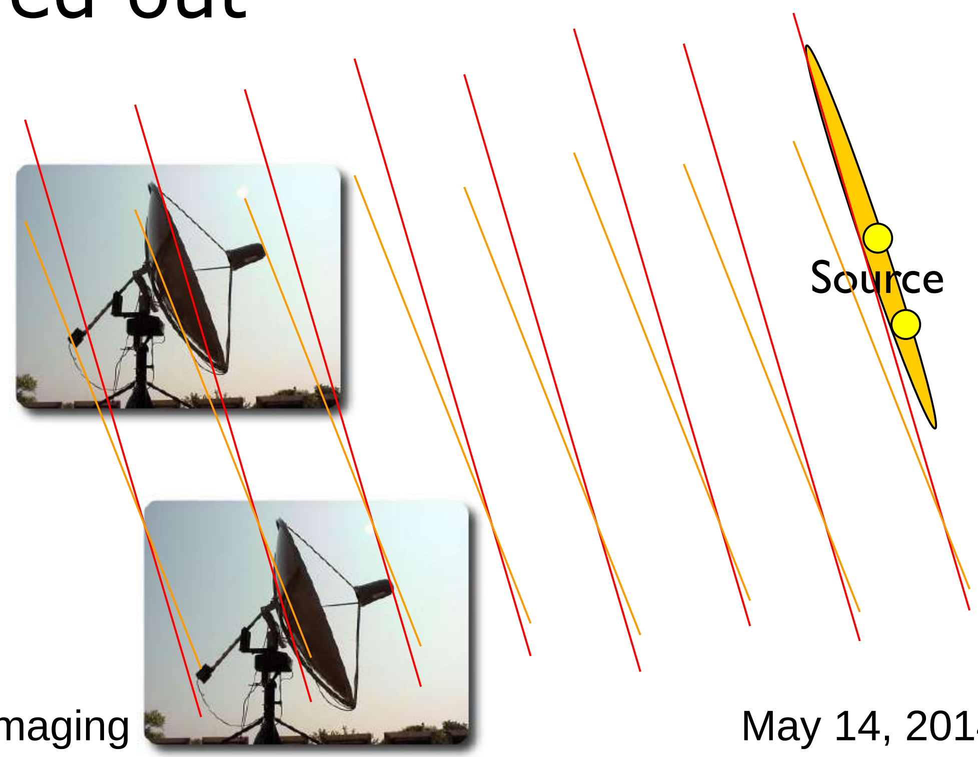
- Clearly not just about baseline length…
- What constitutes VLBI is actually a little hard to pin down (its more like a “syndrome” than a “disease”!)
  - Reason: **no** fundamental differece between VLBI and regular interferometry - only technology, convenience and convention
  - One accurate (but not useful) distinction: independent antenna electronics; i.e., anything that’s not “connected element”

What VLBI gives you

- Fundamentals of interferometry say: resolution will be <u>very</u> 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)



Science applications of VLBI

- VLBI provides a tool to study mas-level structure in radio sources - what sources are this compact?
  - Active Galactic Nuclei (AGN)
  - Pulsars
  - Masers
  - Supernova remnants
  - Magnetically active stars

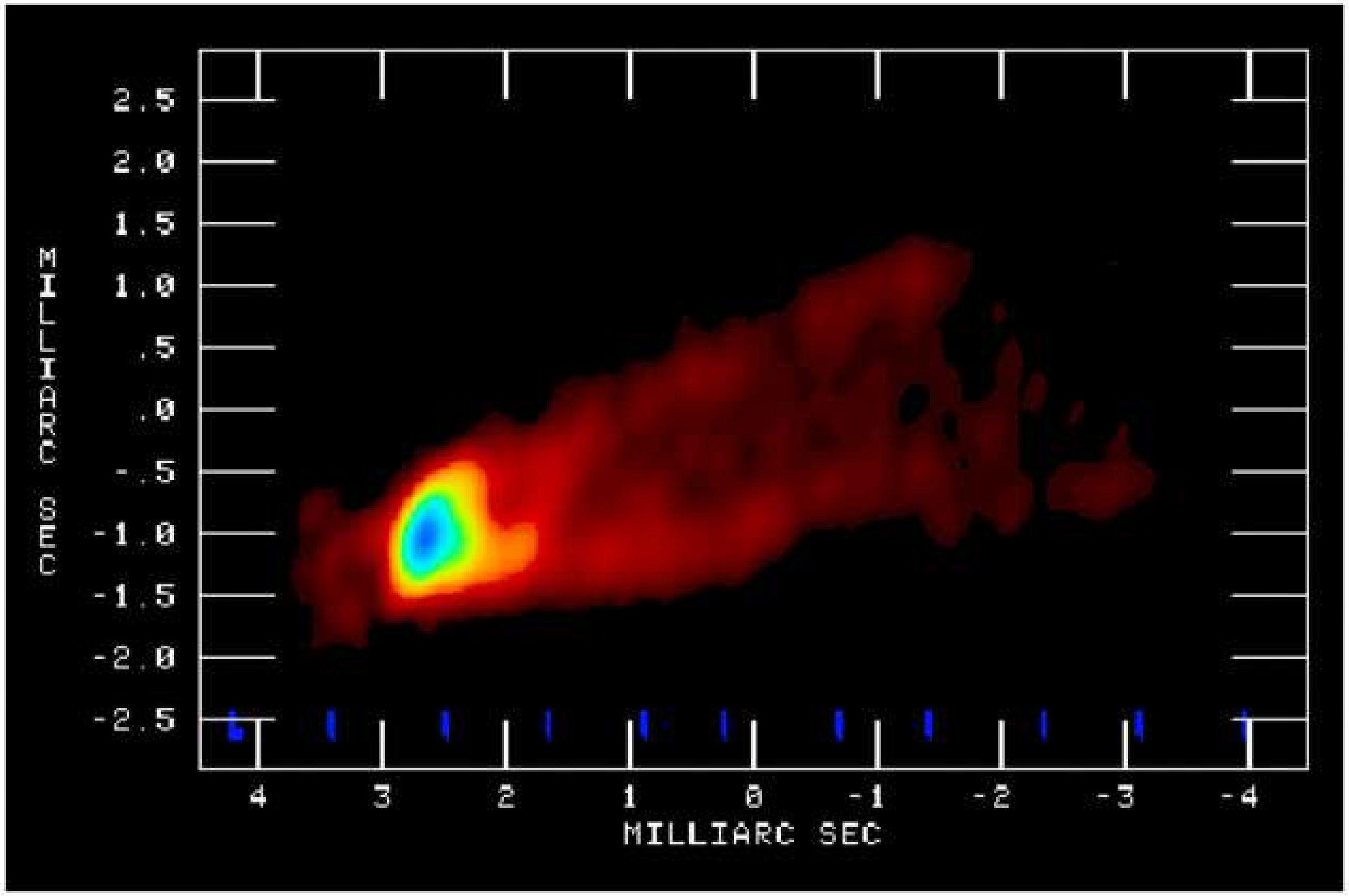
Science applications of VLBI

- 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?

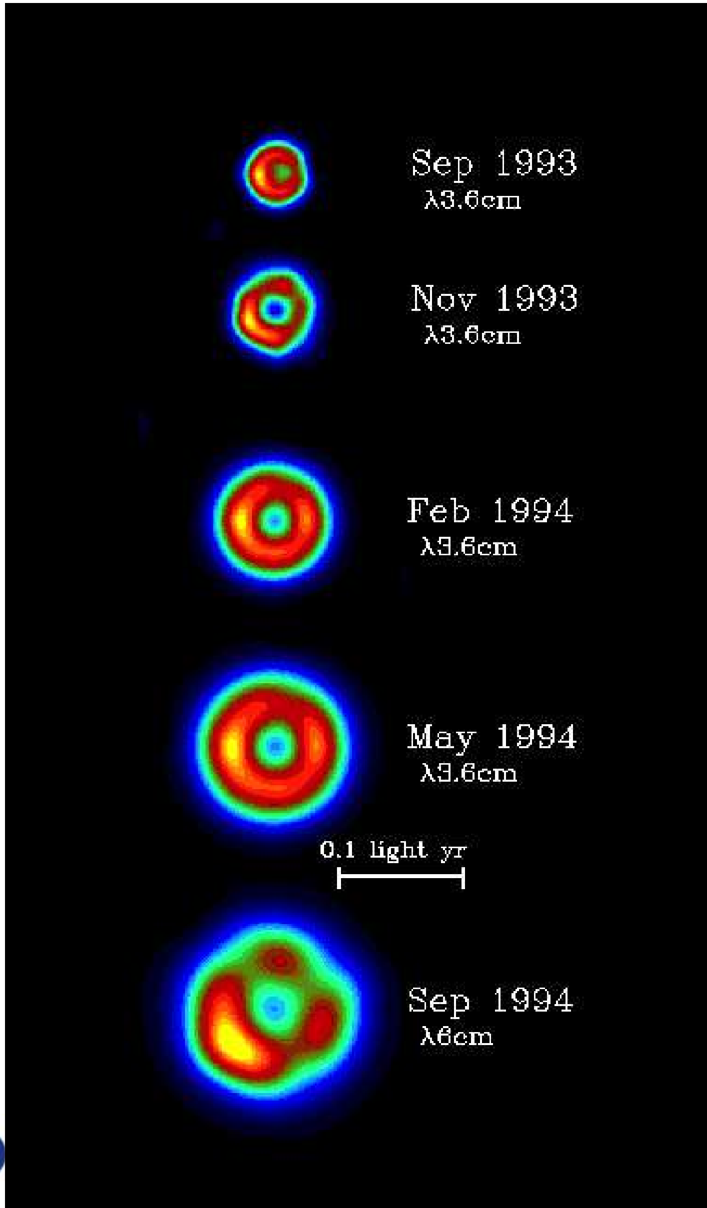
- A VLBI detection instantly identifies a compact non-thermal source
- In the local Universe, that might be a supernova [remnant], pulsar, shock…
- If the source is more distant, it **must** be a (radio loud) AGN
- VLBI can make a positive ID / discriminate between source classes

High resolution imaging



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

High resolution imaging

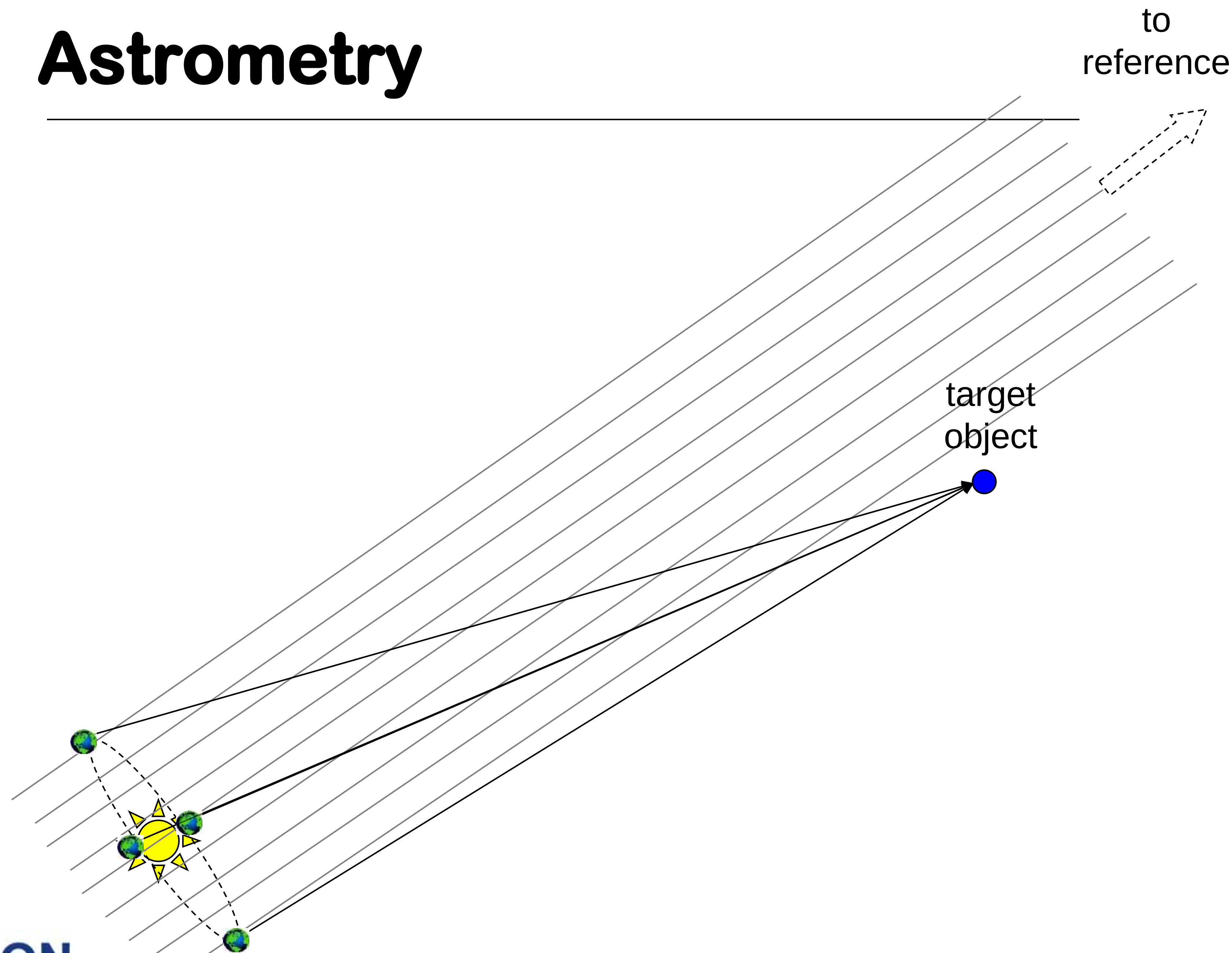


The expansion of SN1993J: Global VLBI observations, J. Marcaide et al.

Astrometry

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

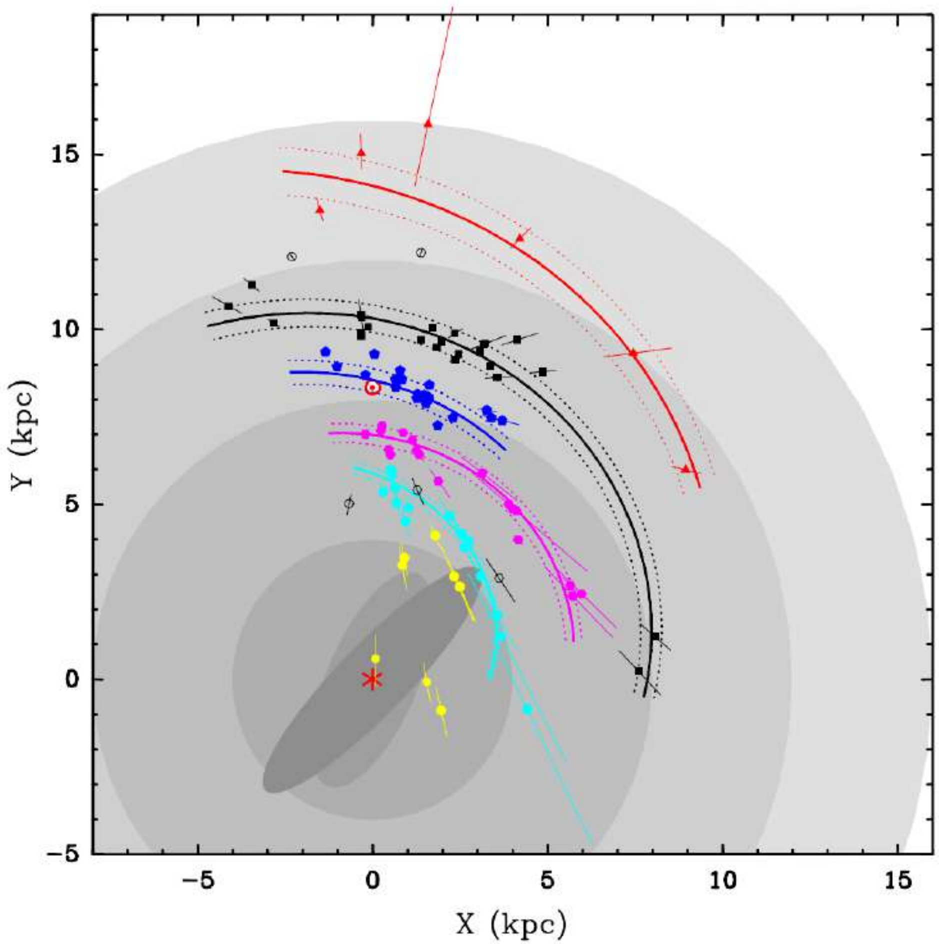
Astrometry



Astrometry highlights

BeSSeL

Bar and Spiral Structure Legacy Survey



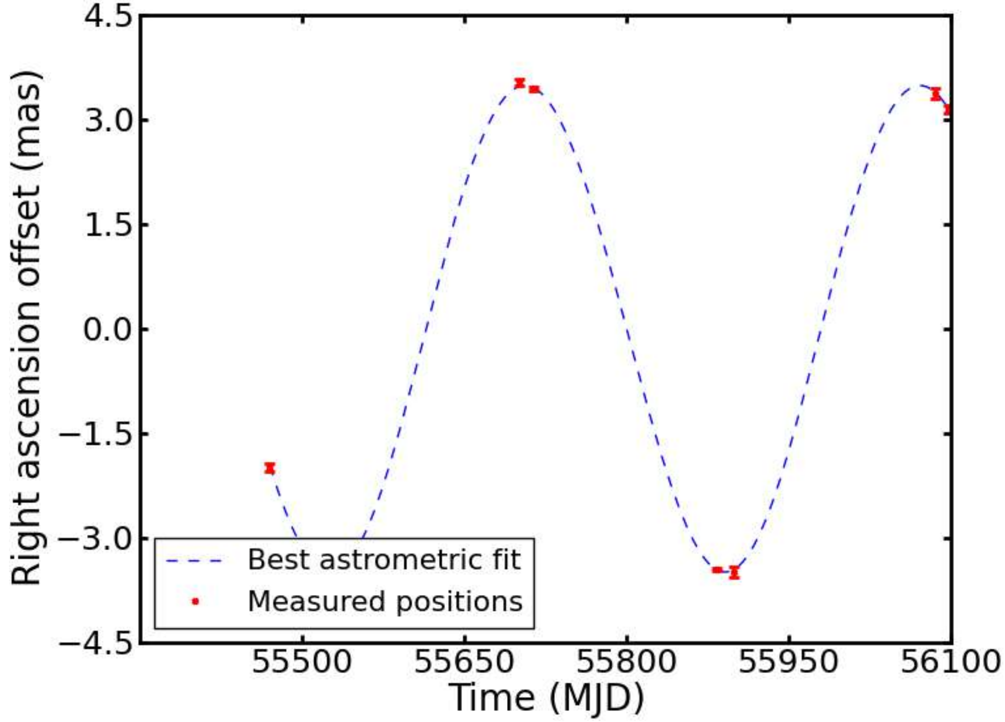
>100 parallax distances to masers around high-mass star forming regions:

- Spiral arm structure
- Distance to Galactic Center
- Galactic rotation curve

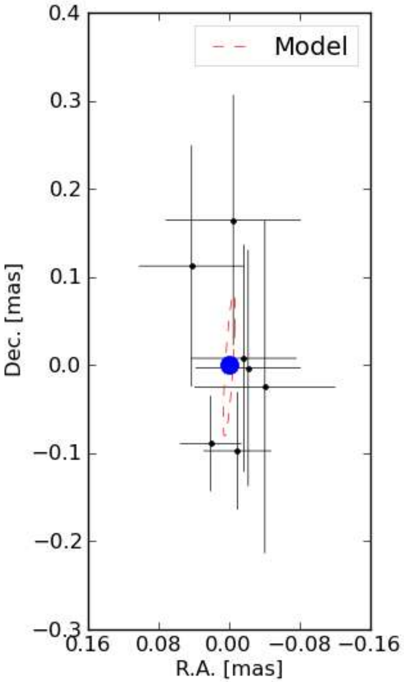
Astrometry highlights

- Distance to PSR J2222-0137 at 0.4% precision; can even see binary motion

Annual parallax

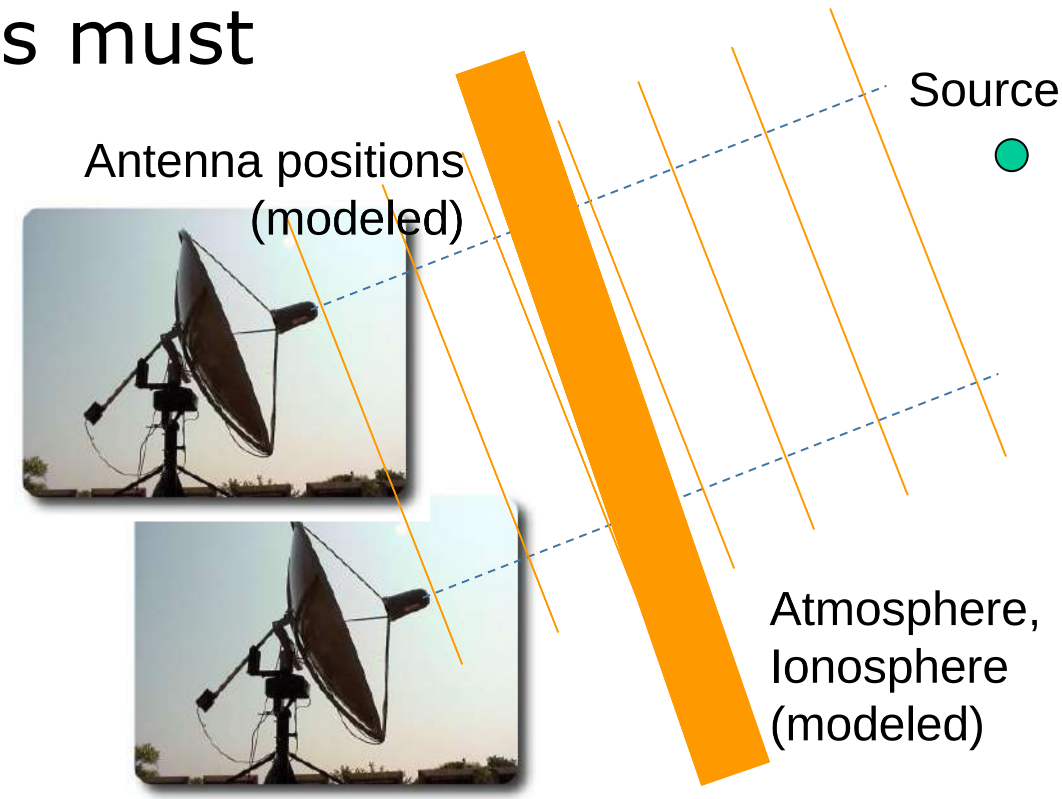


Orbital motion



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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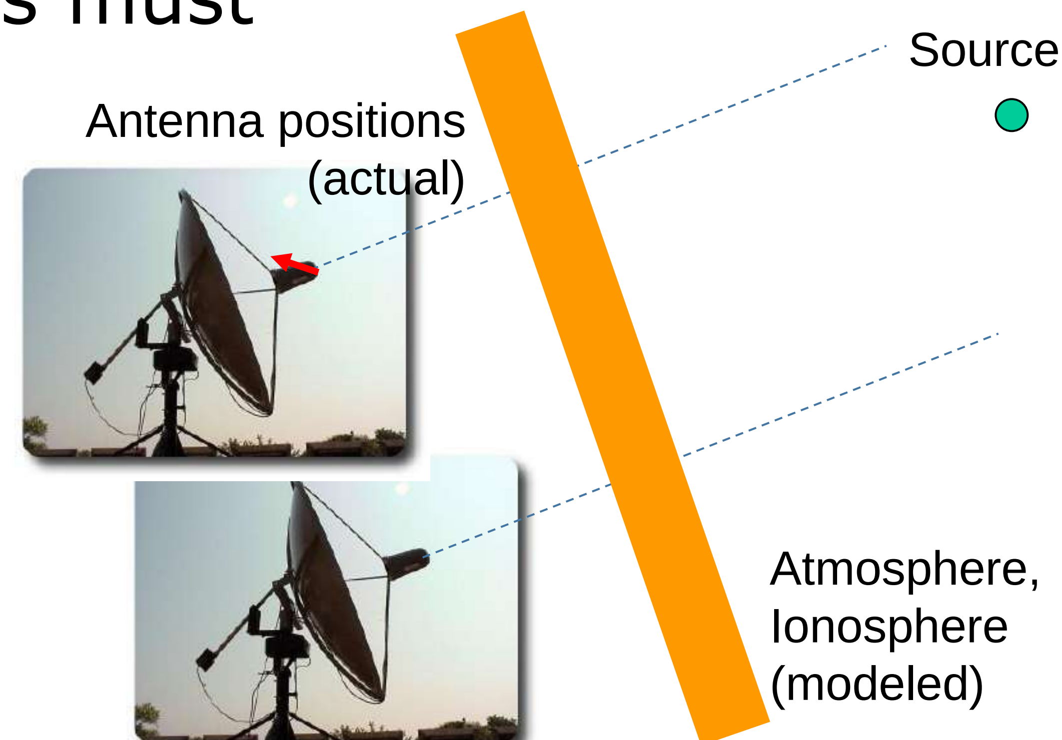

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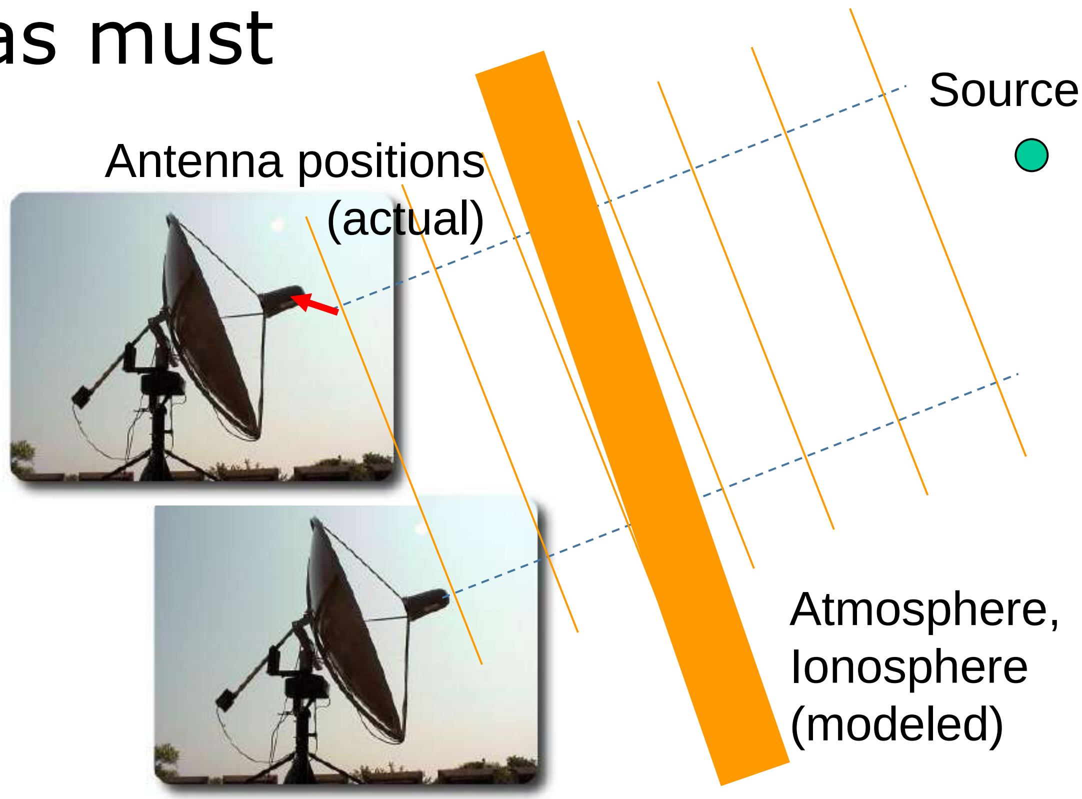

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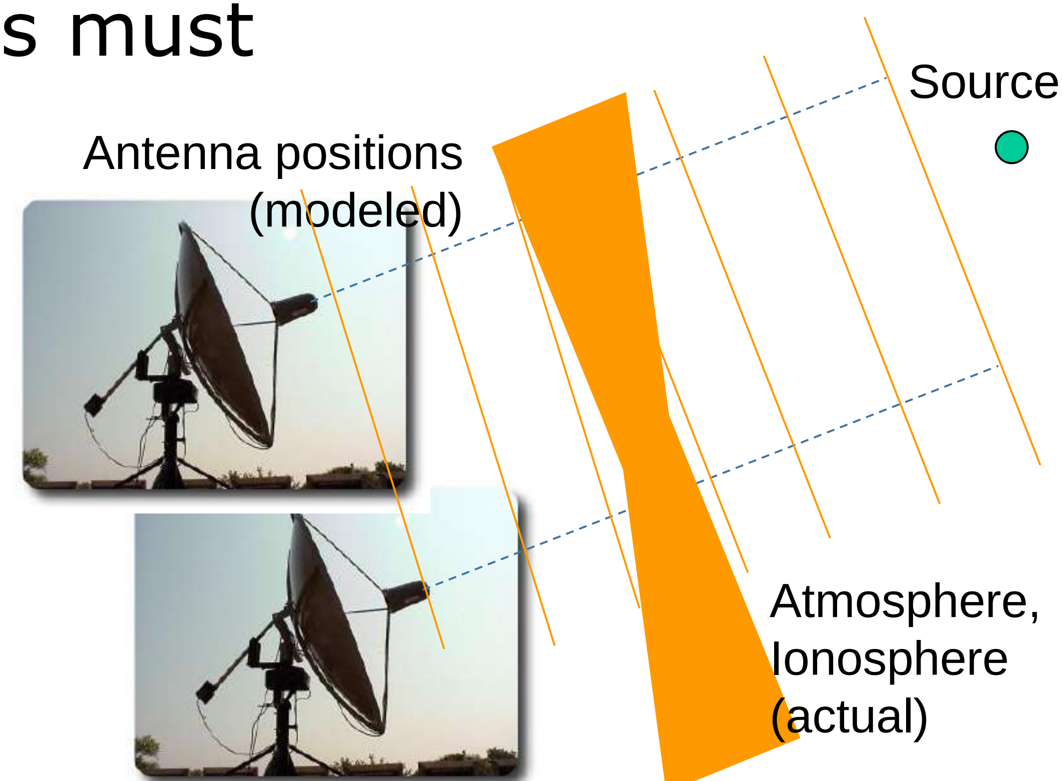


Geodetic results

- 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 2010 earthquake in Chile, the position of the Concepcion antenna was measured to have moved by ~2m

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
- add GBT, VLA, Arecibo for "High Sensitivity Array"

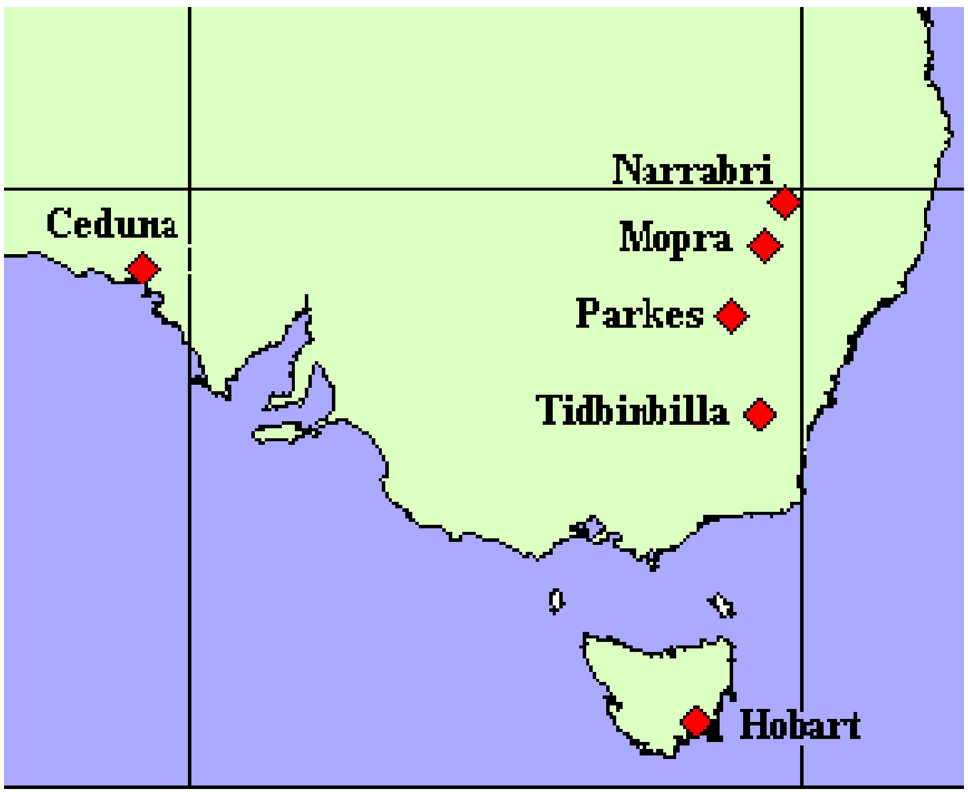
Current VLBI arrays

- 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

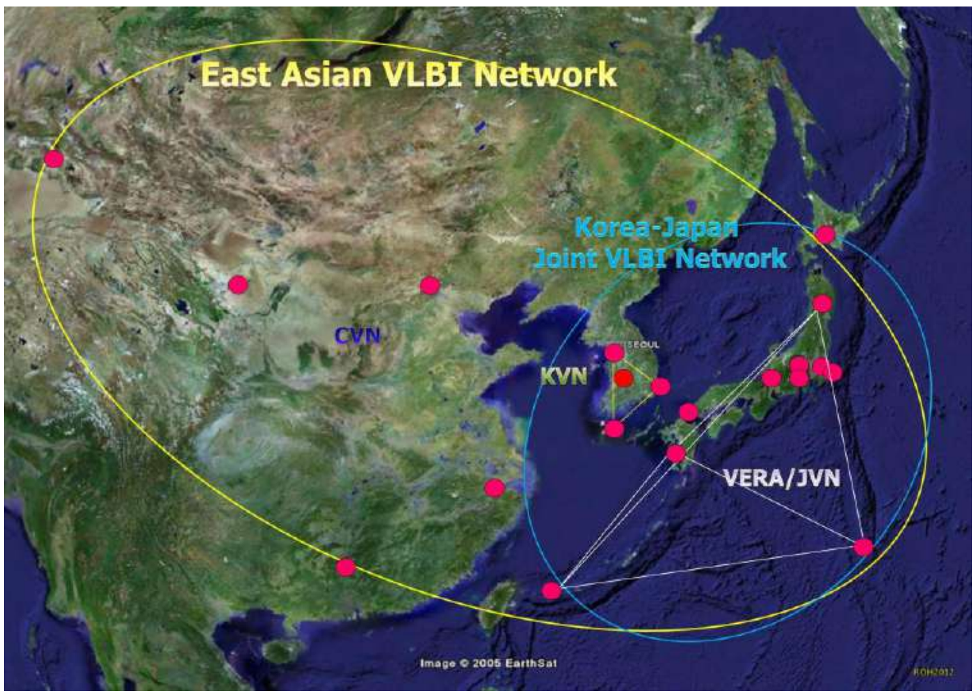
- The Long Baseline Array (LBA)



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

Current VLBI arrays

- East Asian VLBI Network is a collaboration of 3 separate networks:



KVN: Korea, 4 dishes, 22 – 129 GHz
VERA: Japan, focus on astrometry, 2 – 43 GHz
CVN: China, includes some larger dishes
First open call in 2015?

Current VLBI arrays

- LOFAR: Sub-arcsecond imaging at metre wavelengths

8 international stations now, 4 more coming (plus core and 15 more stations in Netherlands).

15 – 240 MHz, full time (open time available)

Current VLBI arrays

- Event Horizon Telescope: highest resolution interferometer, aims for direct imaging of black hole shadows

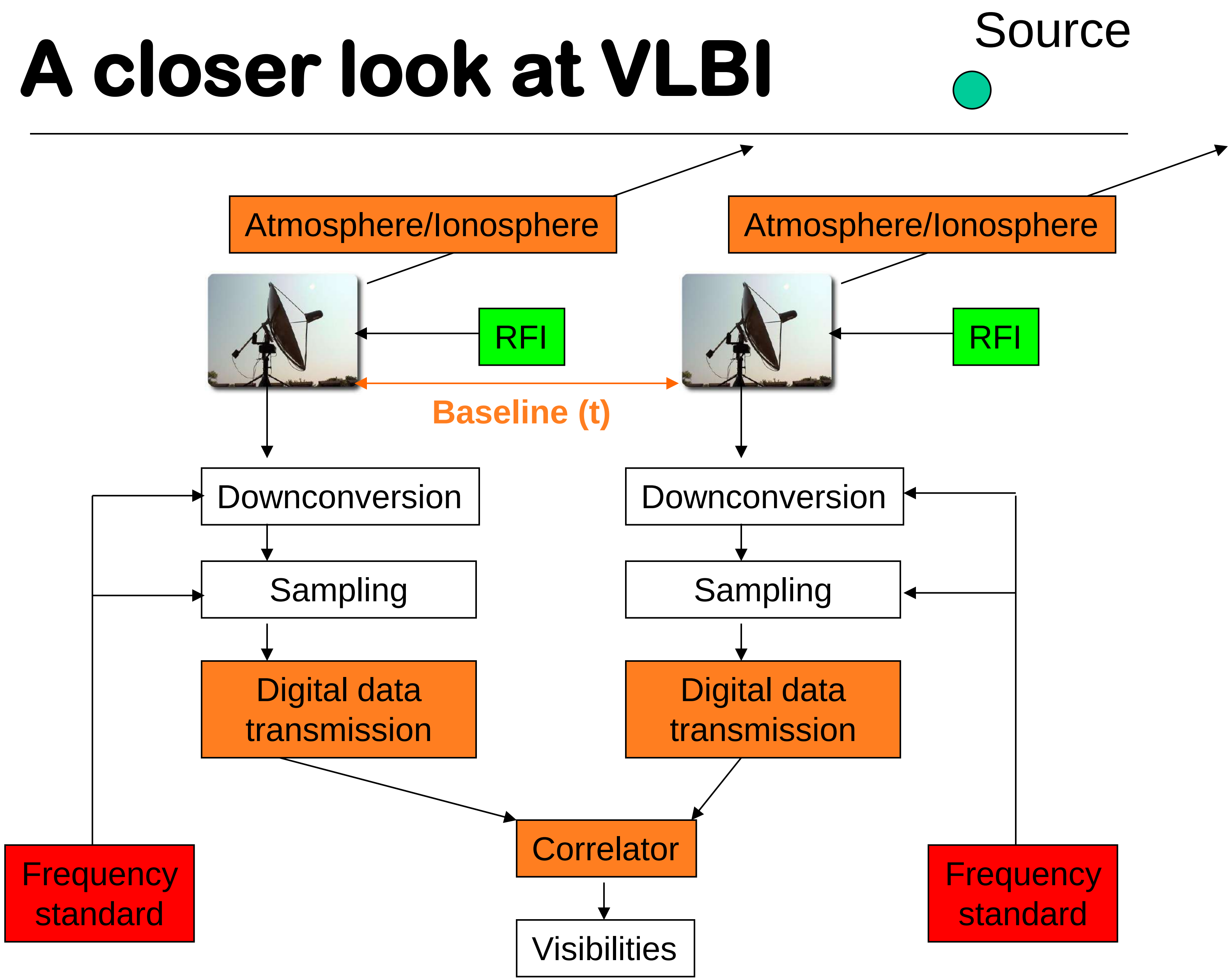
Operating at 230 and 345 GHz, resolution 60 μas (future, with ALMA, 20 μas)

No open time, very limited duty cycle

Current VLBI arrays

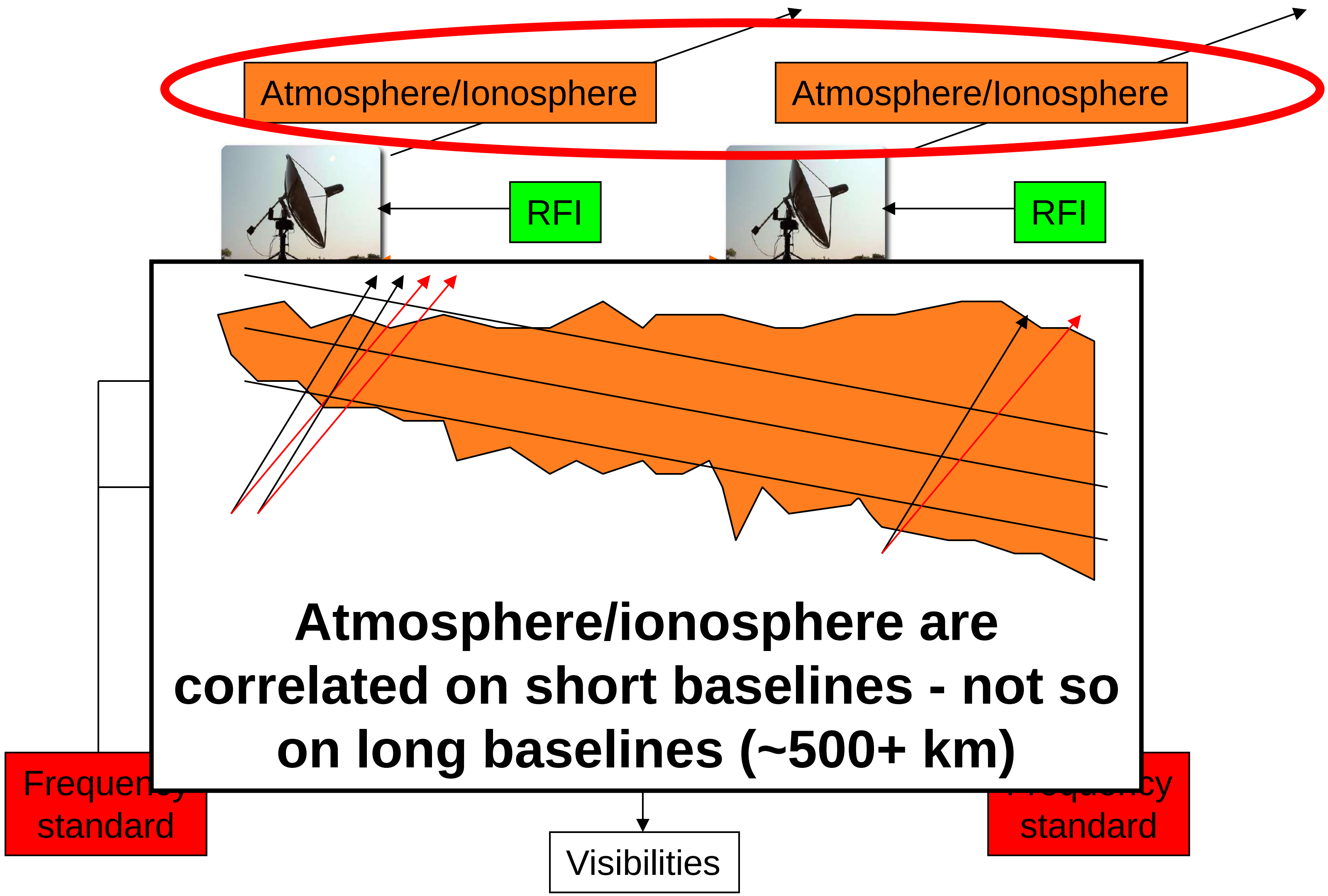
- RadioAstron: 10m telescope operating in space
- Baseline lengths 1,000 – 330,000 km
- 327 MHz, 1.6 GHz, 4.8 GHz, 22 GHz
- Open time available, must arrange other telescopes too

A closer look at VLBI

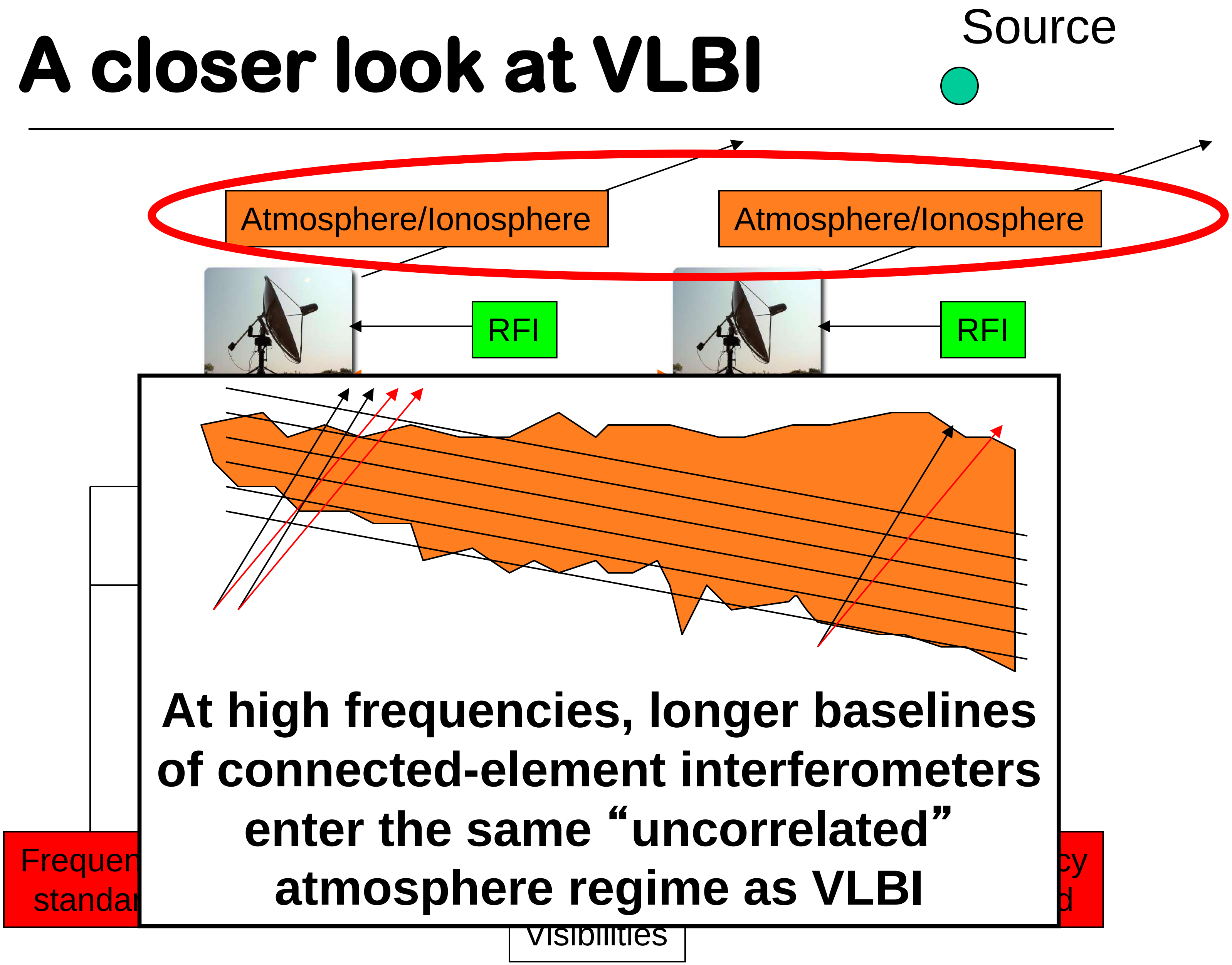


A closer look at VLBI

Source

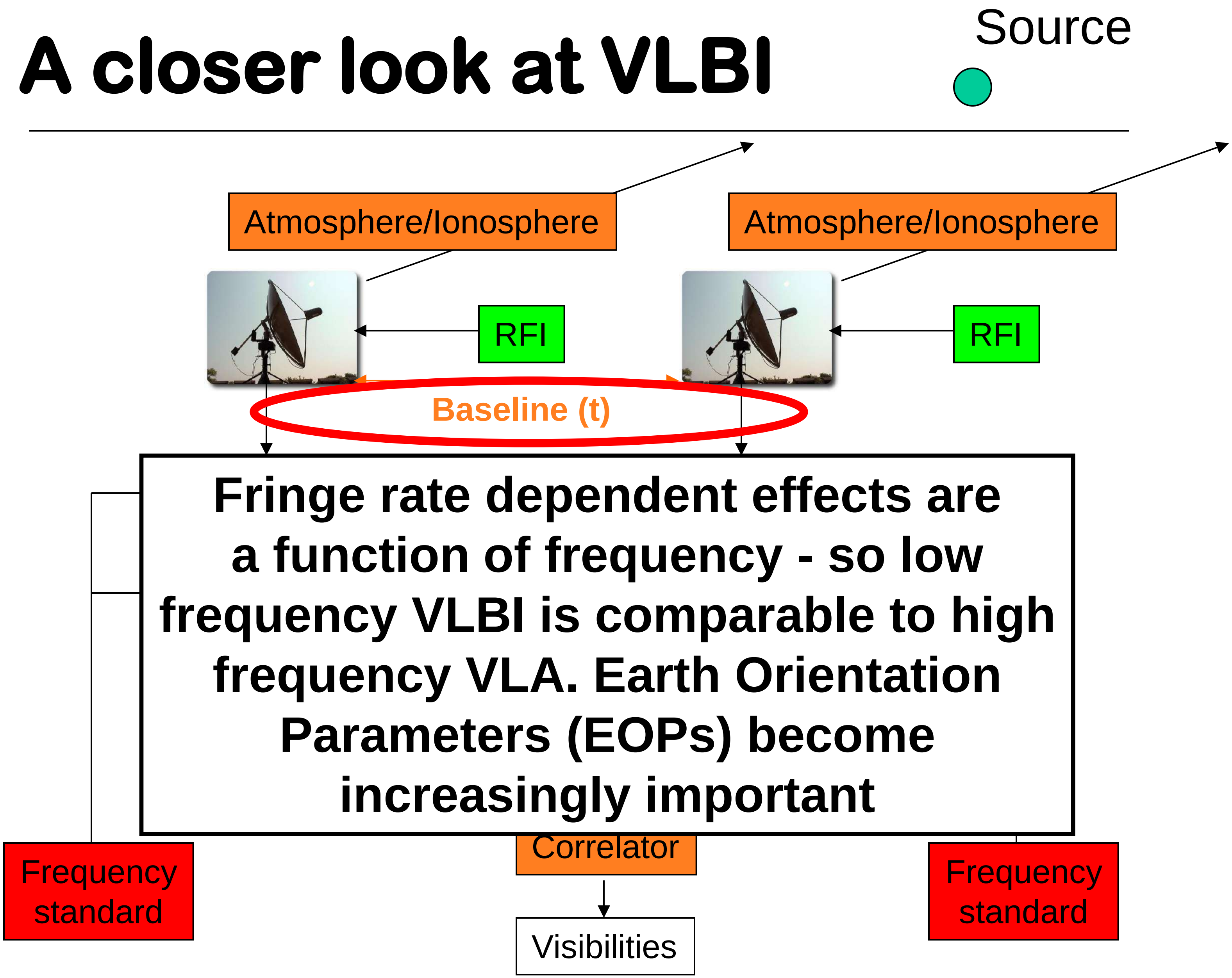


A closer look at VLBI



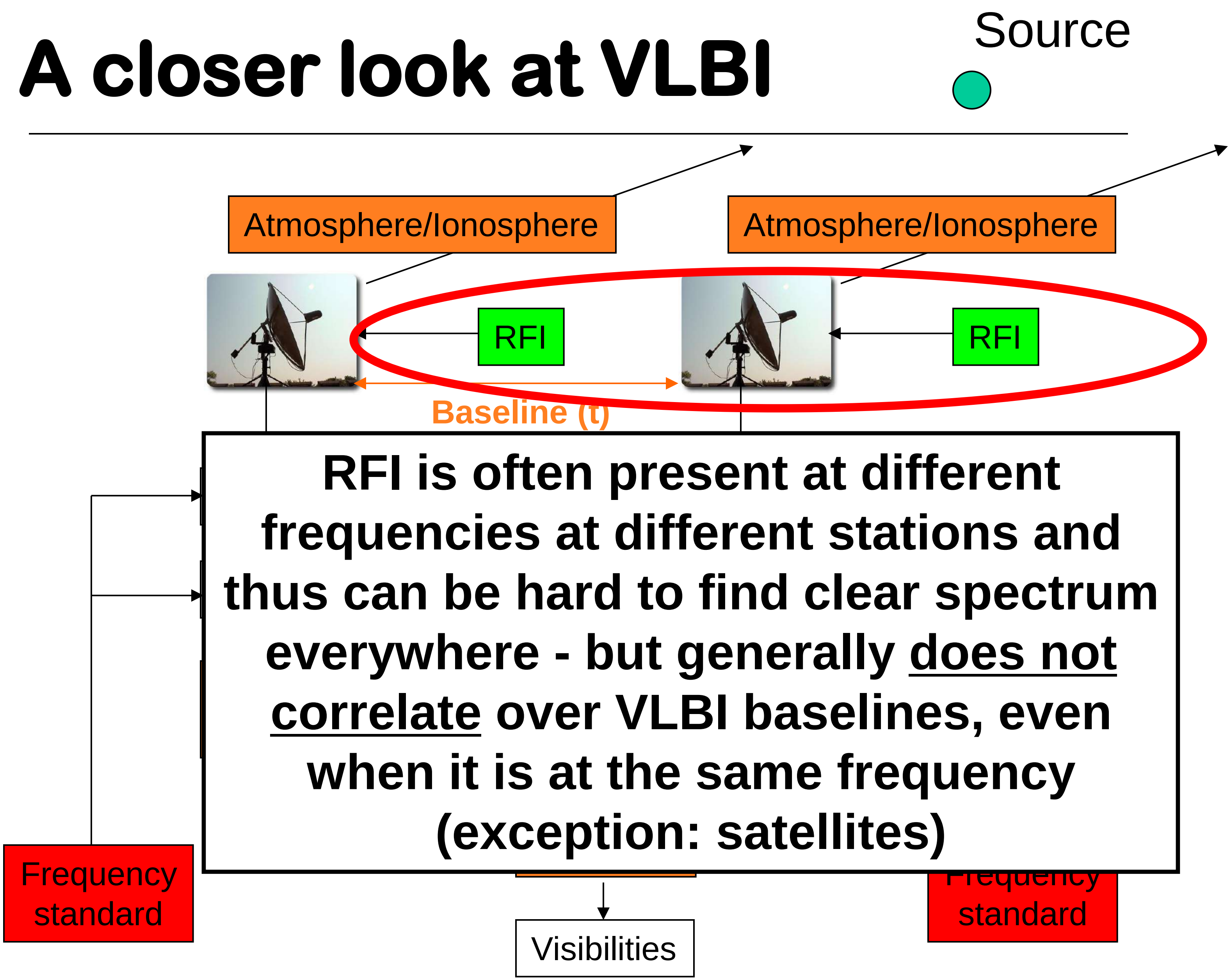
At high frequencies, longer baselines of connected-element interferometers enter the same "uncorrelated" atmosphere regime as VLBI

A closer look at VLBI



Fringe rate dependent effects are a function of frequency - so low frequency VLBI is comparable to high frequency VLA. Earth Orientation Parameters (EOPs) become increasingly important

A closer look at VLBI



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 (exception: satellites)

A closer look at VLBI

Source

Atmosphere/Ionosphere

Atmosphere/Ionosphere

The data transmission is where VLBI differs most obviously.

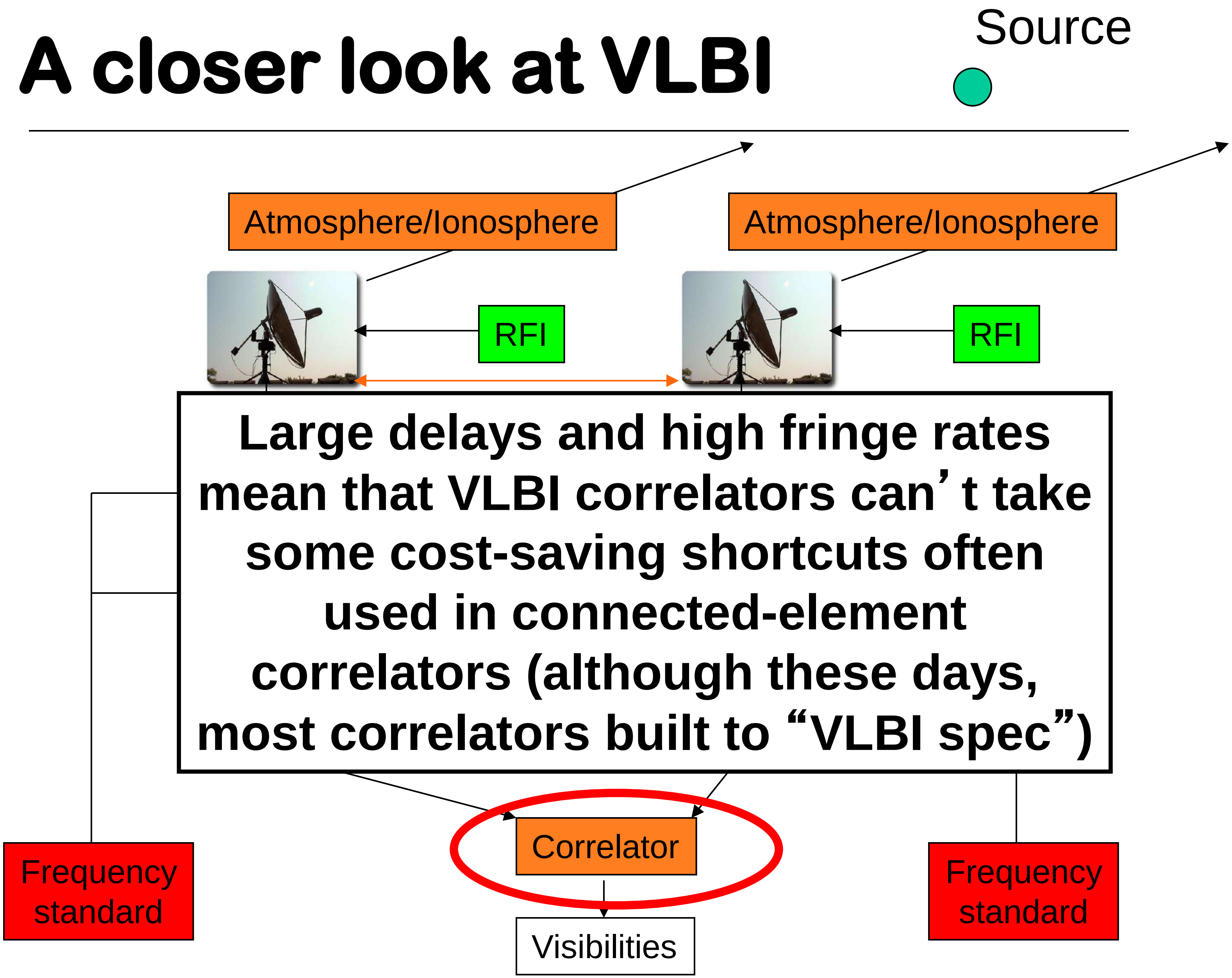
Correlator

Frequency standard

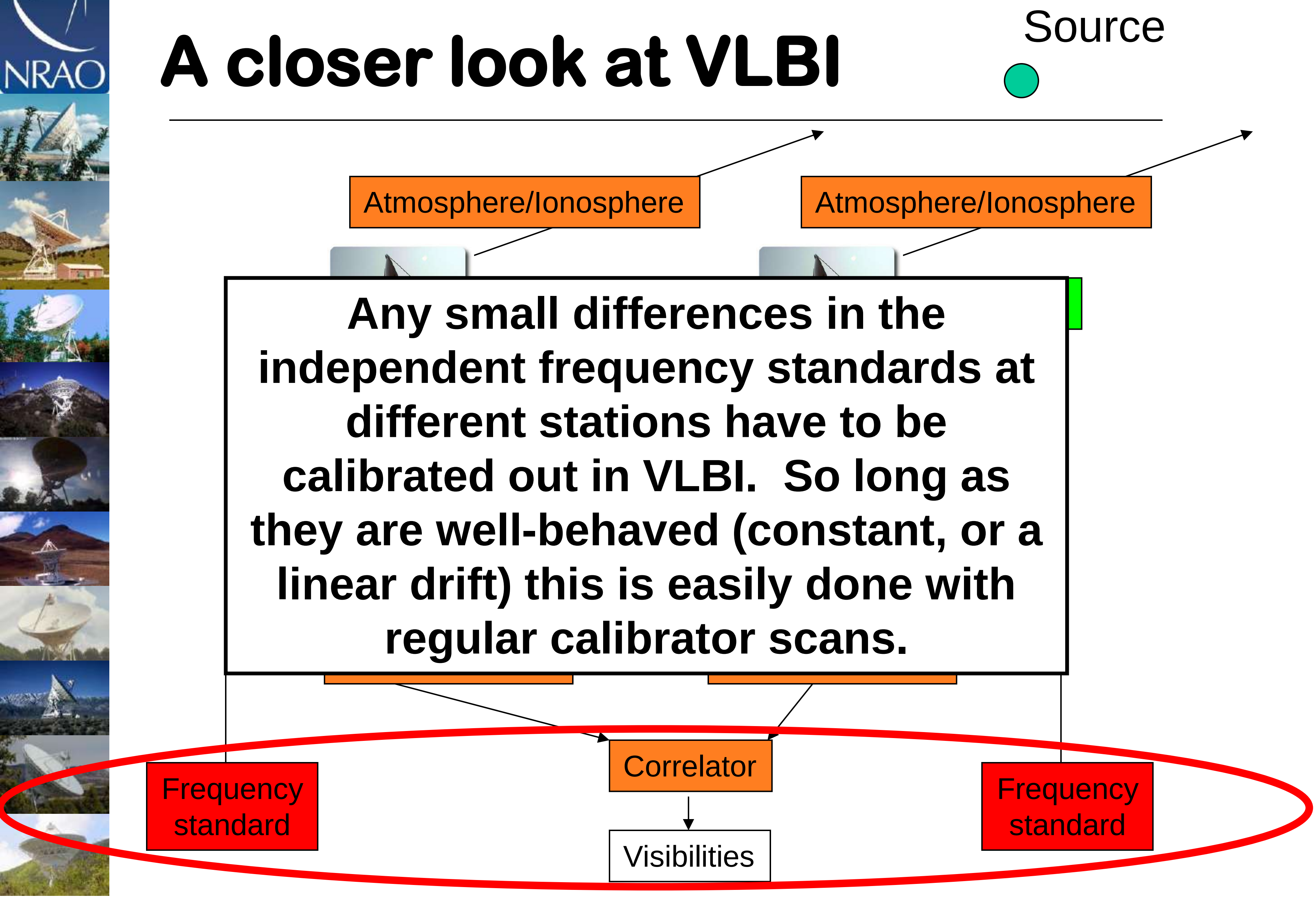
Frequency standard

Visibilities

A closer look at VLBI



A closer look at VLBI



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.

Historical VLBI problems

- VLBI capabilities have leapt ahead in the last few decades!
- Some observational realities remain (set by the physics), sometimes blown out of proportion

#1: Poor sensitivity

- The need to record data historically limited VLBI to narrower bandwidths
  - But it has moved on from the era of 2 Mbps tapes!
- The VLBA + HSA does 2 Gbps (256 MHz, dual pol): beats JVLA continuum point source sensitivity at 1.4 GHz
  - But: surface brightness sensitivity obviously still extremely low!

#2: Unstable systems

- VLBI antennas still have completely independent electronics, time standard noise doesn't "wash out"
- **But:** modern systems (hydrogen masers, digital synthesizers) are stable on timescales of many hours
- Modern all-digital backends make the problem even smaller

#3: Unstable conditions

- This hasn't changed: atmosphere above different antennas is uncorrelated
- But this problem is not limited to VLBI: same is true of mm observing with moderate baselines (EVLA, ALMA)
- Same solution: switch between source and nearby calibrator at a sufficiently rapid interval (sensitivity helps)

#4: Unreliable imaging

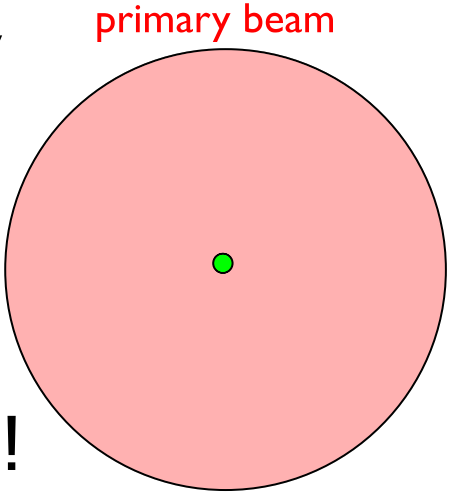
- Mostly a thing of the past (when phase stability was poor)
- Nowadays, set up your observations right (sufficient calibrators) and getting dynamic ranges >10,000 is easy
- Still two remaining problems:
  - Often fewer antennas (10 VLBA / 27 EVLA)
  - Layout is often not optimal (antenna placement determined by geography, infrastructure)

#5: Uncertain flux scale

- There are no constant-flux VLBI sources
  - Anything compact enough is always variable - quasars eject blobs of material, pulsars scintillate…
  - Thus cannot use a “flux calibrator”
- Compensate with extra effort in *a priori* flux calibration (switched noise diode)
- Absolute scale of VLBI flux is probably only valid to ~10% - usually no big deal

#6: Limited field of view

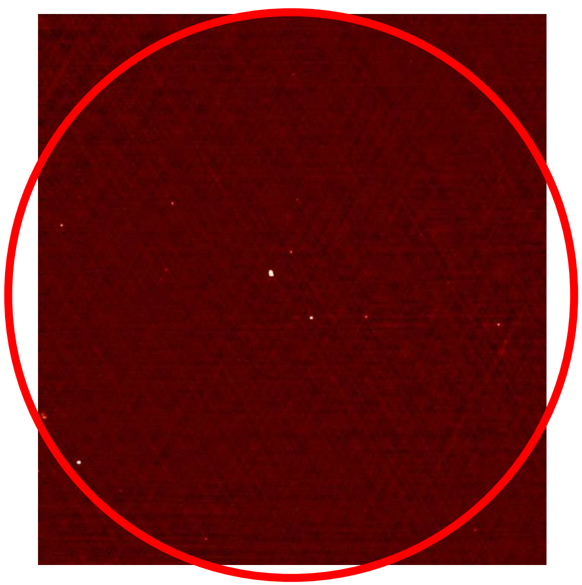
- Time smearing and bandwidth smearing are intense because of high fringe rate
- Older correlators had output rate restrictions, field of view ~arcseconds
- Even if correlator can make necessary visibility dataset, it will be **HUGE**
- And: image is 99.9999999% noise!

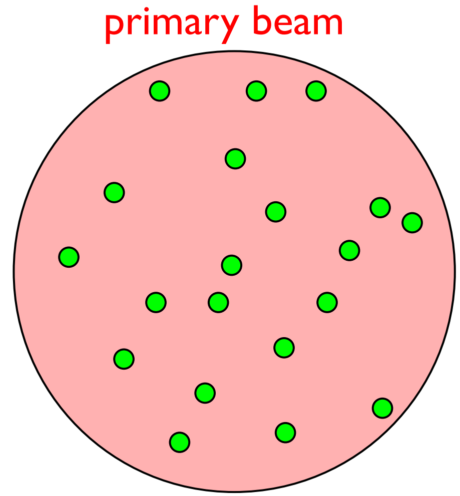


12h VLBA observation
Small field (5”):
5 GB visibiilities
64 MB image
Full primary beam:
30 TB visibilities
10 TB image

#6: Limited field of view

- Cool new feature in modern correlators allows “multi-field” VLBI
- Multiple small output datasets centered on sources of interest – use a “finder image” from e.g. VLA, GMRT, ATCA

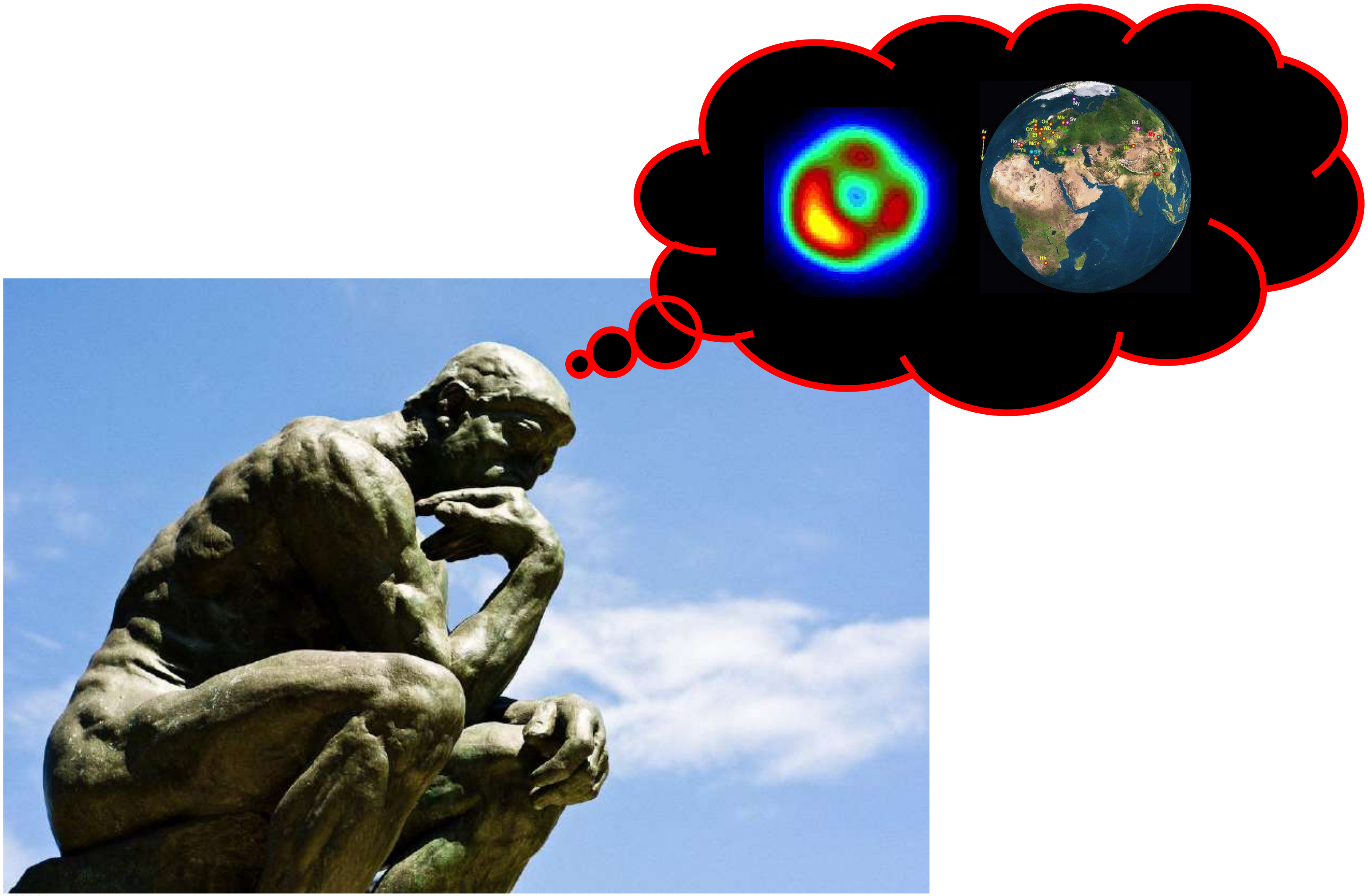




12h VLBA observation

1 small field (5”):
5 GB visibiilities
64 MB image
20 small fields:
100 GB visibilities
1.5 GB image

The practicalities of VLBI



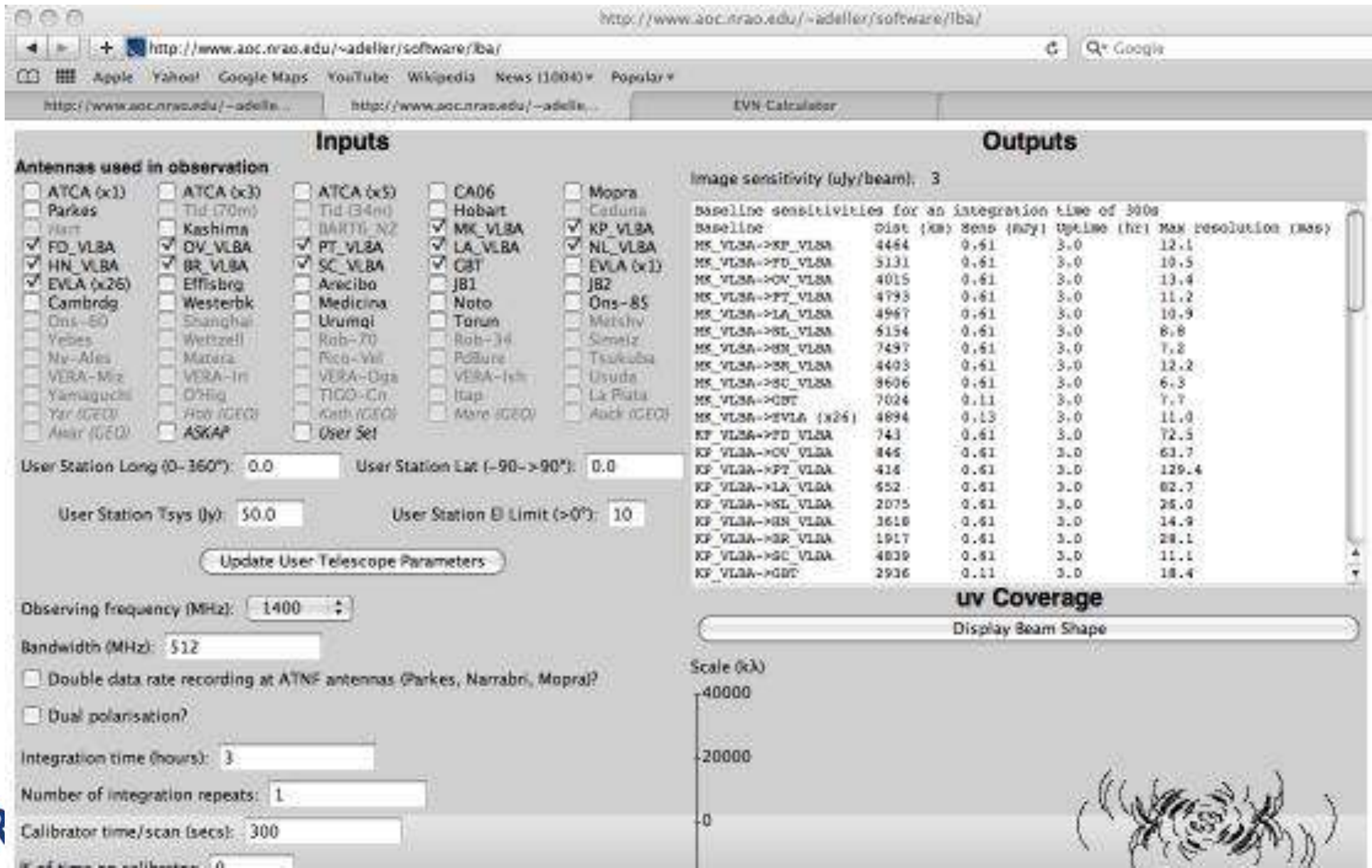
The practicalities of VLBI

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

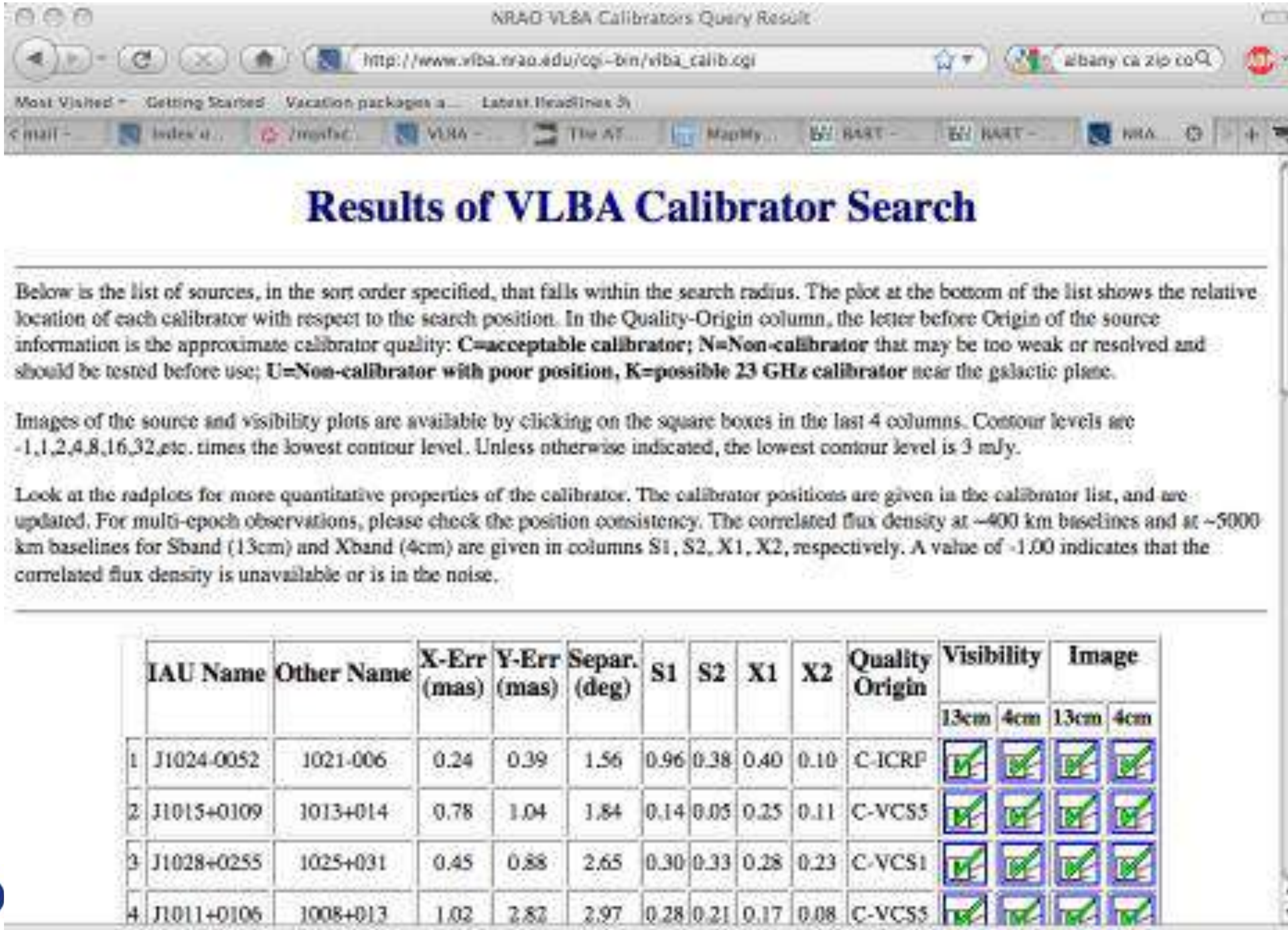
Plan

- 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)
ATCA (x3)
ATCA (x5)
CA06
Mopra
Parkes
Hobart
Kashima
MK_VLBA
KP_VLBA
FD_VLBA
OV_VLBA
PT_VLBA
LA_VLBA
NL_VLBA
HN_VLBA
BR_VLBA
SC_VLBA
GBT
EVLA (x1)
EVLA (x26)
Effisbrg
Arecibo
JB1
JB2
Cambrdg
Westerbk
Medicina
Noto
Ons-85
Urumqi
Torun
ASKAP
User Set
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



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.

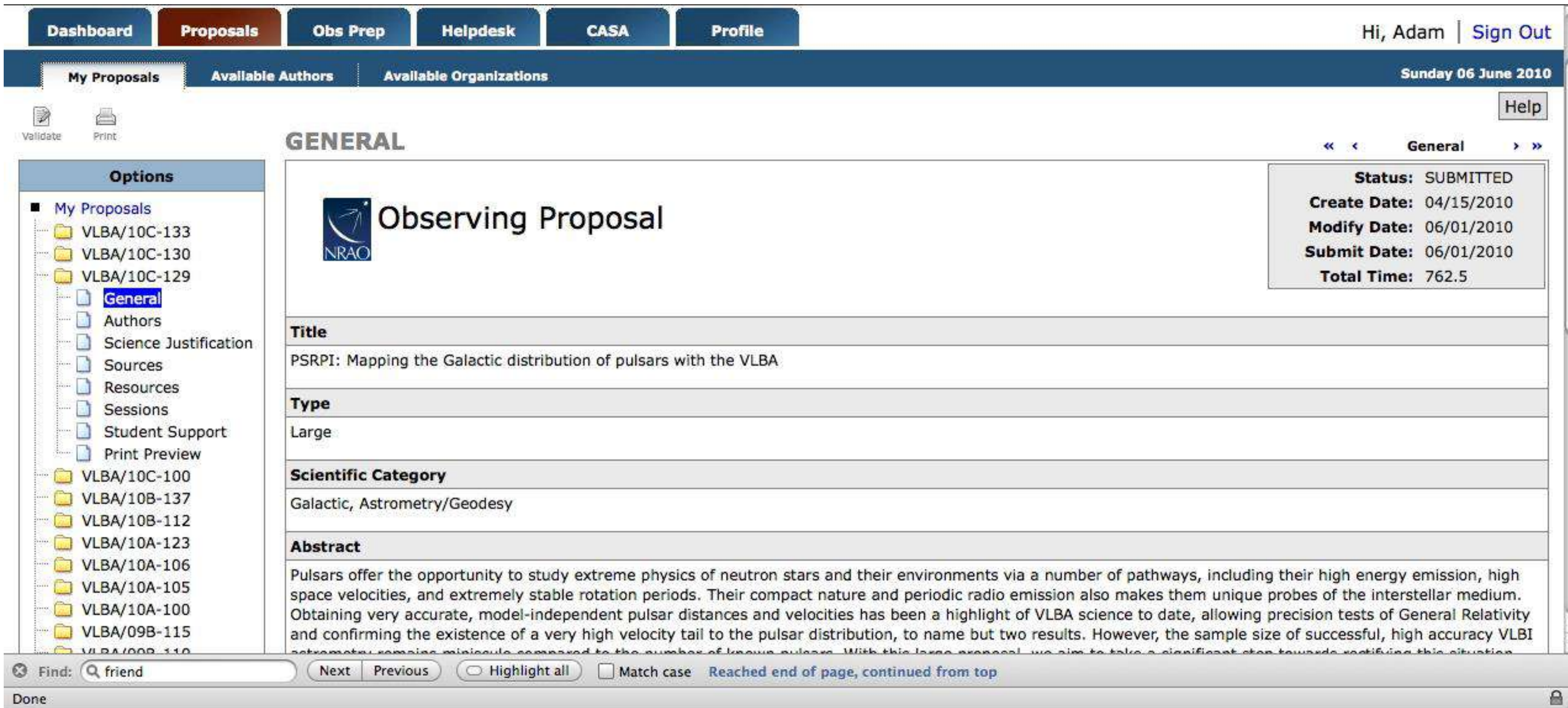
Look at the radplots for more quantitative properties of the calibrator. The calibrator positions are given in the calibrator list, and are updated. For multi-epoch observations, please check the position consistency. The correlated flux density at ~400 km baselines and at ~5000 km baselines for Sband (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
- VLBA February 1, August 1
- EVN February 1, June 1, October 1
- LBA June 15 and December 15
- Director's Discretionary Time for rapid response
- Standard info: **where** (sources), **how** (resource setup) and **when** (duration, date constraints); help available

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; 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**

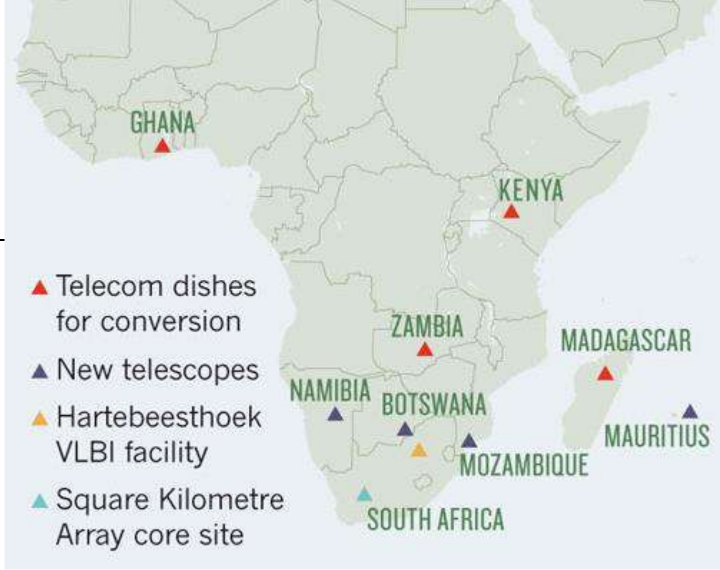
Data reduction (imaging)

- 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 now 1 Gbps routinely, soon 4 Gbps?
  - VLBA[HSA] now 2 Gbps , 40[3] μJy 1σ (1 hr)
- New processing techniques
  - Software correlators; high time/freq resolution, multiple fields, pulsar processing
  - Improved astrometric analysis
- Real-time correlation ("eVLBI")
  - LOFAR, EVN, some LBA: offers potentially higher data rates (plus data sooner!)

The future of VLBI



- African VLBI Network: network of re-purposed ex-telecoms dishes
- Phased ALMA for mm-VLBI and Event Horizon Telescope
- Existing facilities: more bandwidth increases, data processing innovations
- Longer term (5+ years): phased SKA1-mid and SKA1-survey; huge advance for southern observations

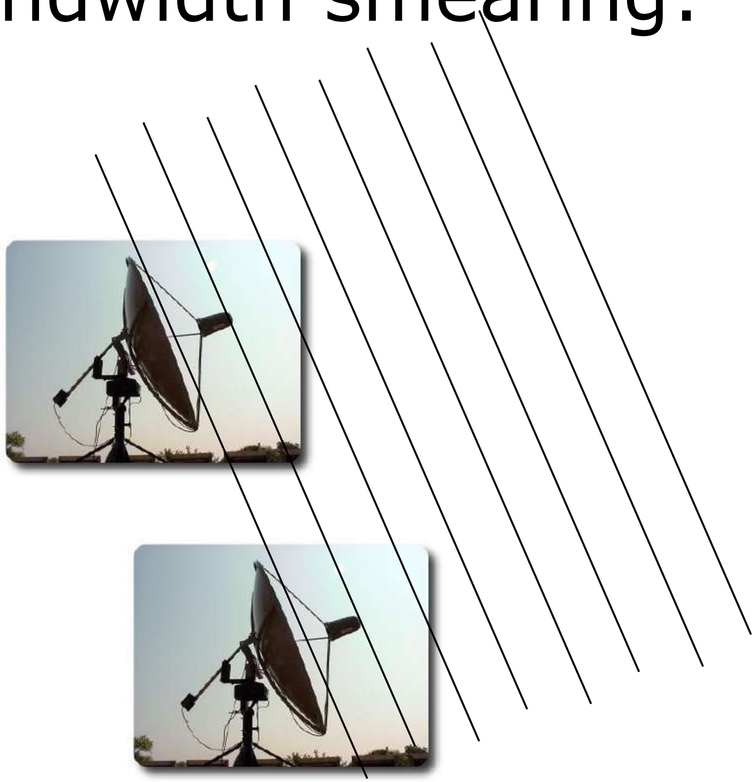
Conclusions

- 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
- With limitations (determined by physics); only compact objects
- VLBI is **not** a “black art” – no harder than high frequency VLA observing

Questions?

#6: No field of view

- Bandwidth smearing:

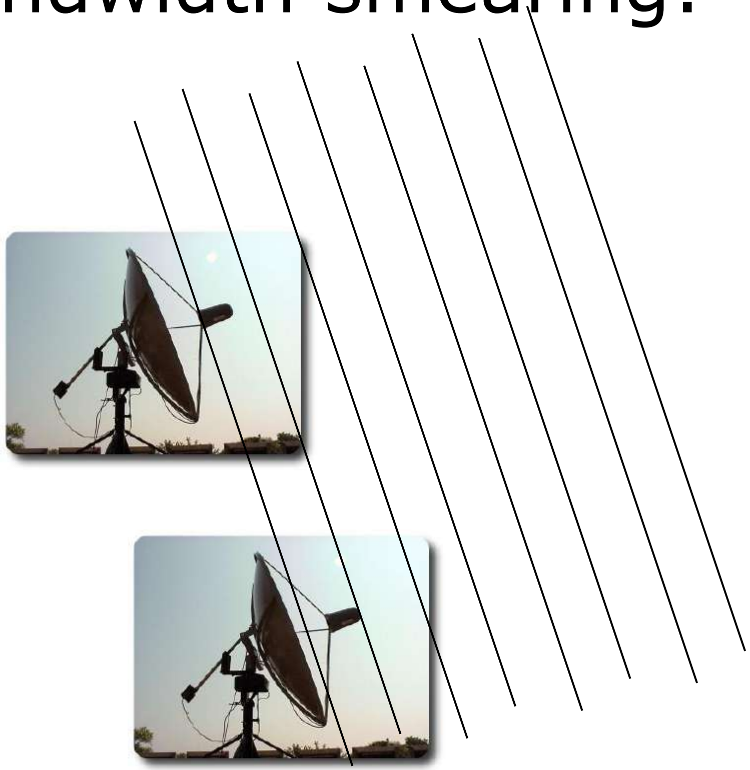


At the phase centre, all frequencies have zero phase, all the time

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

#6: No field of view

- Bandwidth smearing:

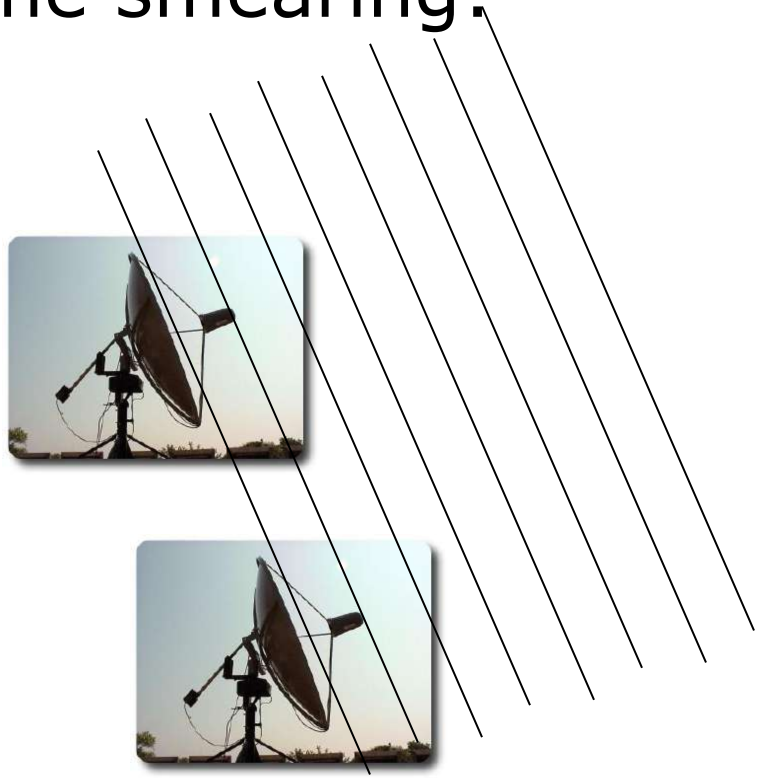


Off the phase centre, phase varies as a function of frequency, so if you average you get decorrelation

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

#6: No field of view

- Time smearing:

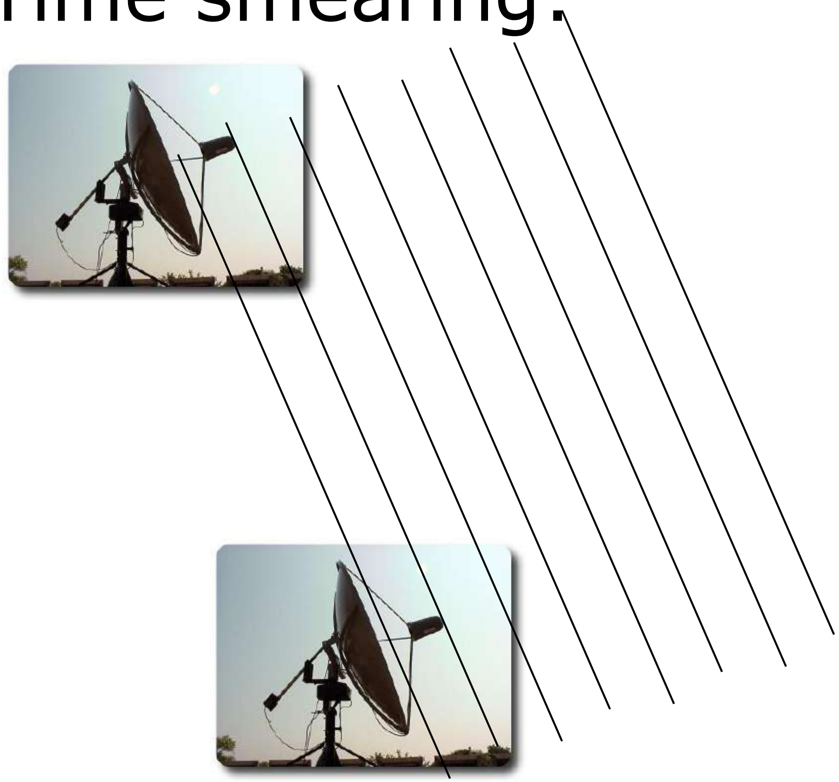


At the phase centre, all frequencies have zero phase, all the time

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

#6: No field of view

- Time smearing:



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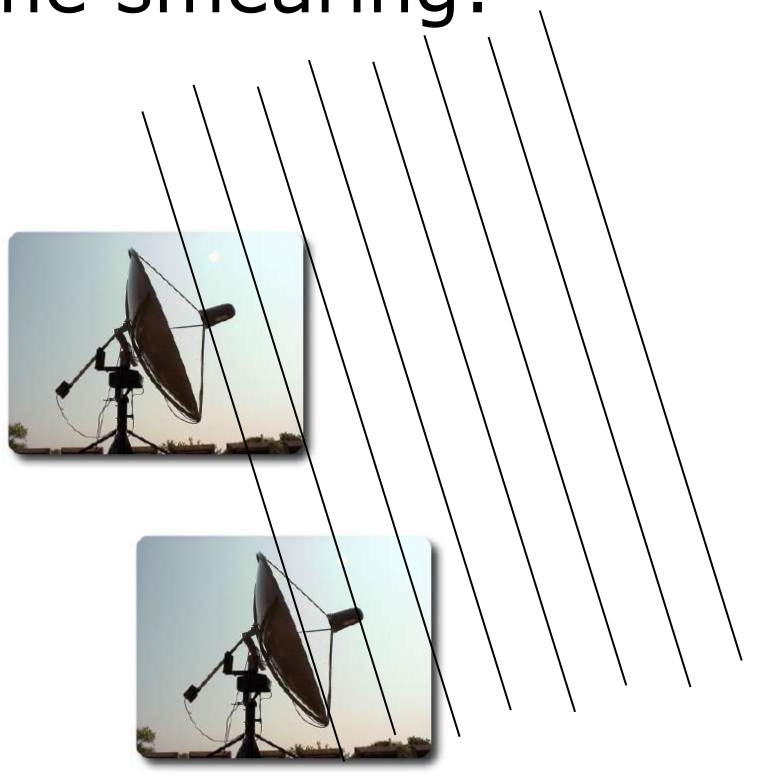
#6: No field of view

- Time smearing:



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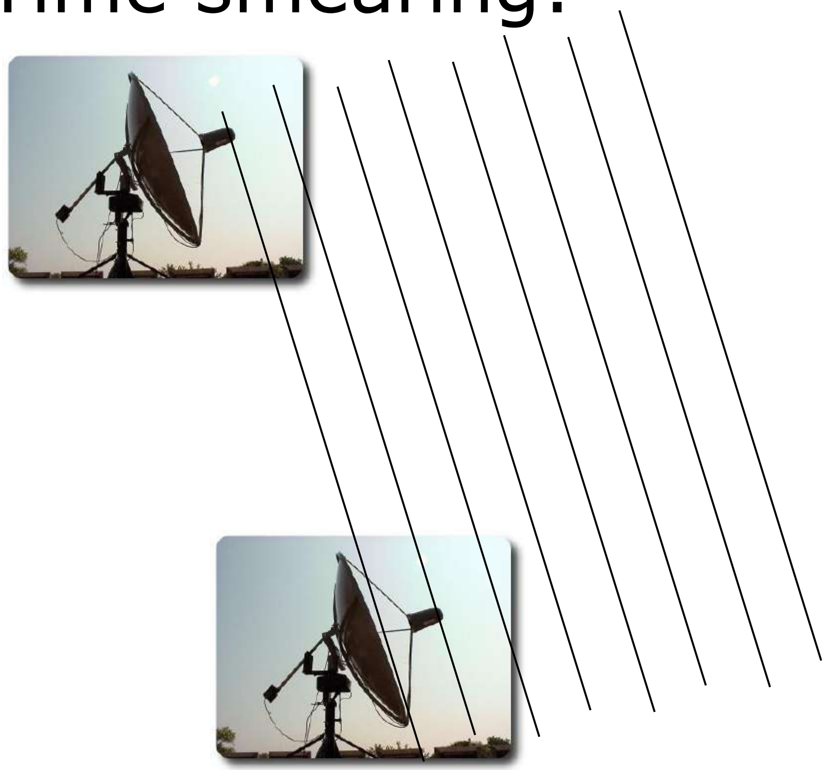


Off the phase centre, phase varies as a function of time, so if you average you get decorrelation

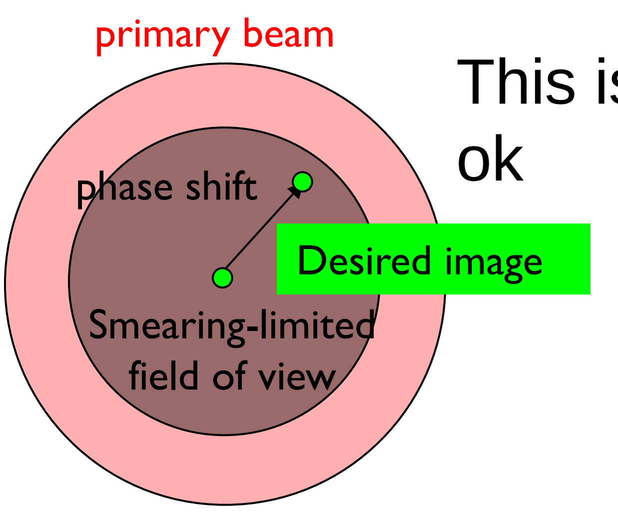
For 8,000km baselines @ 1.6 GHz, 2 sec averaging limits the FOV to <20”

#6: 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

New stuff: multiple field centers

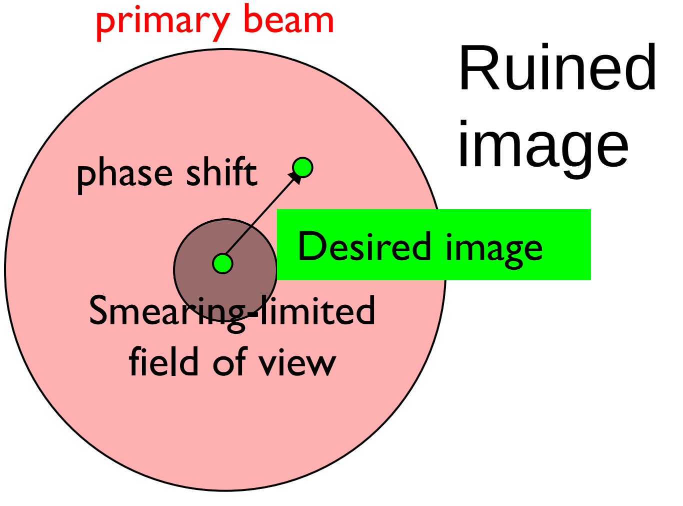
- “Pointing” a correlator involves appropriate delay and phase corrections
- “Re-pointing” correlated visibilities requires the appropriate differential phase change (fn of baseline/freq/time)



This is ok

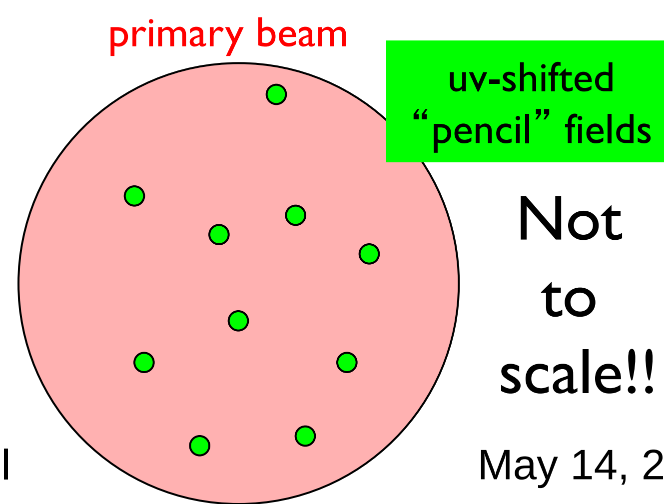
New stuff: multiple field centers

- "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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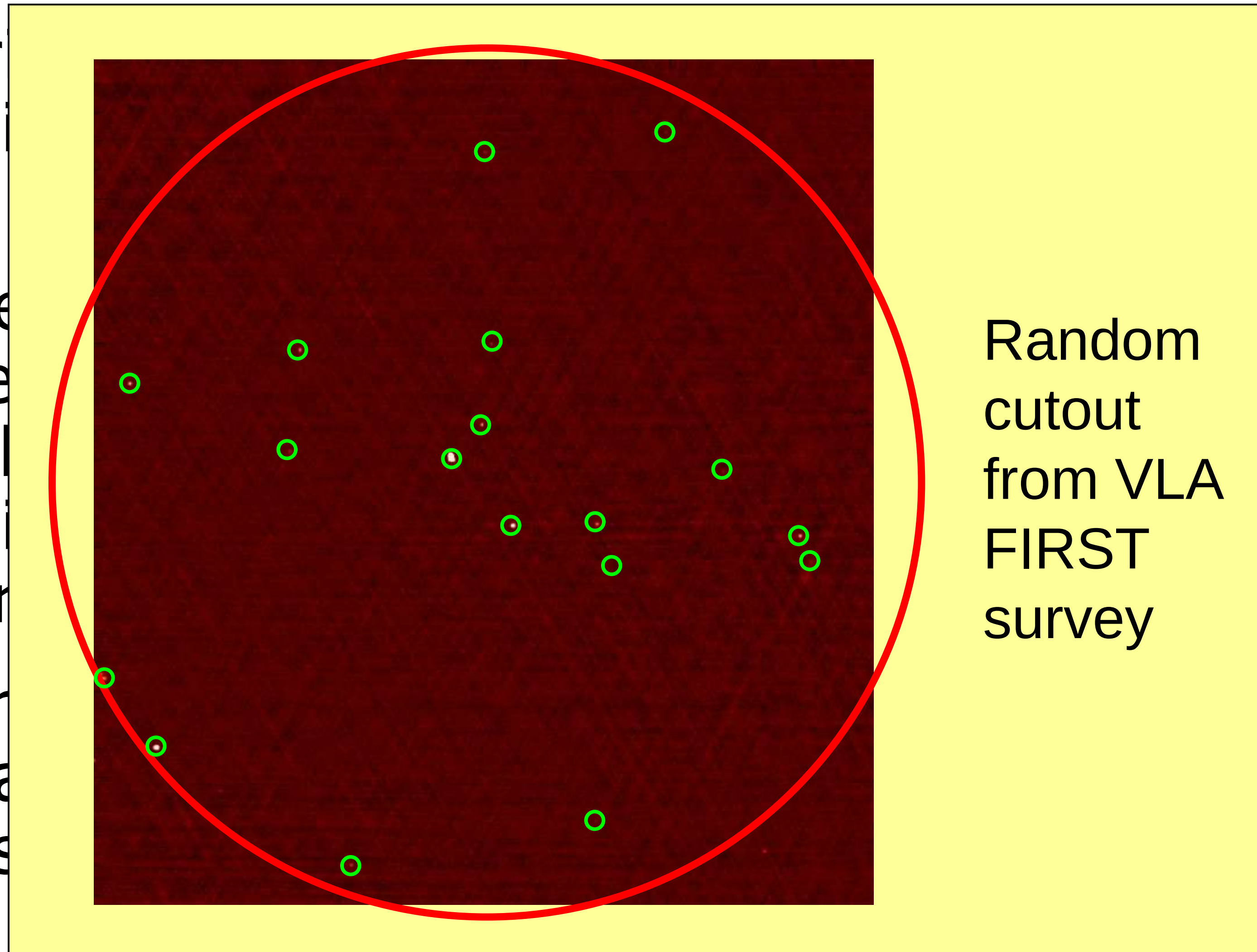
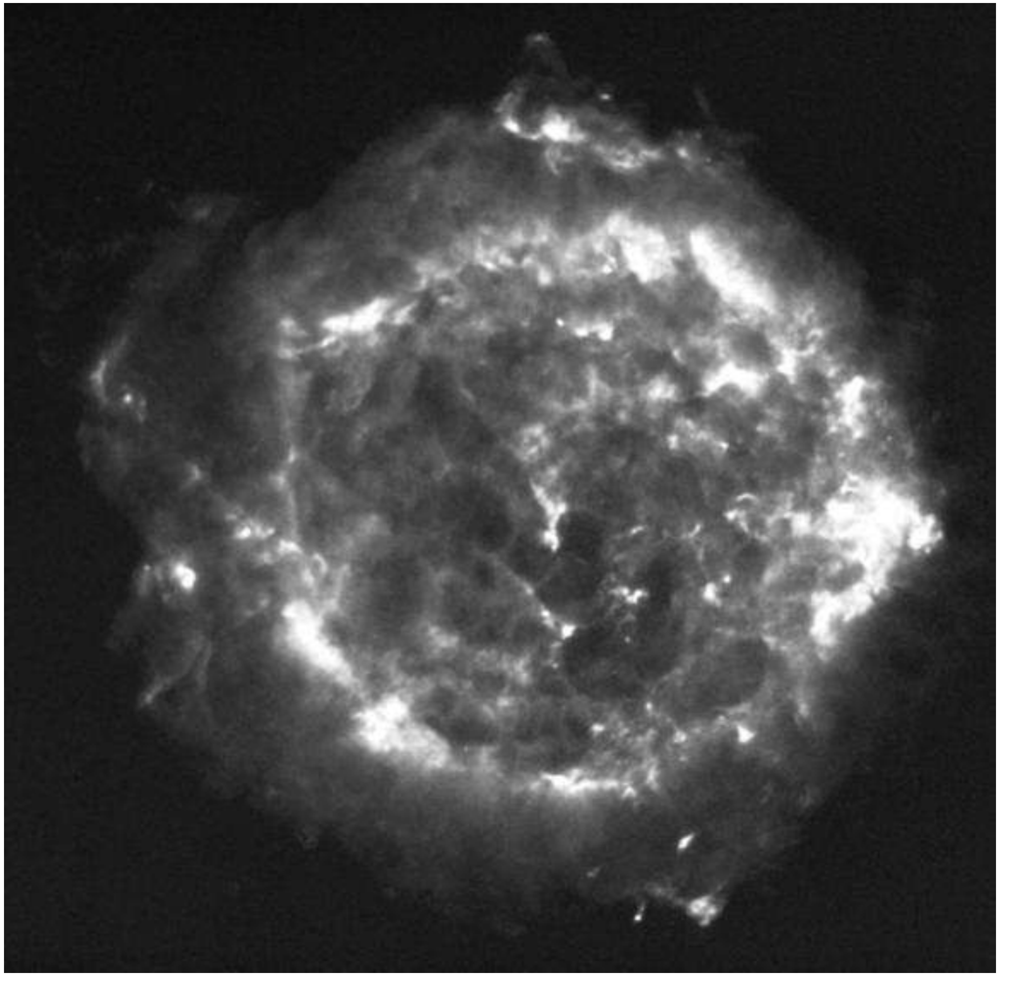


… but there's always a catch

6'



VLA beam

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

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