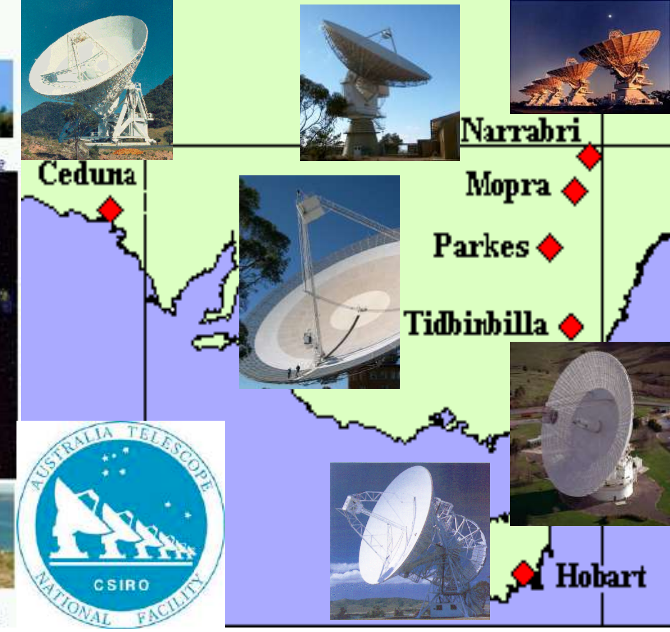
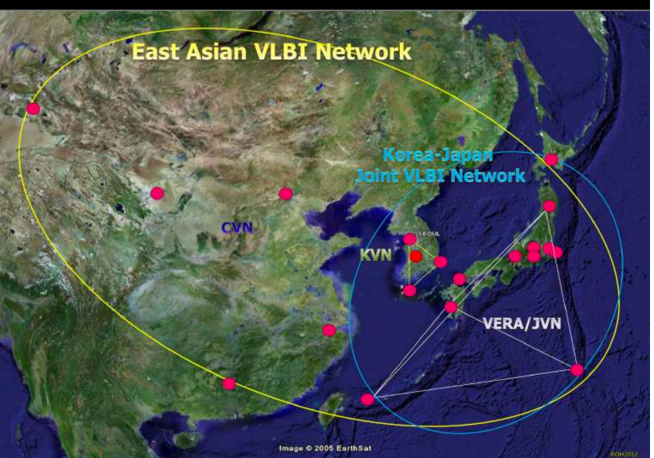




EventHorizonTelescope

Very Long Baseline Interferometry

Adam Deller

16th NRAO Synthesis Imaging Workshop

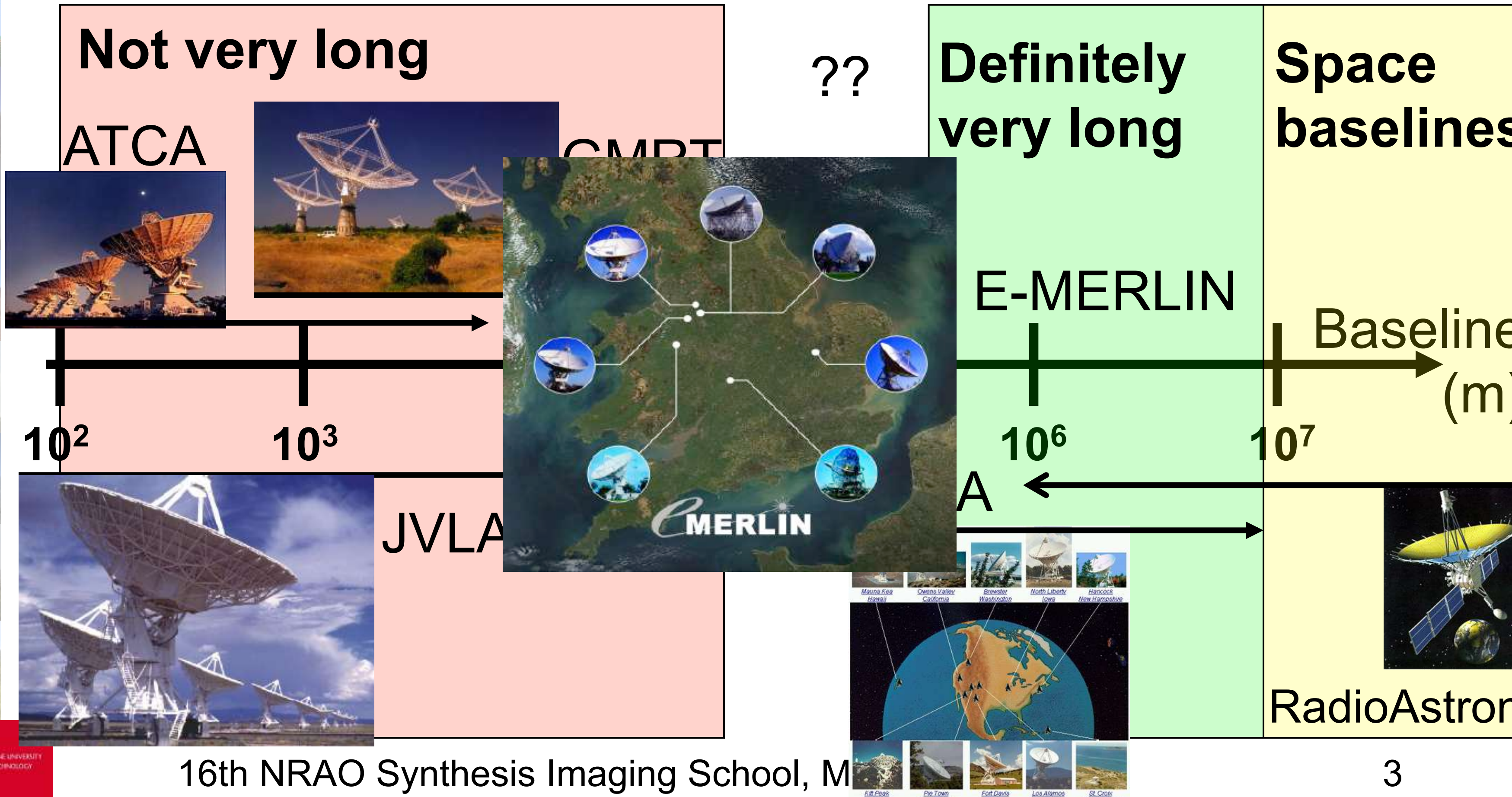
May 18, 2018

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

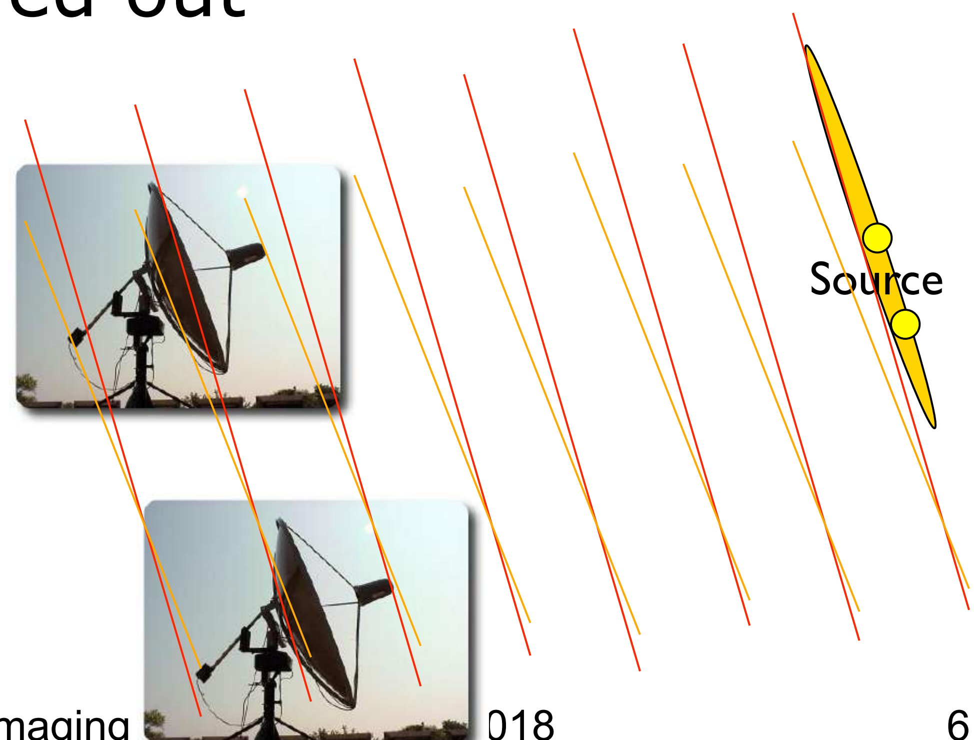
- Clearly not just about baseline length…
- What constitutes VLBI is actually a little hard to pin down (its more like a "syndrome" than a "disease"!)
  - Reason: **no** fundamental difference between VLBI and regular interferometry - only technology, convenience and convention
  - One potential (but 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 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!
  - 230 GHz (1mm): 30 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

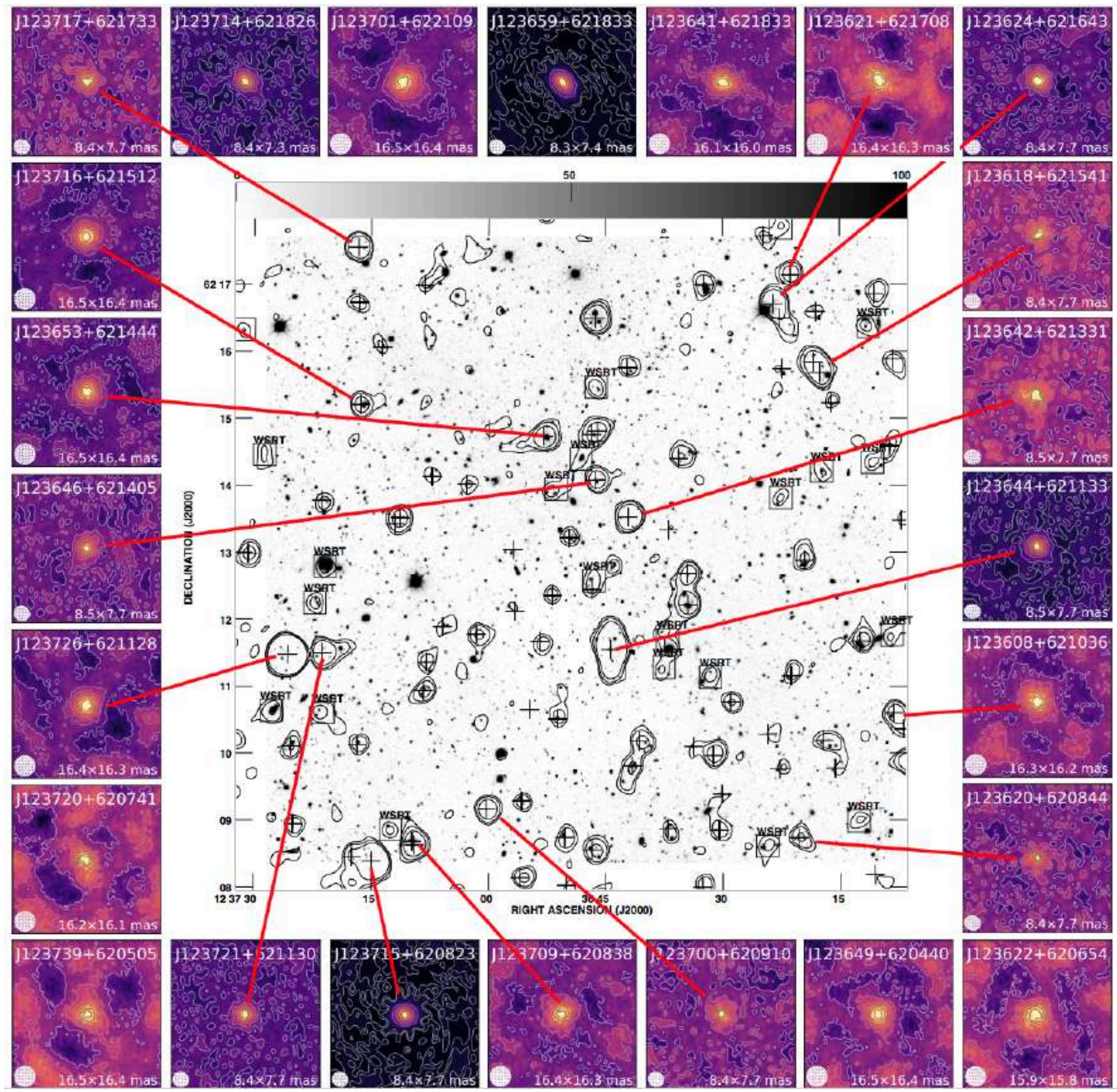
Science applications of VLBI

- 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, GW afterglow evolution with time?]
  - Their precise location, to obtain source kinematics or distance [astrometry]
  - A “test source” to model the propagation through the ISM/atmosphere/ionosphere or the receiving telescopes location [geodesy, interplanetary/interstellar “weather”]

Hallo? Any (compact) body there?

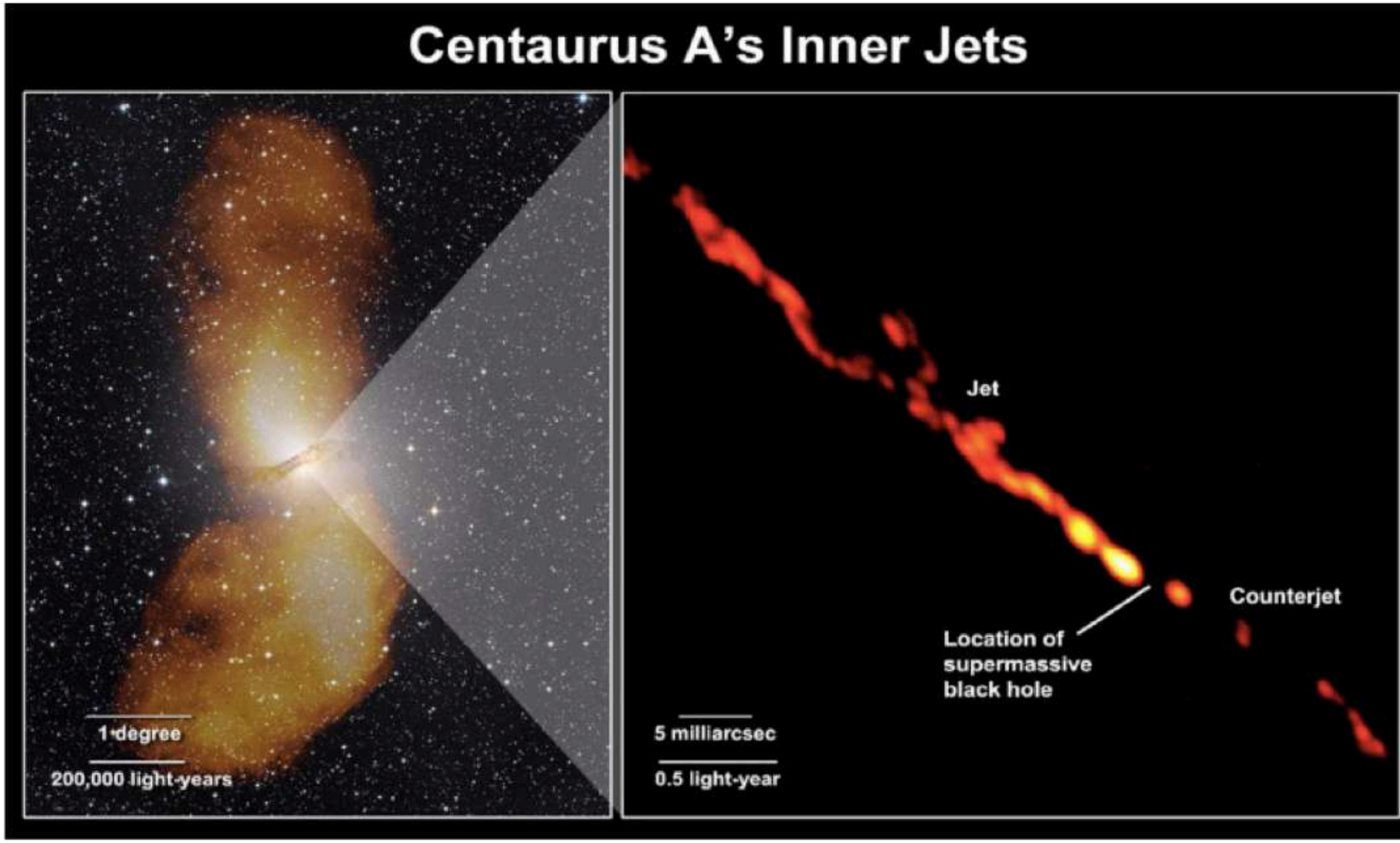
- A VLBI detection instantly identifies a compact non-thermal source
- In the local Universe, that might be a supernova [remnant], pulsar, shock…
- If the source is more distant, it **must** be a (radio loud) AGN
- VLBI can make a positive ID / discriminate between source classes

Hallo? Any (compact) body there?



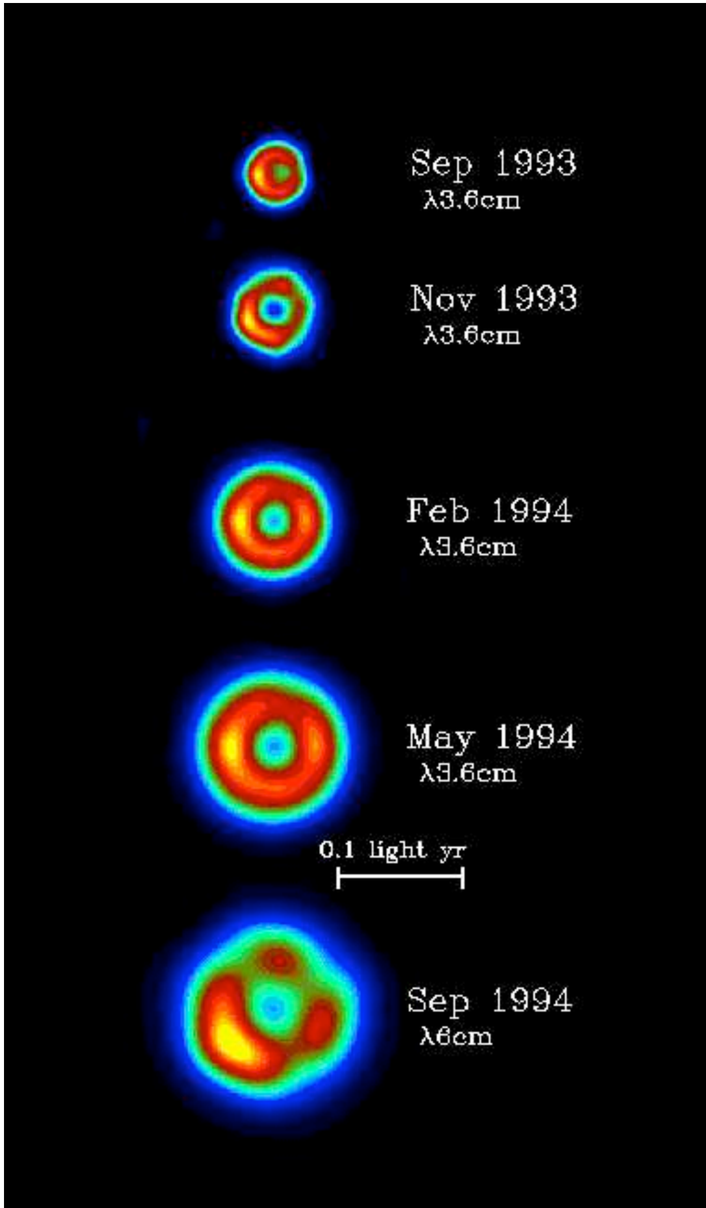
Radio AGN in the GOODS-N field; Radcliffe et al., submitted

High resolution imaging



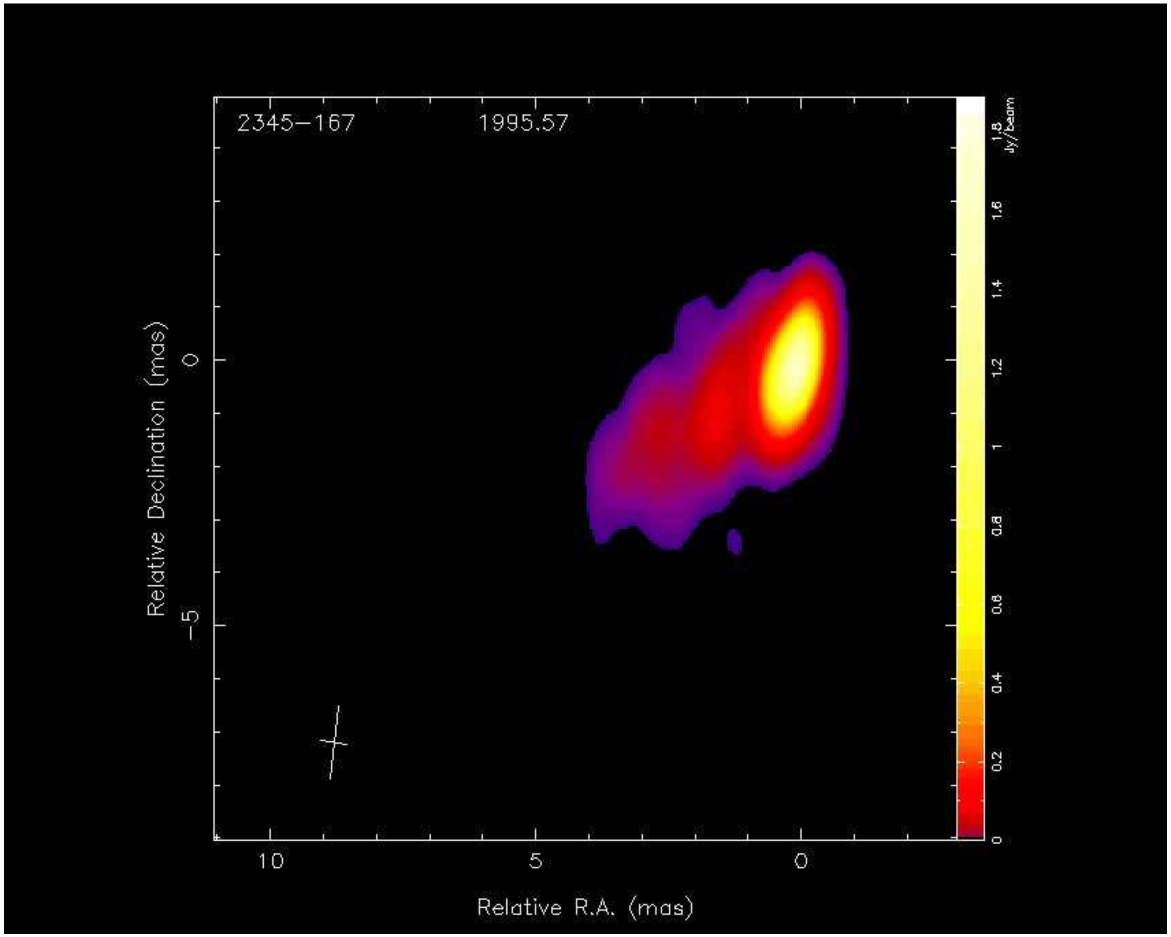
Zoom in 400,000x on Centaurus A: TANAMI / C. Muller

High resolution imaging



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

High resolution imaging



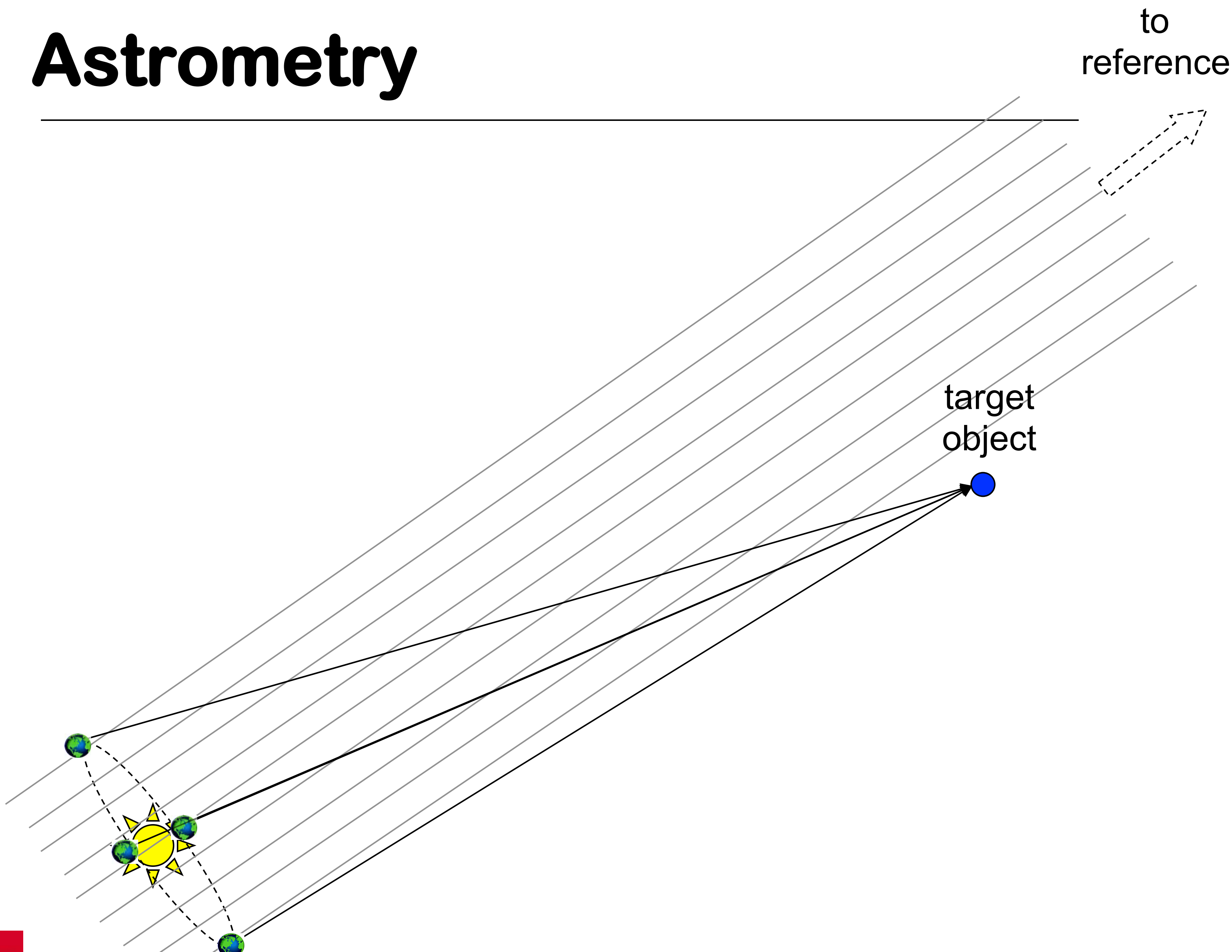
Superluminal motion in B2345-167 (MOJAVE timelapse, 15 GHz)

http://www.physics.purdue.edu/astro/MOJAVE/

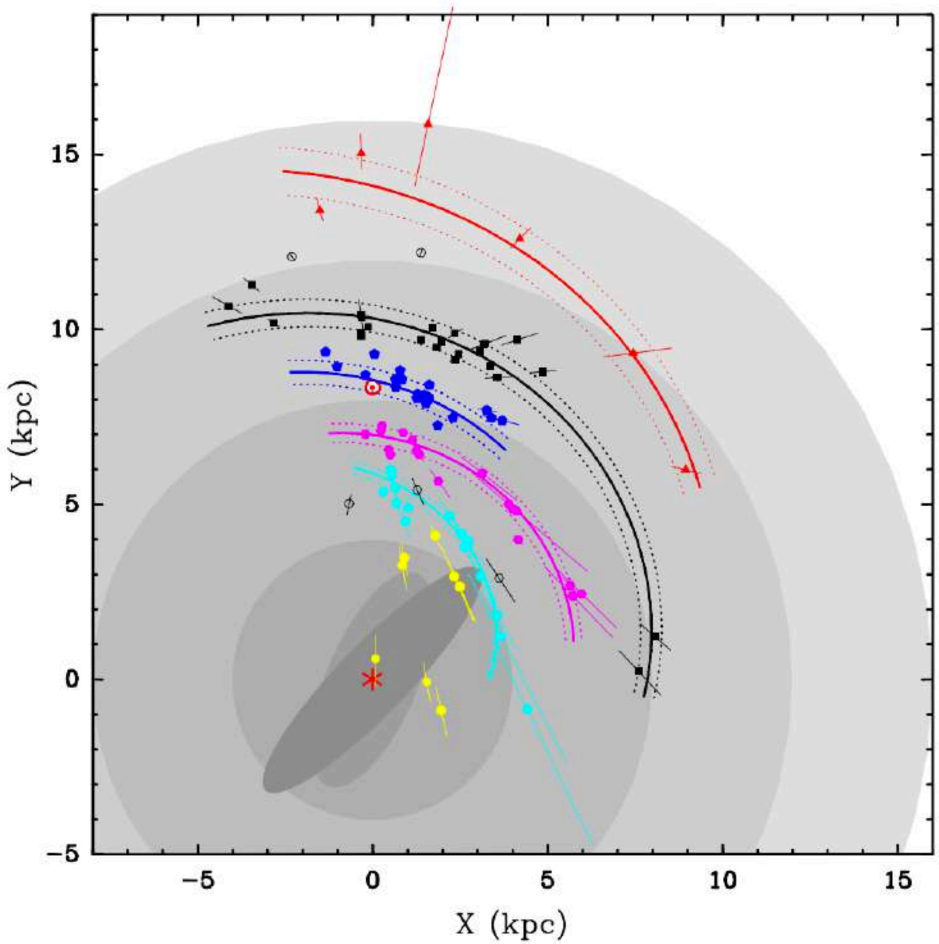
Astrometry

- With VLBI we can centroid an object's location to the ~0.01 mas level
  - *Gaia*-level accuracy (already for years, and also can access the Galactic plane!)
- Ideally unchanging point sources
- I will focus on relative astrometry: discern proper motions and parallaxes of objects across the Galaxy

Astrometry



Astrometry highlights



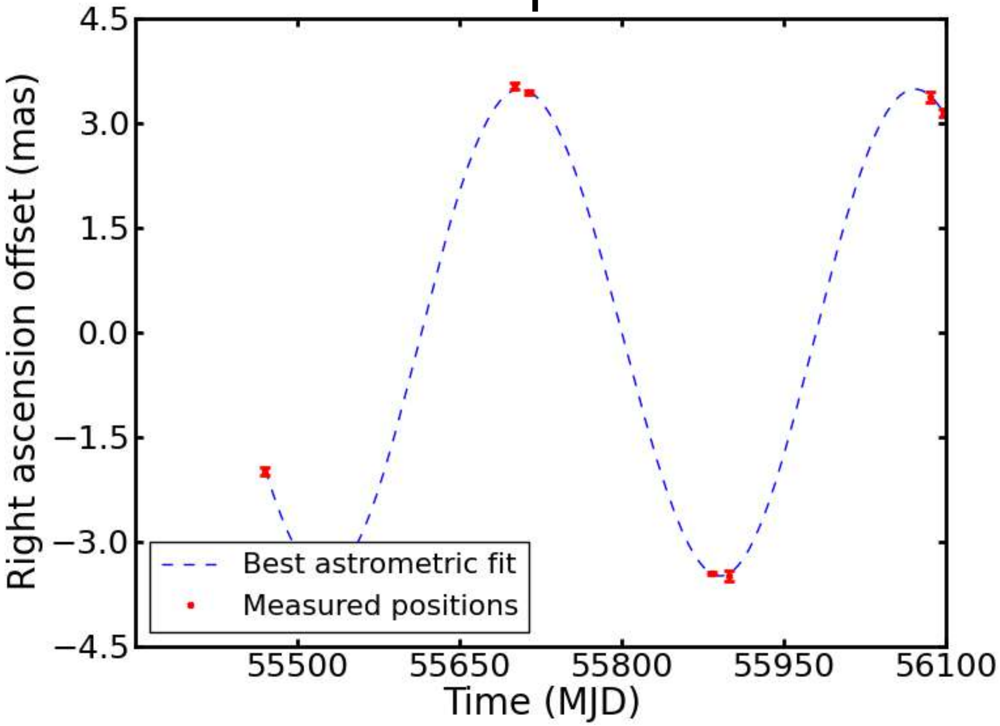
>100 parallax distances to masers around high-mass star forming regions:

- Spiral arm structure
- Distance to Galactic Center (8.34 ± 0.16 kpc)
- Galactic rotation curve (240 ± 8 km/s)

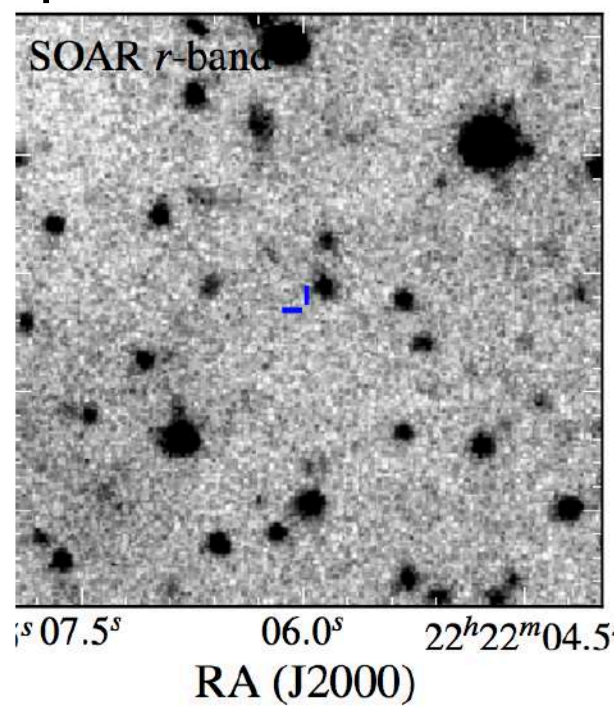
Astrometry highlights

- PSR J2222-0137 distance with 0.4% precision; interpret optical info on WD companion

Annual parallax

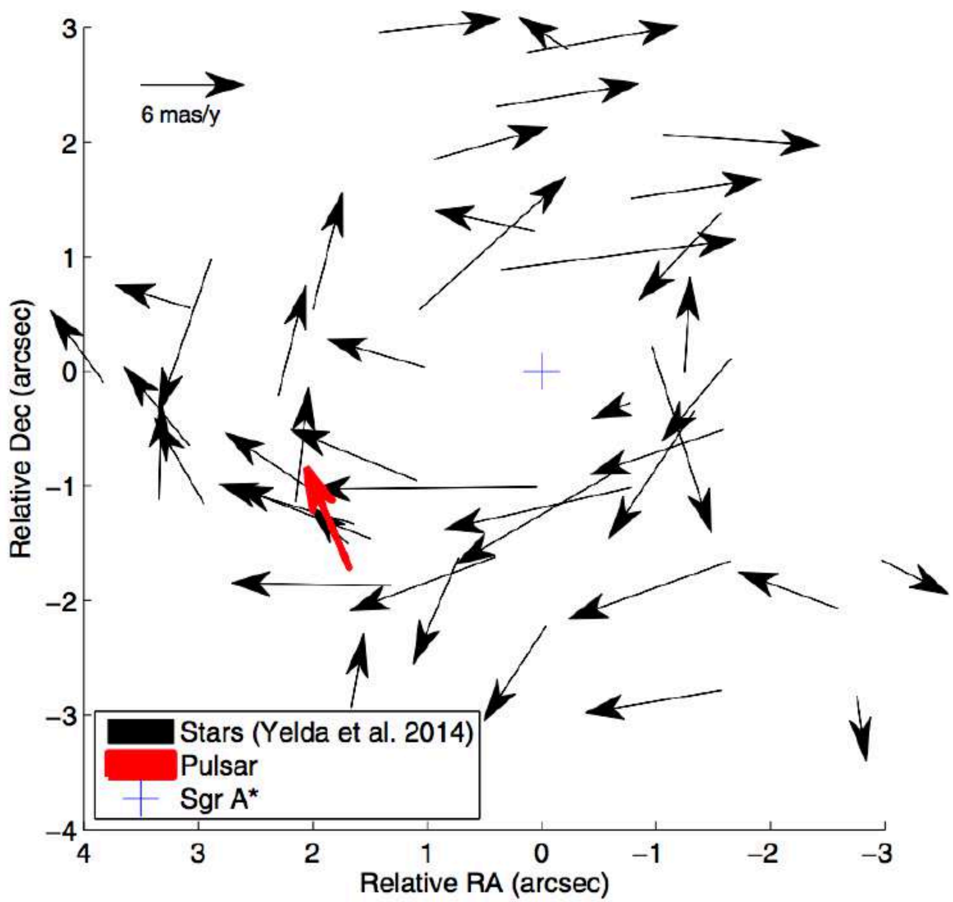


Optical non-detection



Deller et al. 2012, Kaplan et al. 2014

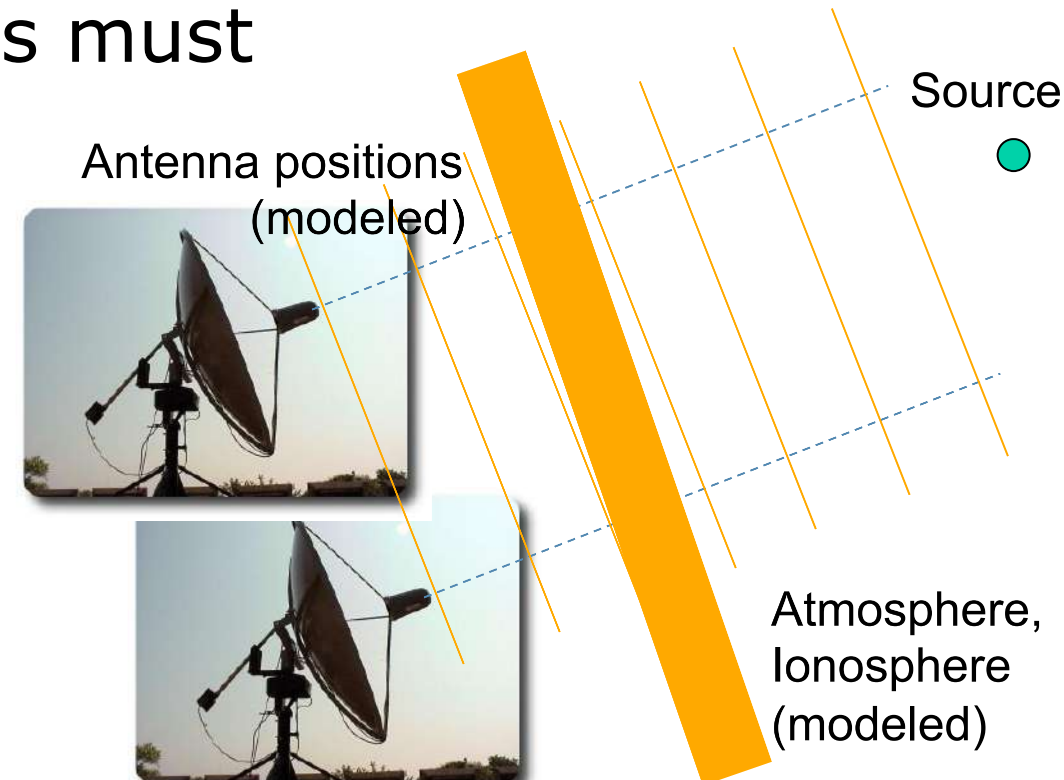
Astrometry highlights



The only known Galactic Center pulsar (PSR J1745-2900, a magnetar) shown to likely originate in the stellar disk and be bound to Sgr A* (Bower et al. 2015)

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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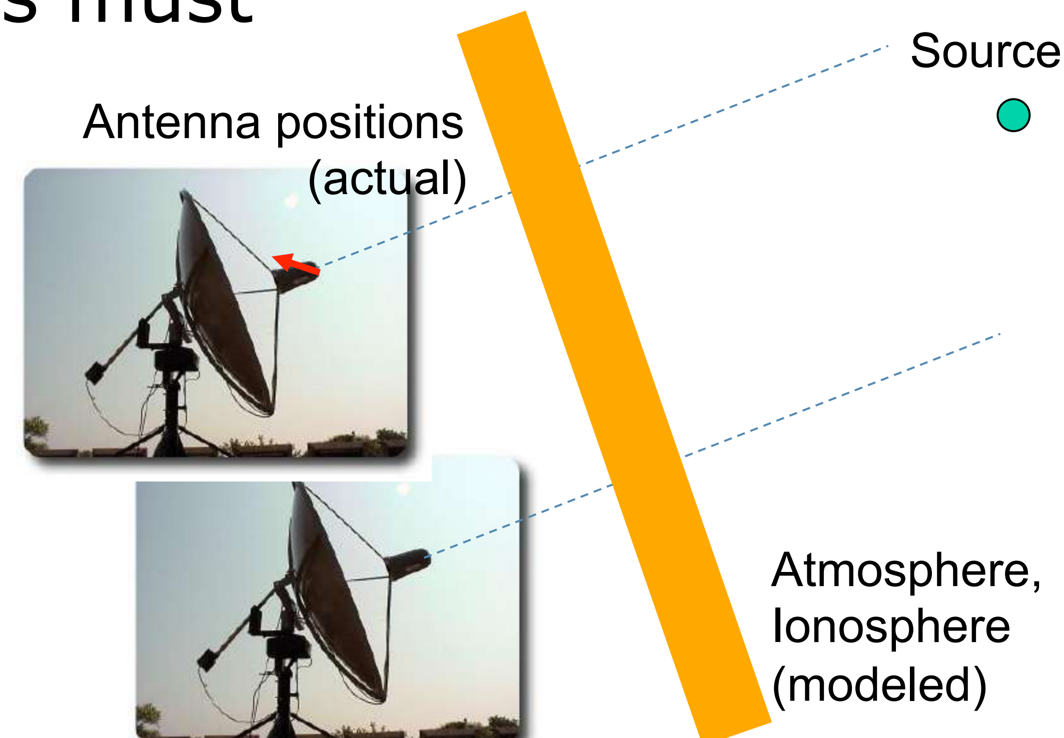

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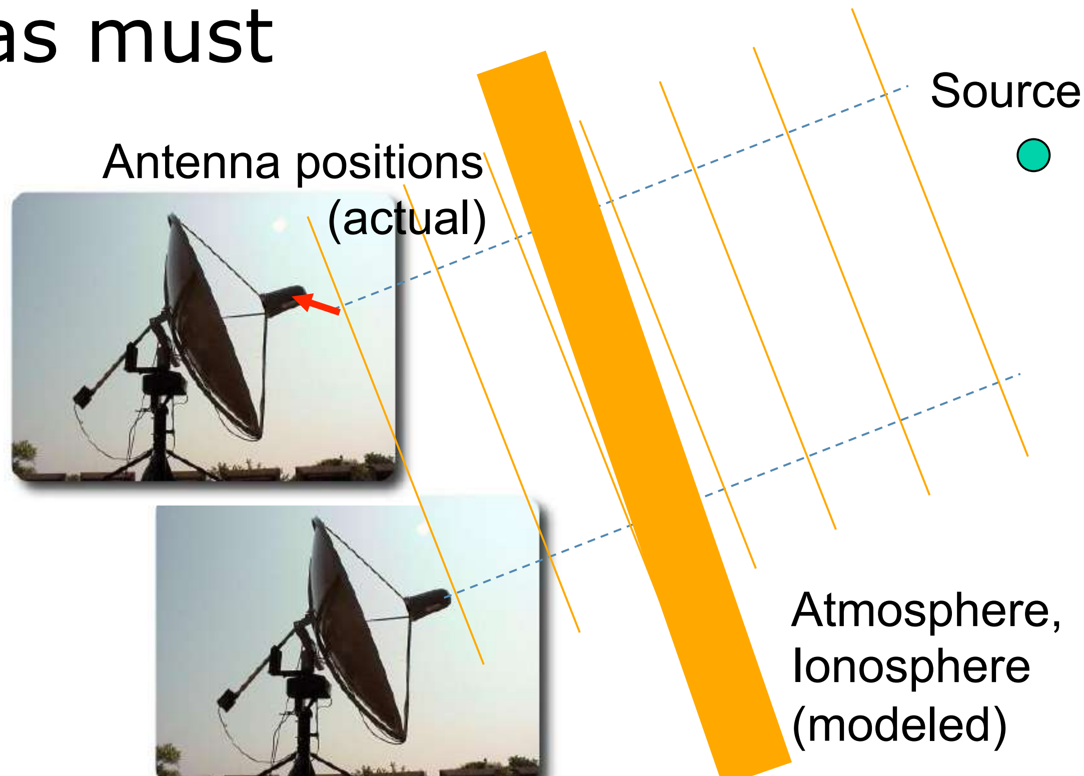

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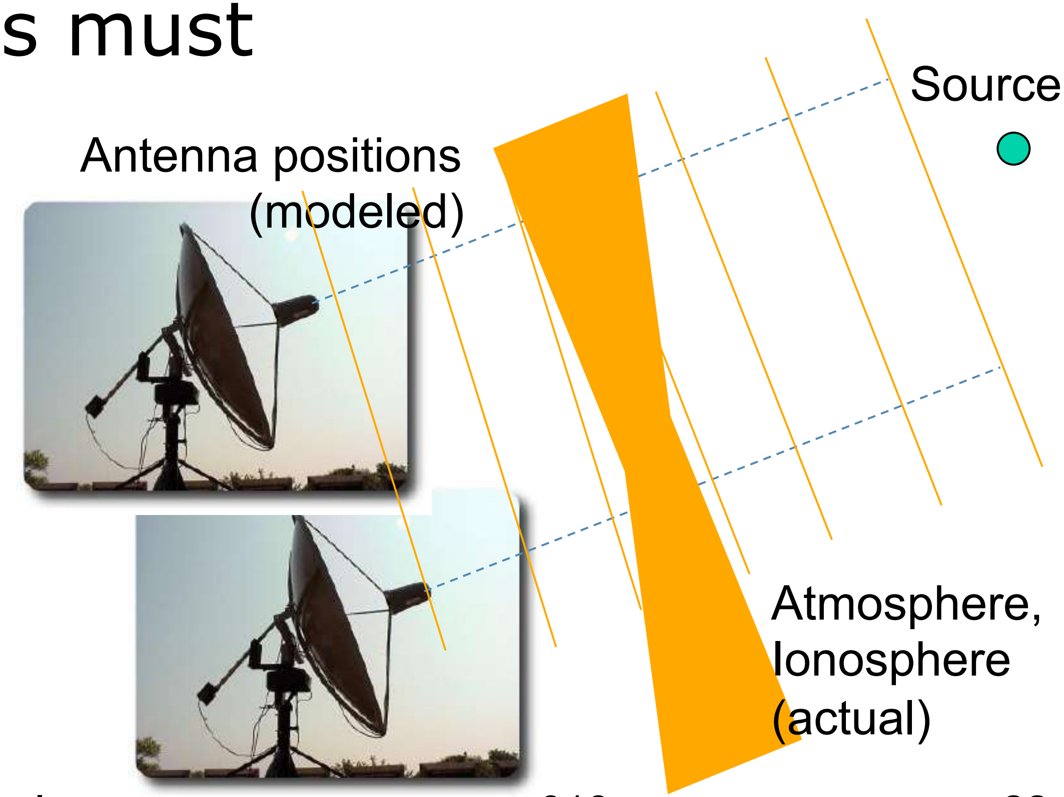


Geodetic results

- 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
- VLBI2010 / VGOS: Ambitious program to outfit new small antennas (fast slews, many sources per hour) with wide bandwidths (still good sensitivity)
  - Determine positions to 1mm in 24h

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”

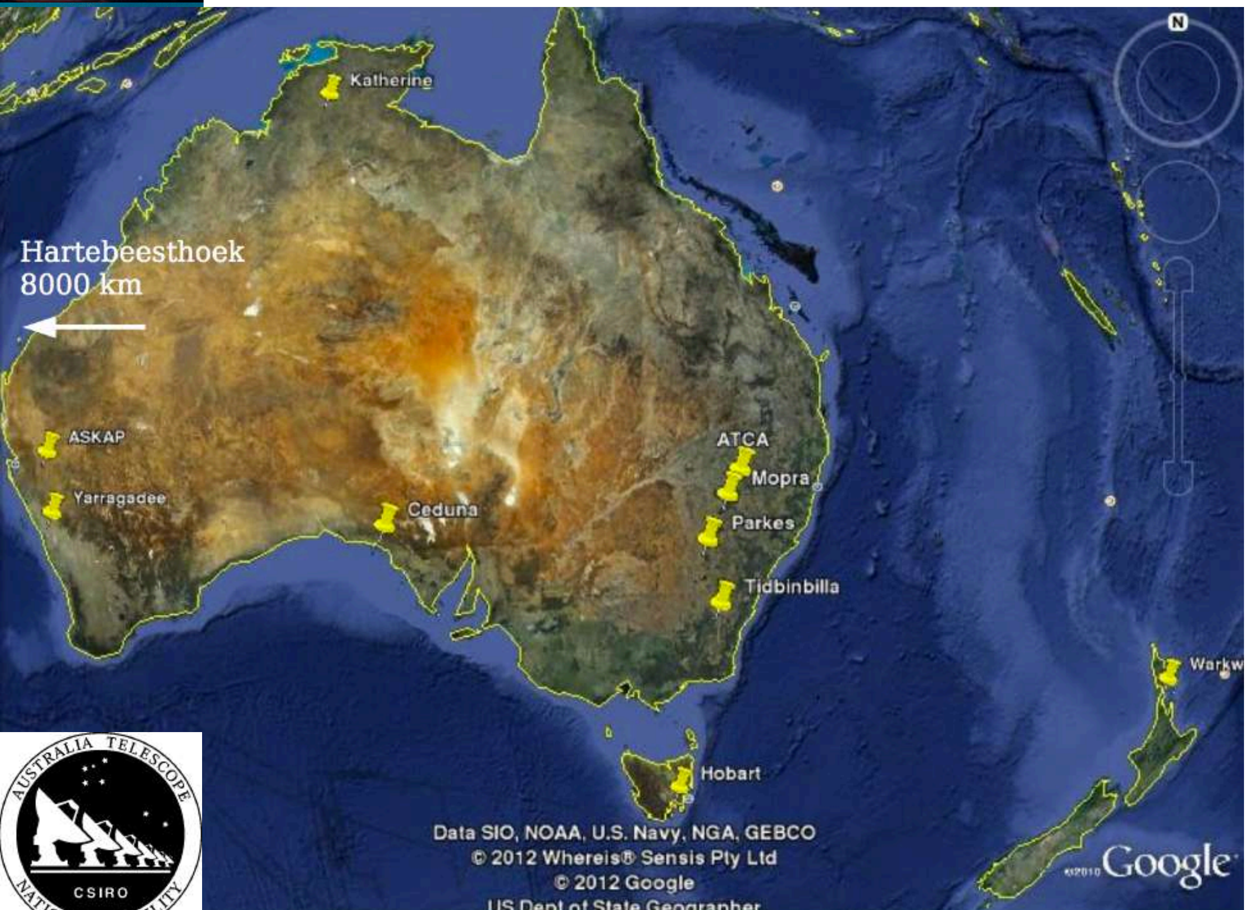
Current VLBI arrays

- The European VLBI Network (EVN)

- ~23 stations, 10m -> 100m
- 0.3 - 43 GHz
- maximum baseline ~8,000 km
- operates ~3 months/year
- plus monthly fast turnaround, out-of-session observations

Current VLBI arrays

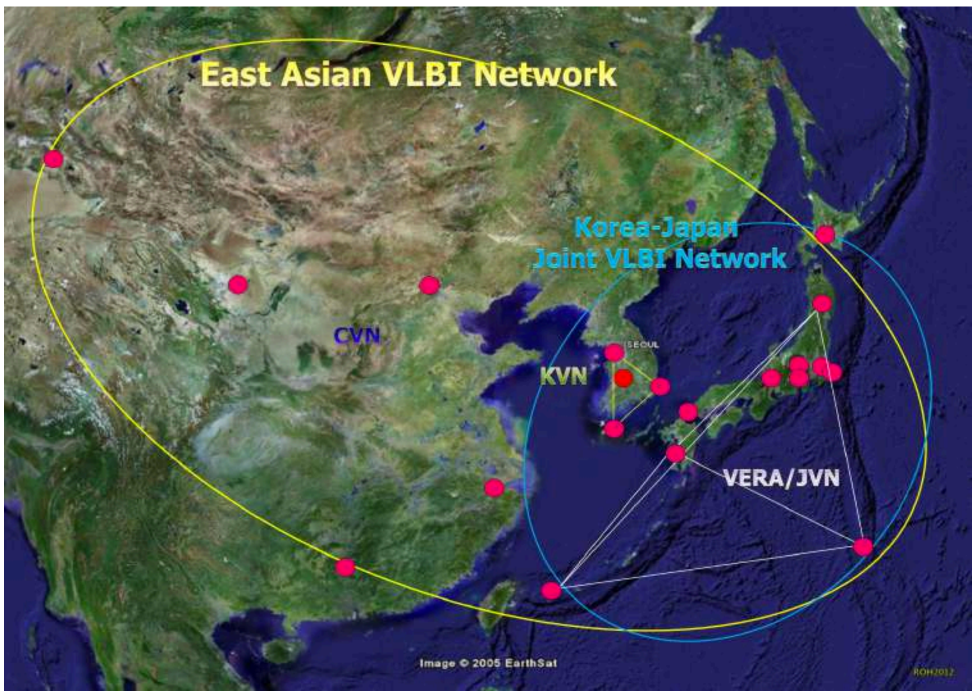
- The Long Baseline Array (LBA)



- Up to 10 stations, 22m -> 70m
- 1.3 - 22 GHz
- maximum baseline ~1,700 – 8,000 km
- operates ~3 weeks/year
- only Southern Hemisphere instrument

Current VLBI arrays

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

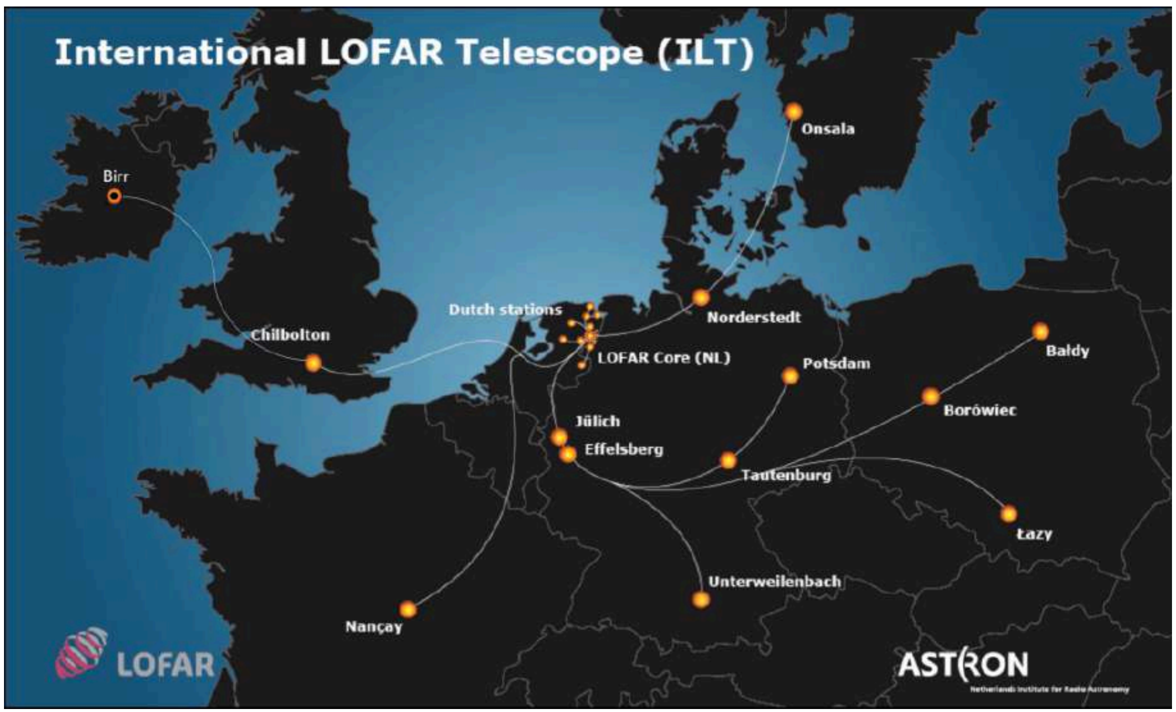


KVN: Korea, 4 dishes, 22 – 129 GHz
VERA: Japan, focus on astrometry, 2 – 43 GHz
JVN: VERA + other Japanese antennas
CVN: China, includes some larger dishes

First open call for proposals closes on June 1 2018

Current VLBI arrays

- LOFAR: Sub-arcsecond imaging at metre wavelengths (>1500 km baselines)



13 international stations (plus core and 15 more stations in the Netherlands)

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

Current VLBI arrays

- Global mm VLBI Array (GMVA):
  Sub-mas observations at 3 mm / 86 GHz

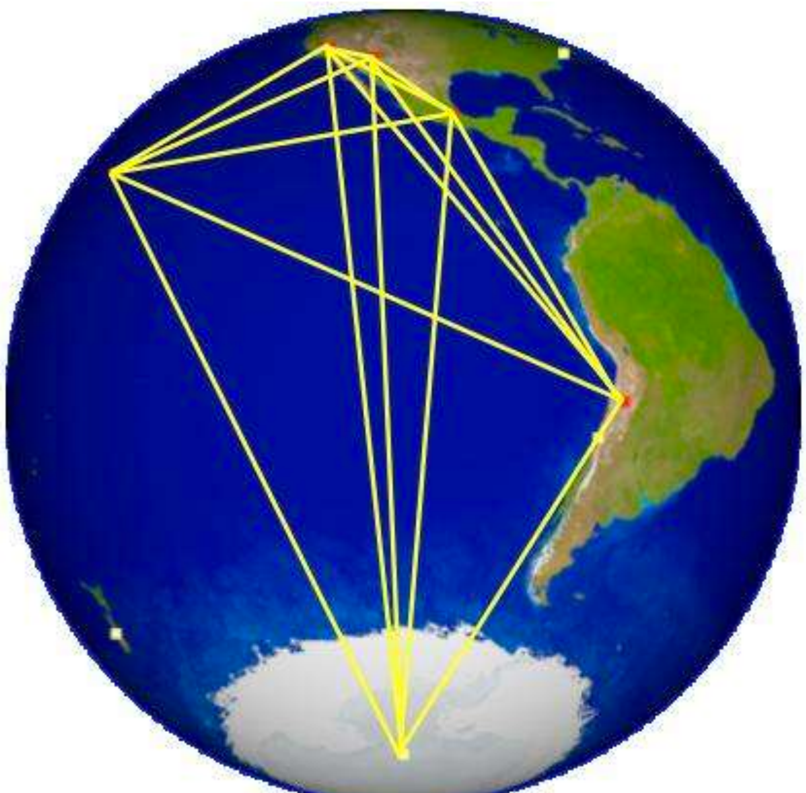
Two sessions per year. (pray for good weather!)

Unmatched sensitivity and resolution at high frequency.

ALMA now available!!

Current VLBI arrays

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

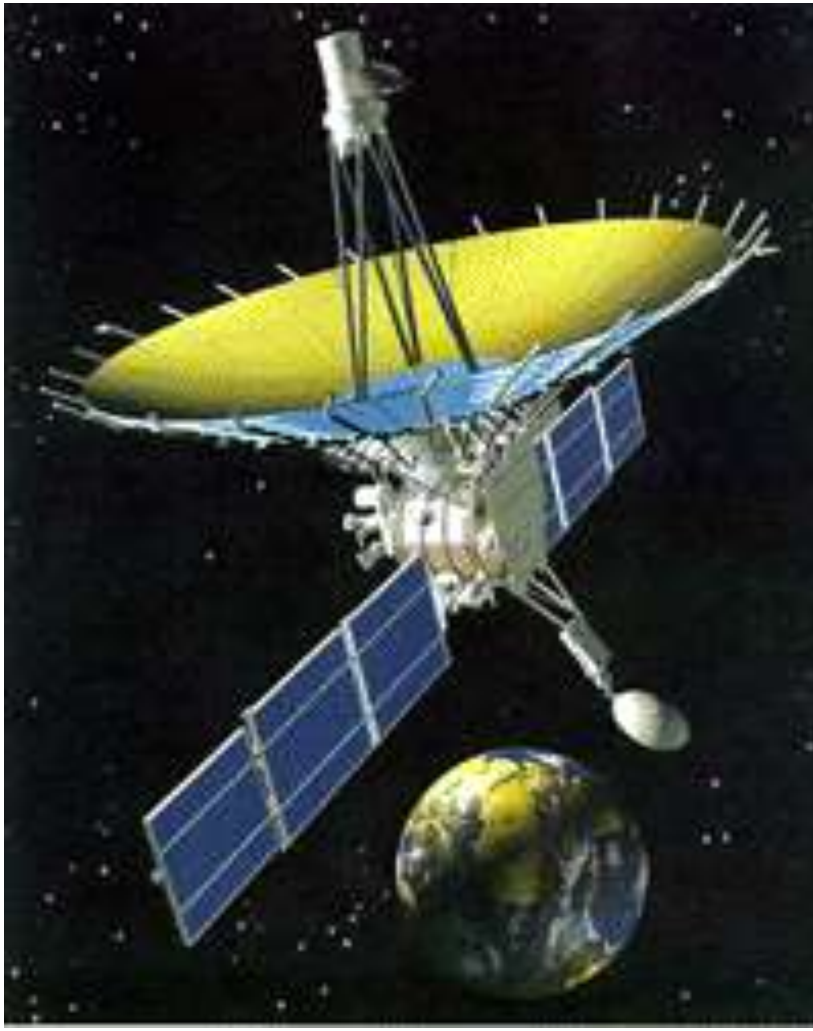


Operating at 230 and 345 GHz (and now with phased ALMA), resolution ~30 μas

230 GHz with ALMA available for proposals!

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



Historical VLBI challenges

- 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 the era of 2 Mbps tapes is long gone… At low frequencies, we are now constrained by the front-end just like everyone else.
- The VLBA + HSA does 2 Gbps (256 MHz, dual pol): beats JVLA point source sensitivity at 1.4 GHz. EVN has tested 4 Gbps (VLBA also plans), EHT 64 Gbps!
  - 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 (VLA, ALMA)
- Same solution: switch between source and nearby calibrator at a sufficiently rapid interval (sensitivity helps)

#4: Unreliable imaging

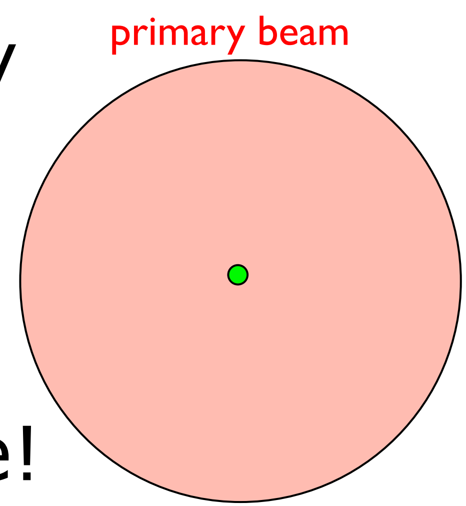
- Mostly a thing of the past (when phase stability was poor)
- Nowadays, set up your observations right (sufficient calibrators) and getting dynamic ranges >10,000 is easy
- Still two remaining problems:
  - Often fewer antennas (10 VLBA vs 27 VLA)
  - Layout is often not optimal (antenna placement determined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

#6: Limited field of view

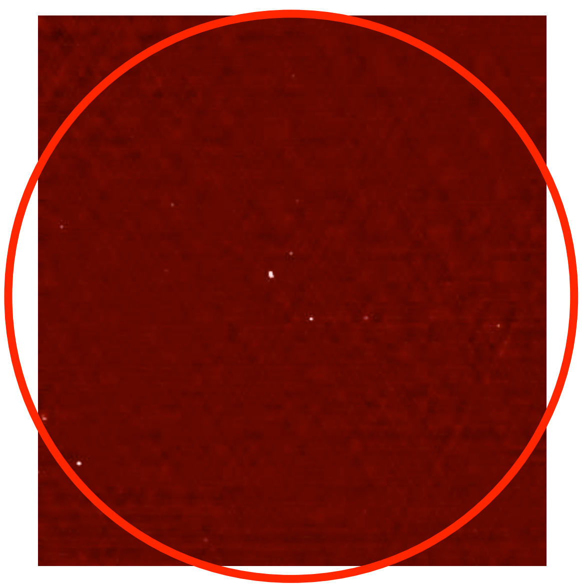
- Time smearing and bandwidth smearing are intense because of high fringe rate
- Older correlators had output rate restrictions, field of view ~arcseconds
- Even if correlator can make necessary visibility dataset, it will be **HUGE**
- And: image is 99.9999999% noise!

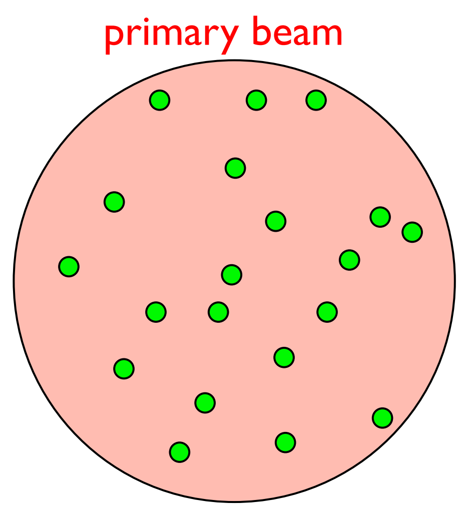


12h VLBA observation
Small field (5”):
5 GB visibiilities
64 MB image
Full primary beam:
30 TB visibilities
10 TB image

#6: Limited field of view

- Cool 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

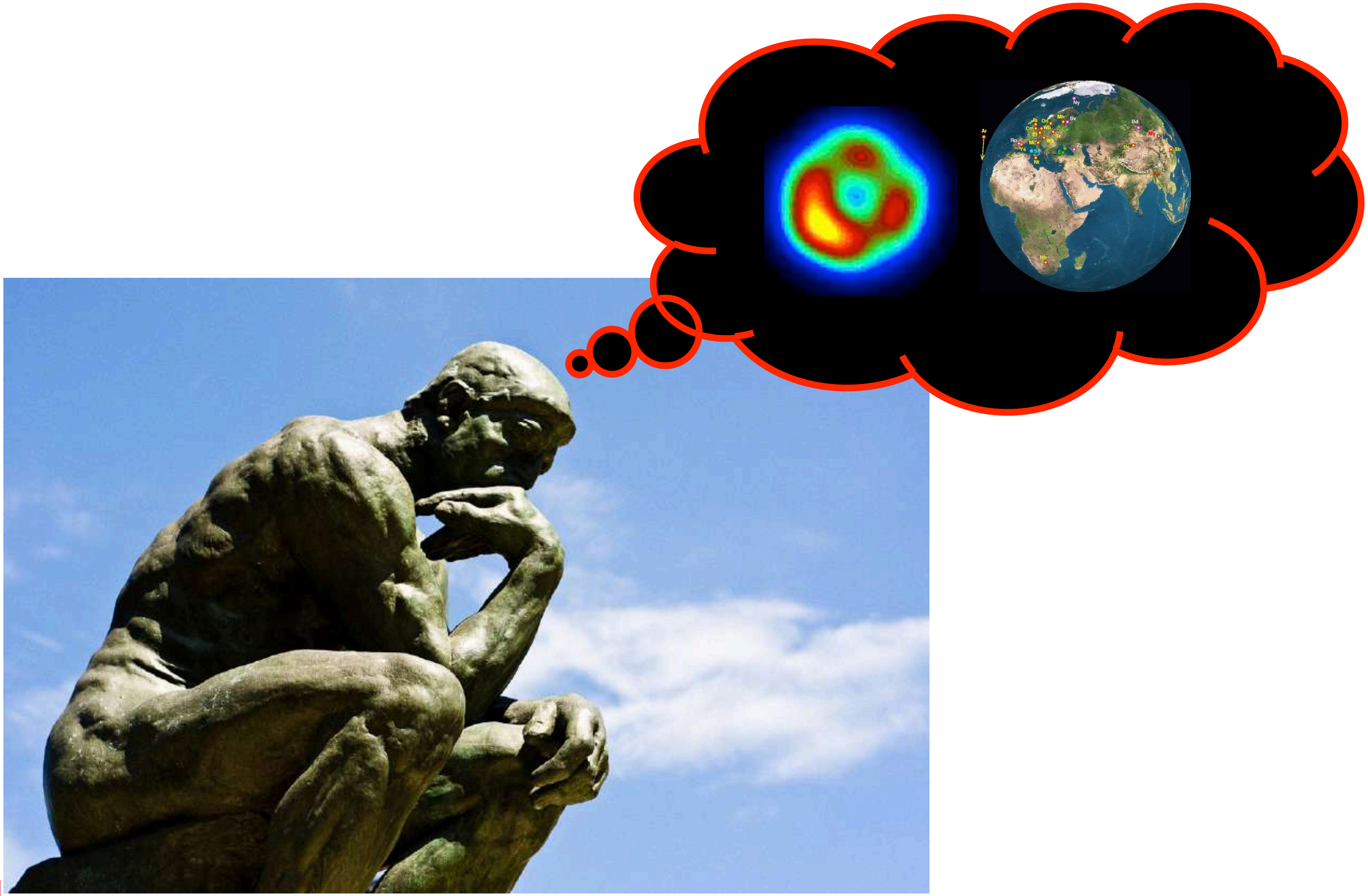




12h VLBA observation

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

The practicalities of VLBI



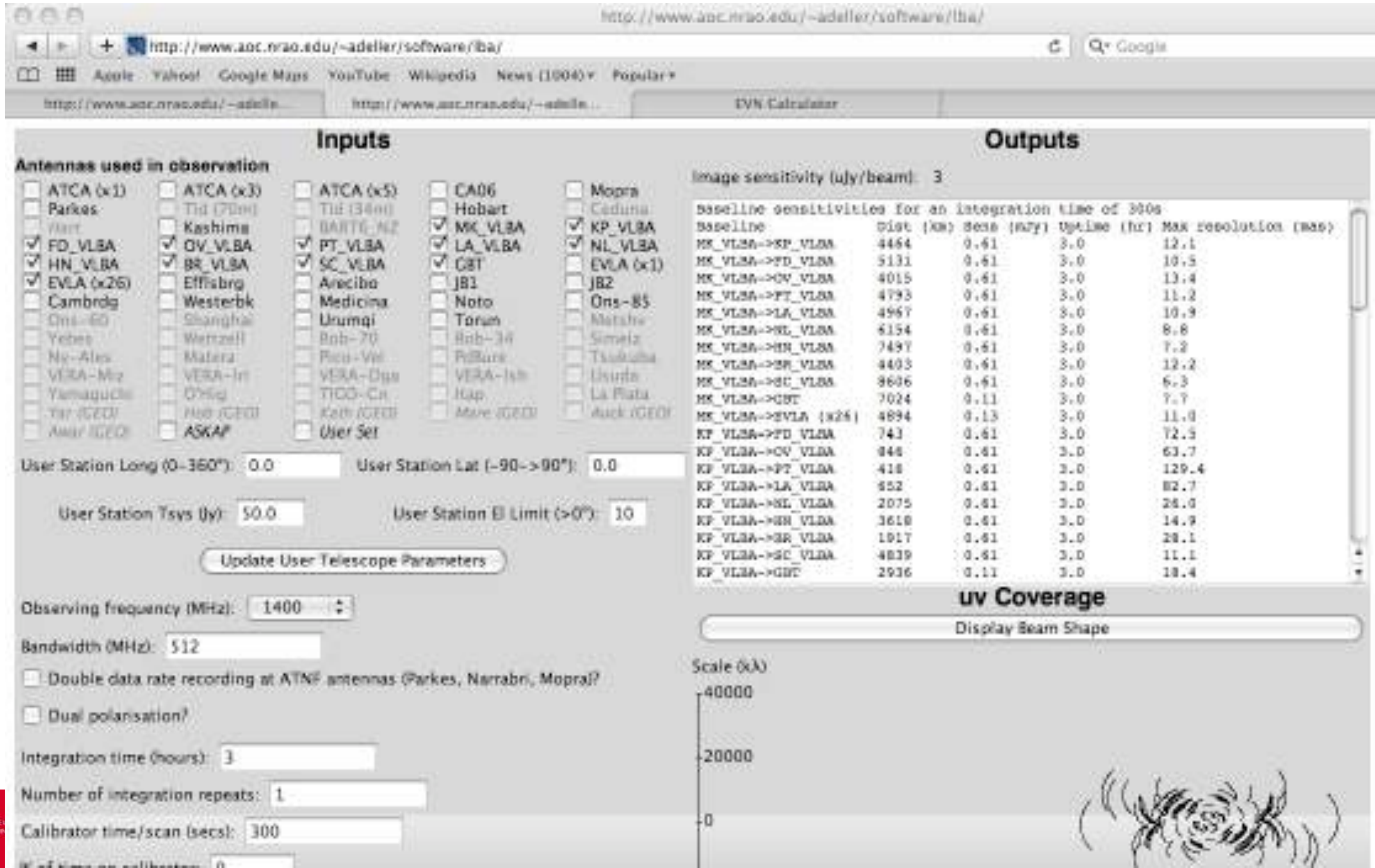
The practicalities of VLBI

- 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/ for calculating uptime, sensitivity, resolution
  - Or http://www.evlbi.org/cgi-bin/EVNcalc
  - 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/iba/
EVN Calculator
Inputs
Outputs
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)
Efflsbrg
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
Image sensitivity (uJy/beam): 3
Baseline sensitivities for an integration time of 300s
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
- VLBA/HSA/GMVA February 1, August 1
- EVN February 1, June 1, October 1
- LBA June 15 and December 15
- Director’s Discretionary Time for out-of-cycle rapid response
- Standard info: **where** (sources), **how** (resource setup) and **when** (duration, date constraints); help available

VLBI proposals

Scheduling

- The program SCHED 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 assist with the observations (a great way to learn interferometry!)

Data reduction (calibration)

- AIPS is the primary package for VLBI calibration; CASA should soon be an alternative (key steps now beta testing)
- 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 1 Gbps now, 2 Gbps EVN subset
  - 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

- Existing facilities: more bandwidth increases, data processing innovations
- m-VLBI: LOFAR imaging is new/unique
  - Need better calibration algorithms
- mm-VLBI: phased ALMA here
  - Crazy mm sensitivity!
- cm-VLBI: the traditional VLBI band, but new sensitive telescope (phased SKA-mid) won’t be in an ideal location
  - Further in the future: ngVLA

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