


Radio Astronomy

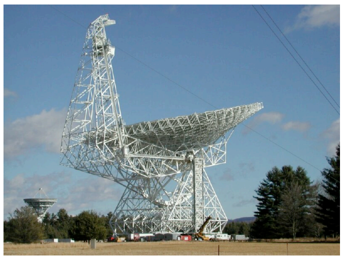
Lecture 10

The Techniques of Time-Domain Radio Astronomy II: High time resolution with an interferometer

Lecturer: Jason Hessels (j.w.t.hessels@uva.nl)

A1.20 - May 13th, 2015



- Welcome to Lecture 10 of Radio Astronomy, in which we'll be discussing how interferometers can be used to produce high-time-resolution data (as opposed to visibilities for standard interferometric imaging).

Observing Proposals

How's it going???

Make sure you consult with your "mentor" this week in case you have questions or need more feedback before your presentation.

Presentations: please also consider these as a) an opportunity to get more feedback to incorporate in your final written proposal and b) a chance to learn more about other science areas.

The Home Stretch...

- May 13th (Today): VLA practicum finishes (due May 15th).
- May 18th: Last lecture.
- May 18th: Start *short* practicum on pulsar data analysis (using LOFAR data).
- May 19th: 9-13h: Presentations of observing proposals.
- May 20th: Pulsar practicum due.
- May 22nd: Written observing proposals due.
- May 27th: 13-15h: final exam.

Lecture outline

- Motivation for high time resolution with an interferometer
- Beam-forming with an interferometer
- **Break**
- Pulsar and “fast transient” searches
- Fast imaging and uv-plane techniques
- Astrometry and pulsar distances

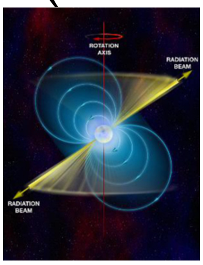
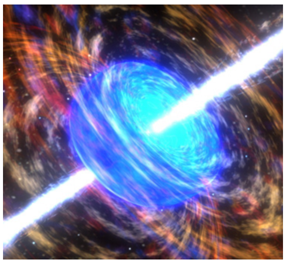
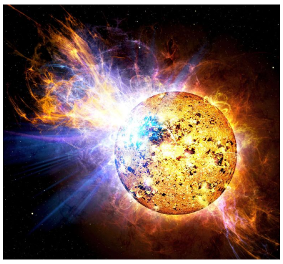
- The majority of the time, radio interferometers are used to make interferometric images, as you have done during the VLA imaging practicum.
- However, if one sacrifices imaging capability for time resolution, it’s possible to record high-time-resolution data within the same data rate budget.
- This has various interesting scientific applications, as we’ll see in this lecture.

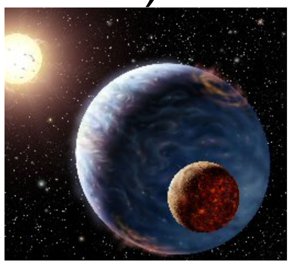
Motivation for high time resolution with an interferometer

• If we care more about time resolution than angular resolution then why not just use a large single-dish radio telescope? Surely that must be easier than using an interferometer, right?

What is “high time resolution” and why do we need it?

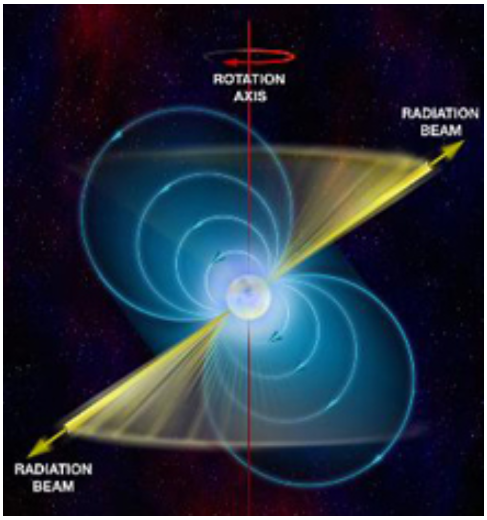
- Here, “high time resolution” means t_samp < 1s.
- Several astronomical source classes are known to vary on this timescale, e.g.: pulsars, magnetars, the Sun, (exo)planets, flare stars... possibly also jets in accreting systems.
- Explosive, dynamic events, a.k.a “fast transients”.
- Huge potential discovery space for new phenomena (microsecond - second timescales not well explored).



- Exploring the variability of the “radio sky” on the short timescales is an interesting new avenue of research (cf. “fast radio bursts”).
- Because such observations are technically challenging it means that little is known in this astronomical parameter space. If we’re lucky there’s interesting phenomena to discover.

You've already heard a lot about pulsars



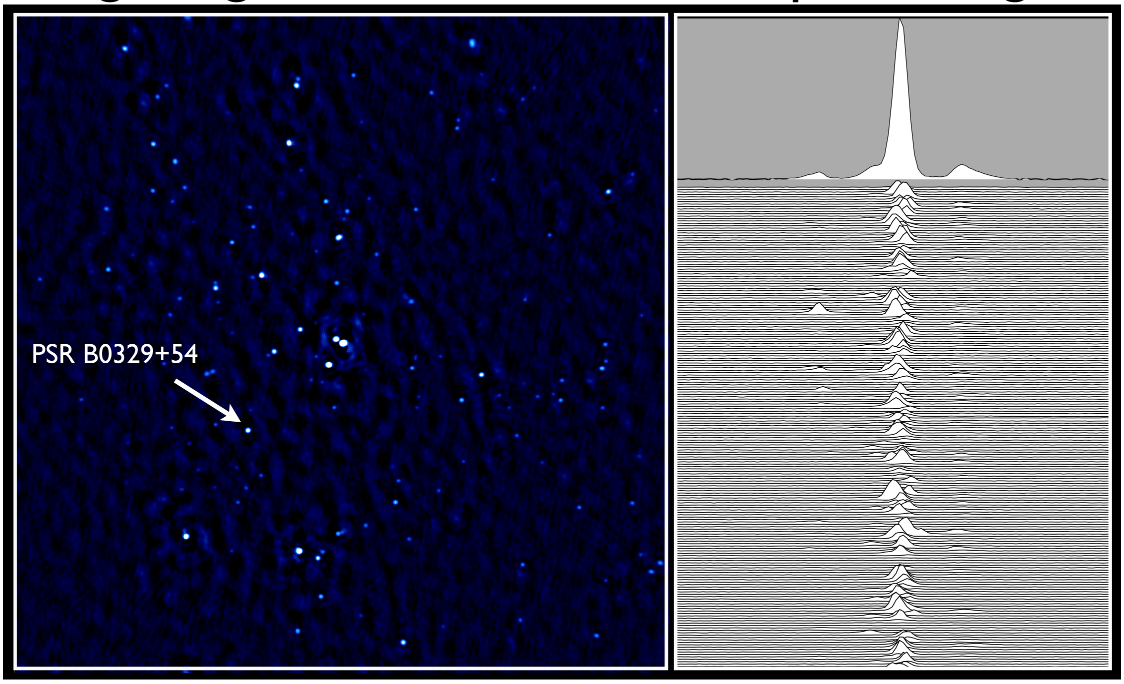
...so I shouldn't have to tell you that they require high time resolution data.

- For example, for a millisecond pulsar, the whole pulse period is only a few milliseconds and the pulse itself might only be 100 microseconds wide.
- With 1-s interferometric images, there's no way you could detect the pulsations, though you might be able to see a continuum source in an image *if* the pulsar is bright enough.
- Weak pulsars might only be visible when you can resolve the pulse in time. If you average it out over the full pulse period then it might be buried in the noise. We'll come back to this when we discuss gating near the end of the lecture.

Simultaneous Imaging and Pulsar Obs.

High angular resolution | 1-pixel image

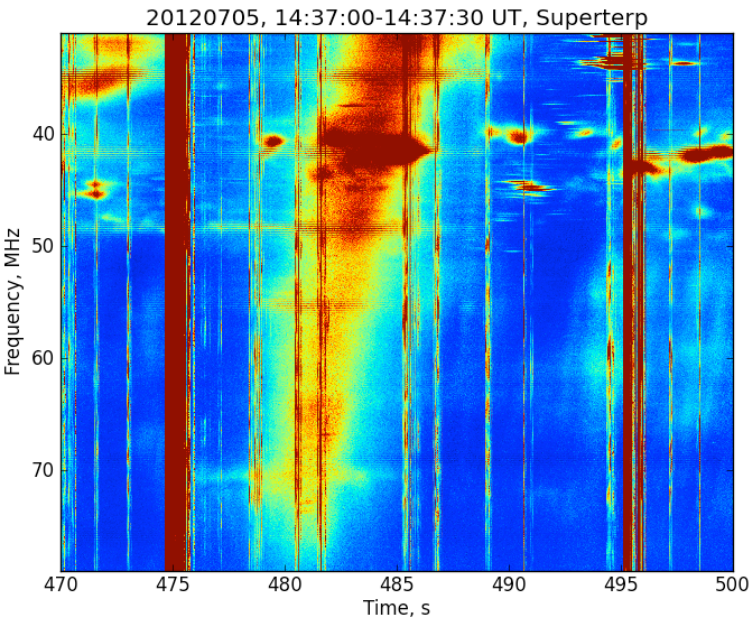
LOFAR HBA data



1-second time resolution | 1-ms time resolution

• It is sometimes possible to detect pulsars in radio continuum imaging. There are various applications if one can do this. For some science cases, you might want to make a continuum and pulsed detection at the same time.

Dynamic Spectra of Solar Bursts
(not an image)



Fallows

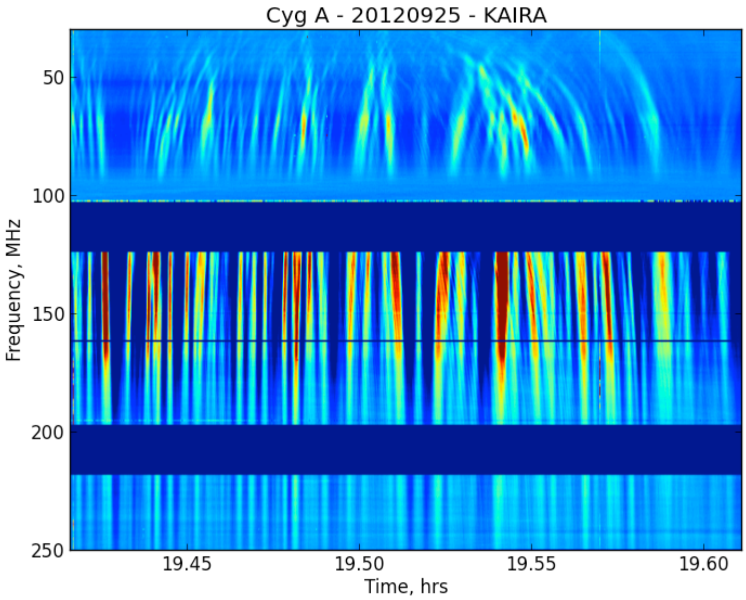
LOFAR LBA data

- Type-III solar bursts.
- Emission goes from high to low frequency.
- Vertical lines are from a thunderstorm at the same time. (radio studies of thunderstorms are also interesting, though not astrophysics)

• "Type-III' solar radio bursts. These appear in a dynamic spectrum as a rapid drift from high to low frequencies. Their source is usually above an active region on the Sun and they arise from electrons being accelerated within a solar flare and propagating along magnetic field lines through the solar corona and sometimes out into interplanetary space.

• Also at this time, there was a powerful thunderstorm passing over the region. The strong full-bandwidth emission seen in the image is most likely to be due to lightning flashes. Evidently a thunderstorm is no barrier to observing the Sun!

Ionospheric Scintillation
(again a dynamic spectrum; not an image)



Fallows LOFAR LBA+HBA data

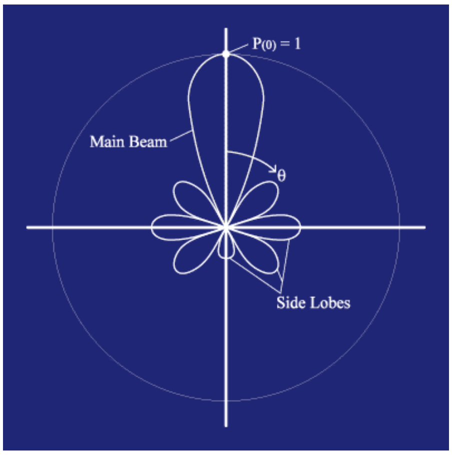
- Can use a bright background radio source to study the intervening material through processes like scintillation.
- By having widely separated elements in an interferometer it's even possible to constrain or measure the characteristic scales of the intervening material.

- The scintillation of point-like radio sources arises from the diffraction and refraction of light due to density variations in the line-of-sight between the source and the observer. Usually, scintillation occurs due to one or more distinct regions in the line-of-sight.
- Shown: ionospheric scintillation towards Cygnus A as seen by LOFAR.
- This offers new methods of studying the plasma structures giving rise to the scintillation.

Wait, what about imaging?

Comparison with Single Dish

- Roughly speaking, an interferometer provides a multi-pixel image with a field-of-view dictated by the primary (individual antenna) field-of-view.
- A single dish offers basically a 1-pixel image of the sky, though remember that the main-lobe and side-lobe pattern can be complicated.
- At high time resolution, we often use an interferometer as a synthesized single-dish, though many "1-pixel" images can be made within the primary field-of-view.



But why not just make a bunch of 1-ms images?

• **QUESTION: WHY DON'T WE JUST MAKE IMAGES EVERY 1ms SO WE CAN HAVE GREAT TIME AND SPATIAL RESOLUTION?**
• If both high angular resolution and high time resolution are interesting, then why don't we just make interferometric images at very high cadence, e.g. once every millisecond.
• One reason is that the data rate would become very high.
• Another reason is that the instantaneous u-v coverage might be too poor to get reasonable images on short timescales.
• Yet another reason is that it might be very difficult to calibrate very short exposures for making images (not enough flux to calibrate).

High-time resolution with an interferometer

Data rate, e.g. LOFAR

- 48 stations - i.e. 1128 baselines
- 256 0.8-kHz chan/subband
- 488 195-kHz subbands
- 1 complex visibility (amplitude and phase) represented in 64 bits (8 bytes)
- 4 polarization products (Stokes I,Q,U,V)
- 1-second visibility dump time

$$N_{\text{baselines}} = \frac{N_{\text{Ant}}(N_{\text{Ant}} - 1)}{2}$$

15TB/hr!

$$\text{Data rate} = \frac{N_{\text{chan}} N_{\text{sub}} N_{\text{base}} N_{\text{pol}} N_{\text{bits}}}{t_{\text{samp}}} = \frac{256 * 488 * 1128 * 4 * 64}{1} = 34\text{Gb/s}$$

- Let's quantify what kind of data rates we're talking about.
- The above calculation gives the data rate for a LOFAR imaging observation.
- Even with 1-s dump time for the images, we're already producing 34Gb/s of data, which is equivalent to 15TB (terabytes!) of data an hour.

High-time resolution with an interferometer

But for pulsars and other "fast transients" we need < 1ms time resolution - at least!

Yeah, right...

$$\text{Data rate} = \frac{256 * 488 * 1128 * 4 * 64}{< 0.001} > 34000\text{Gb/s}$$

Instead we form "tied-array" beams (effectively the synthesized beam) in particular directions:

$$\text{Data rate} = \frac{N_{\text{chan}} N_{\text{sub}} N_{\text{beam}} N_{\text{pol}} N_{\text{bits}}}{t_{\text{samp}}} = \frac{16 * 488 * 1 * 4 * 64}{0.001} = 2\text{Gb/s}$$

In a certain sense, we've traded field-of-view for time resolution.

- 1-ms images with LOFAR would produce ridiculous amounts of data.
- Thus, instead of creating visibilities for each of the baselines, we sum all of the station beams together to form "tied-array" beams, which are comparable to the synthesized beam relevant to the imaging process.
- Having 1 tied-array beam (1 signal instead total instead of 1 signal per baseline) greatly reduces the data rate and allows us to increase the time resolution.
- However, a single tied-array beam offers a limited field-of-view (much smaller than the primary beams of the array elements). So, to recover field-of-view for a wide-area survey we'd need to create many tied-array beams (which again increases the data rate). There's no such thing as a free lunch...

High-time resolution with an interferometer

Advantages

- Higher angular resolution: great for localization and rejecting sky background.
- Each element has a wide field-of-view: survey speed is high if one can process the entire field-of-view (and form many "tied-array" beams).
- Multi-beaming for interference rejection (astronomical signals should just be in one beam, while RFI might be in many).
- Can afford to build a bigger total collecting area.

- High-time-resolution radio astronomy is in many senses easier done with a single-dish. However, there are advantages to using an interferometer.
- Interest in doing this kind of work with interferometers is increasing because computing power has reached a level to make it more feasible (i.e. previously we simply could not handle the required data rates).

High-time resolution with an interferometer

Disadvantages

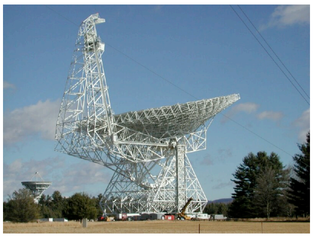
- Very restricted field-of-view unless many beams can be synthesized (tied-array beam becomes narrower as the array becomes more spread out).
- Potentially many data streams and much higher data rate compared with a single-dish.
- Careful calibration required to "phase-up" the array.
- Potentially complicated instantaneous sidelobe pattern.

- ...and here are the disadvantages.

But ultimately, we don't have much choice because...

To build much bigger telescopes, we need to move to interferometers

Single Dishes



GBT

Parkes

Arecibo

Interferometers

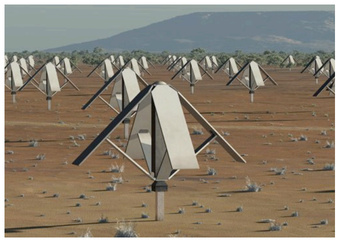
GMRT

WSRT

LOFAR

SKA

SKA Mid



SKA Low

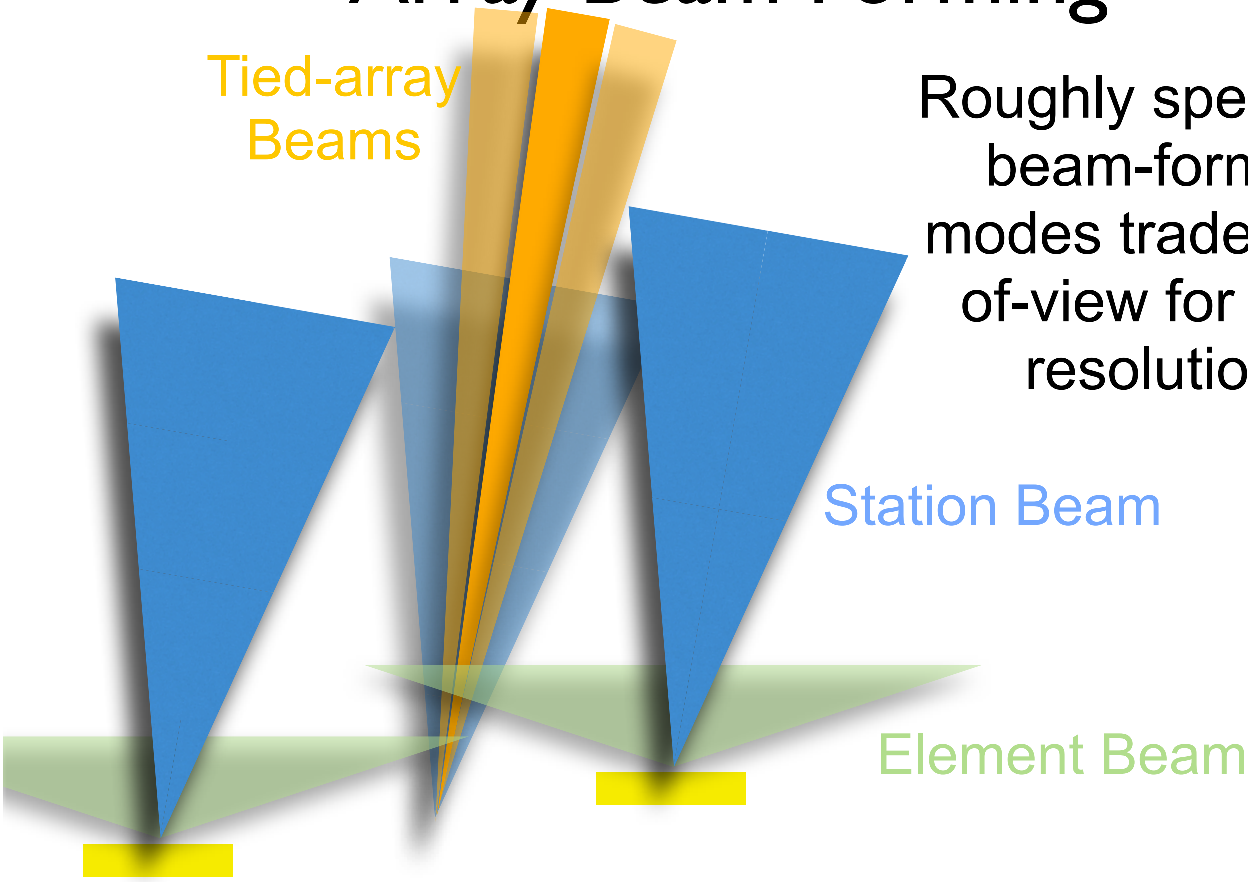
SKA Aperture Array

• Current single dishes are basically at their maximum possible size (the mechanical properties of steel make it basically impossible to build sometime significantly larger than the 100-m Green Bank Telescope).
• To make the next leap in collecting area, we essentially have to use multiple collecting areas that are coherently combined.
• One caveat: in China a 500-m Arecibo-like dish is being built! The only problem: like Arecibo, this dish can only see a restricted part of the sky.

Beam-forming with an interferometer

• Let's now discuss some terminology and different ways of adding (or not) the elements in an interferometric array.

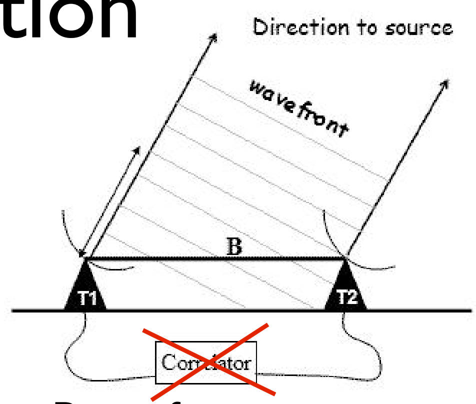
Array Beam Forming



Roughly speaking, beam-formed modes trade field-of-view for time resolution.

- Tied-array beams are the coherent sum (in phase addition) of the various array elements.
- The above diagram is particularly appropriate to the LOFAR situation: each antenna (i.e. "element") has a wide beam shape; the "station beams" (i.e. the sum of all the antennas in a station) has a smaller field-of-view but a higher sensitivity; the coherent sum of many station beams is a "tied-array" beam.
- Important caveat: remember that when we say "field-of-view" we of course mean just the main lobe of the beam pattern. There will still be side-lobes and some sensitivity all over the sky. These side-lobes can be problematic for interpreting the data.

Incoherent Antenna Addition



Beamformer: *sum*

- Collect the various antenna voltage streams.
- Square the signal to produce a total power timeseries from each antenna.
- Correct for geometrical delay between the antennas and the pointing direction on the sky.
- Sum the various streams.
- Produces a single field-of-view equal in size to the primary beams.
- Sensitivity scales with the square-root of the number of antennas added (assuming they are all identical).

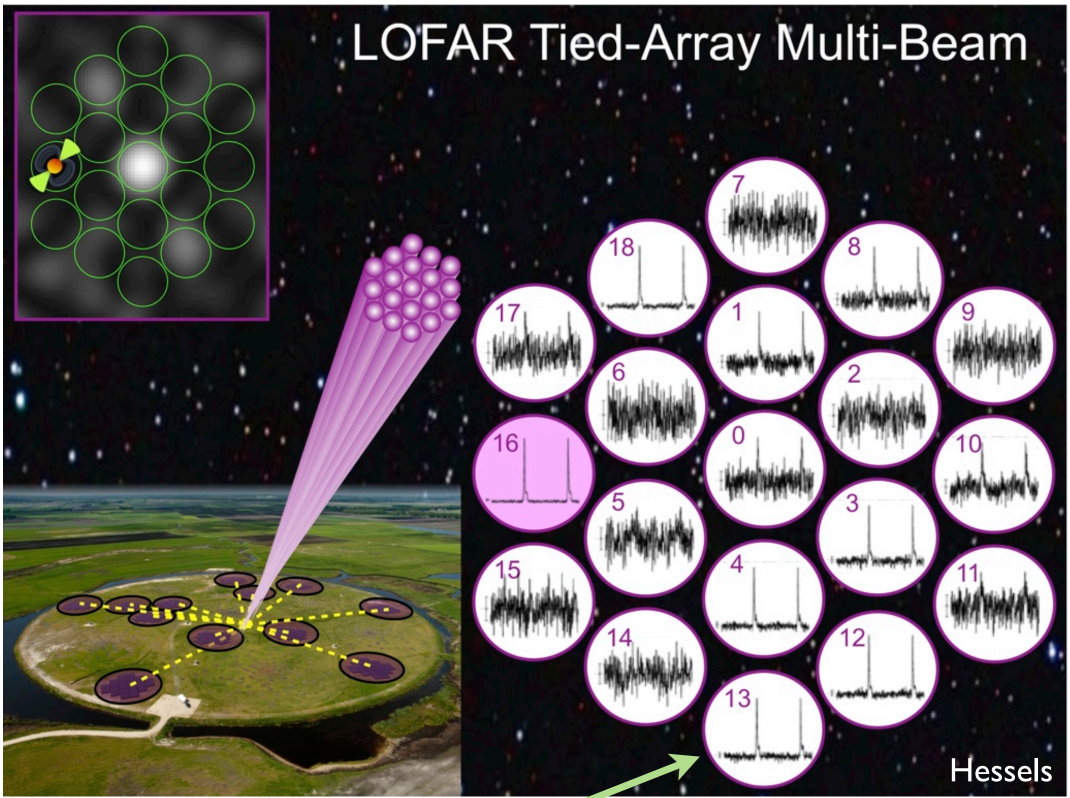
- In LOFAR parlance, we call these "incoherent array beams". The advantage is that you can maintain the field-of-view of the individual elements; the disadvantage is that the sensitivity only scales as the square root of the number of elements being added.

Coherent Antenna Addition

- Collect the various antenna voltage streams.
- Correct for the geometrical delay towards a particular sky position.
- Correct for differential clock delays between the antennas.
- Correct for differential ionospheric delays along the various lines-of-sight.
- Add the calibrated, time/phase-shifted signals.
- Results in a single "tied-array" beam with a FWHM proportional to the maximum baseline.
- Can synthesize many "tied-array" beams within the primary beam.

- In LOFAR parlance, we call these "coherent array beams". The advantage is that you get a sensitivity that is directly proportional to all the collecting area being added; the disadvantage is that the size of the tied-array beam is related to the maximum baseline being used.

Example: LOFAR tied-array beams

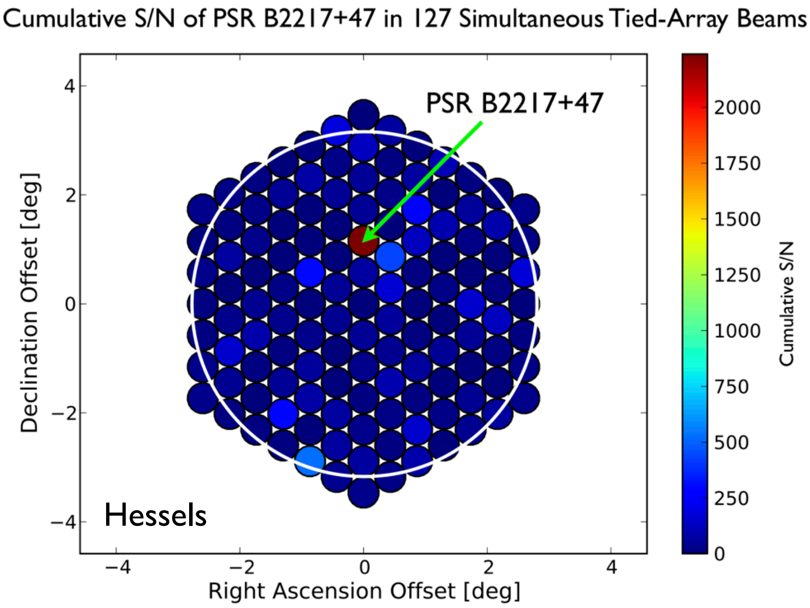


LOFAR HBA data

Folded and dedispersed signal

• Here's an "artist's conception" of synthesizing 19 tied-array beams from the 12 HBA sub-stations on the LOFAR Superterp.
• The top-left plot show's the theoretical beam pattern of each beam as the grey scale. Notice the main lobe and two strong side-lobes. Each of the 19 beams produces this pattern. The actual beam pattern during this observation is rotated on the sky in a different direction.
• The right-hand circles show the integrated pulsar signal (average of many pulses) in each of the beams. The strongest detection is in the direction of the known pulsar position. Notice that the pulsar also weakly shows up in other beams. This is because of the sensitivity in the side-lobes.

Fill Primary Beam with Tied-Array Beams

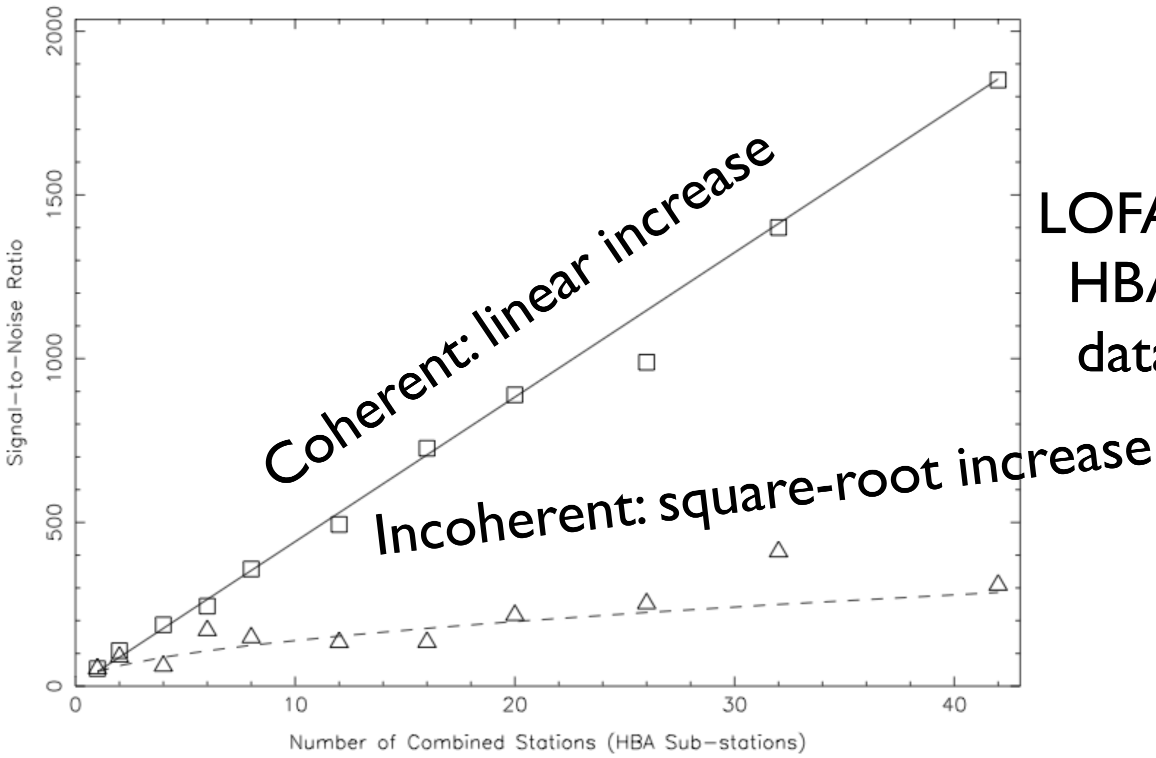


LOFAR HBA data

- White circle = station (primary) beam.
- Colored circles are the tied-array beams using the LOFAR Superterp.
- Color represents the S/N of the pulsar in each beam.

- Here's an example of recovering a larger field-of-view by creating many tied-array beams at once. Obviously, 127 tied-array beams produce 127 times more data than producing just a single beam.

Coherent vs. Incoherent Beams

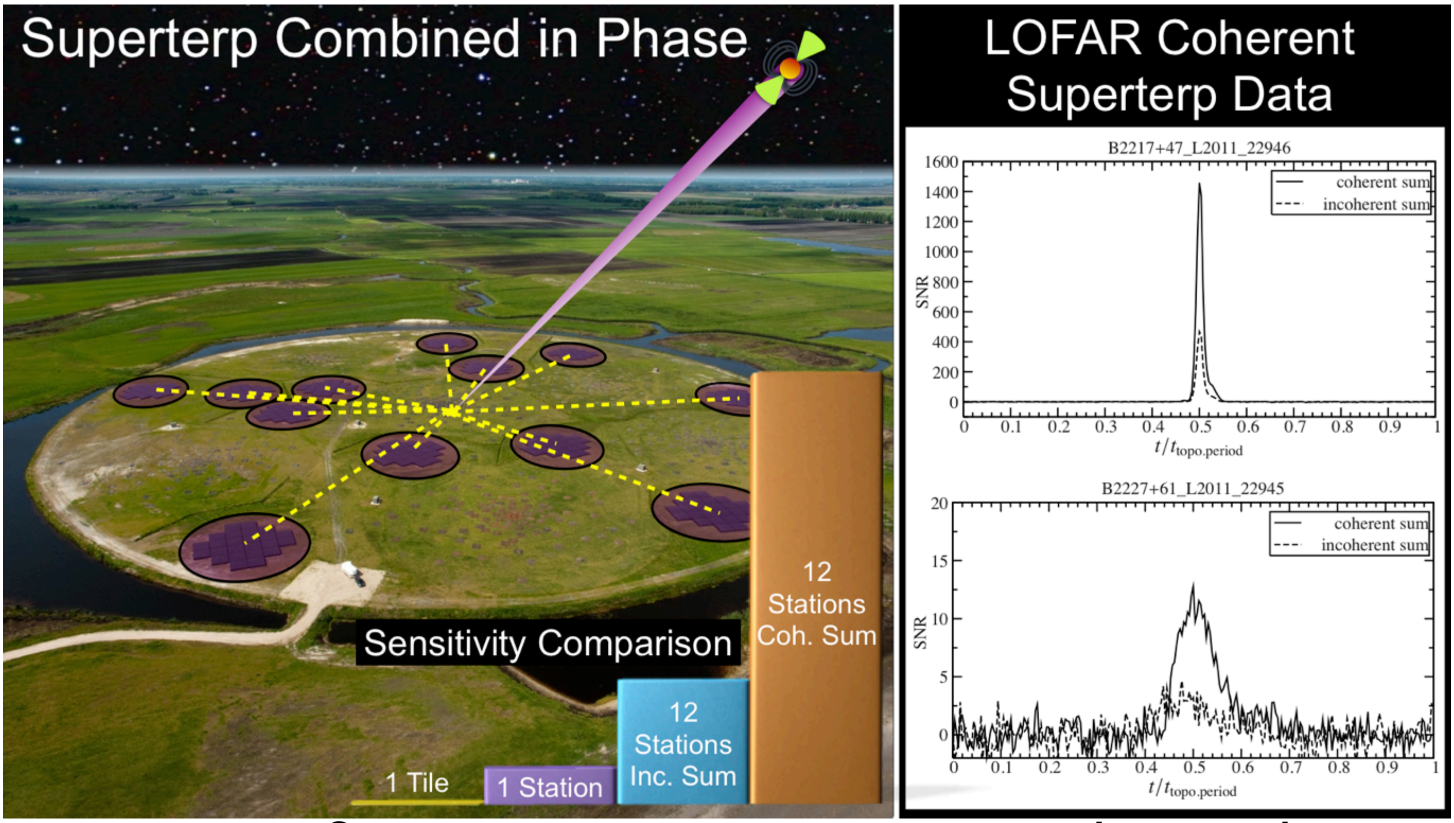


LOFAR
HBA
data

- Compromise between field-of-view and sensitivity.

- Here we see graphically something we said a few slides back: a coherent beam's sensitivity increases linearly with the number of elements combined, while an incoherent beam's sensitivity increases as only the square root.

Coherent vs. Incoherent Beams



- Sensitivity gain sometimes even better than expected due to better interference rejection.

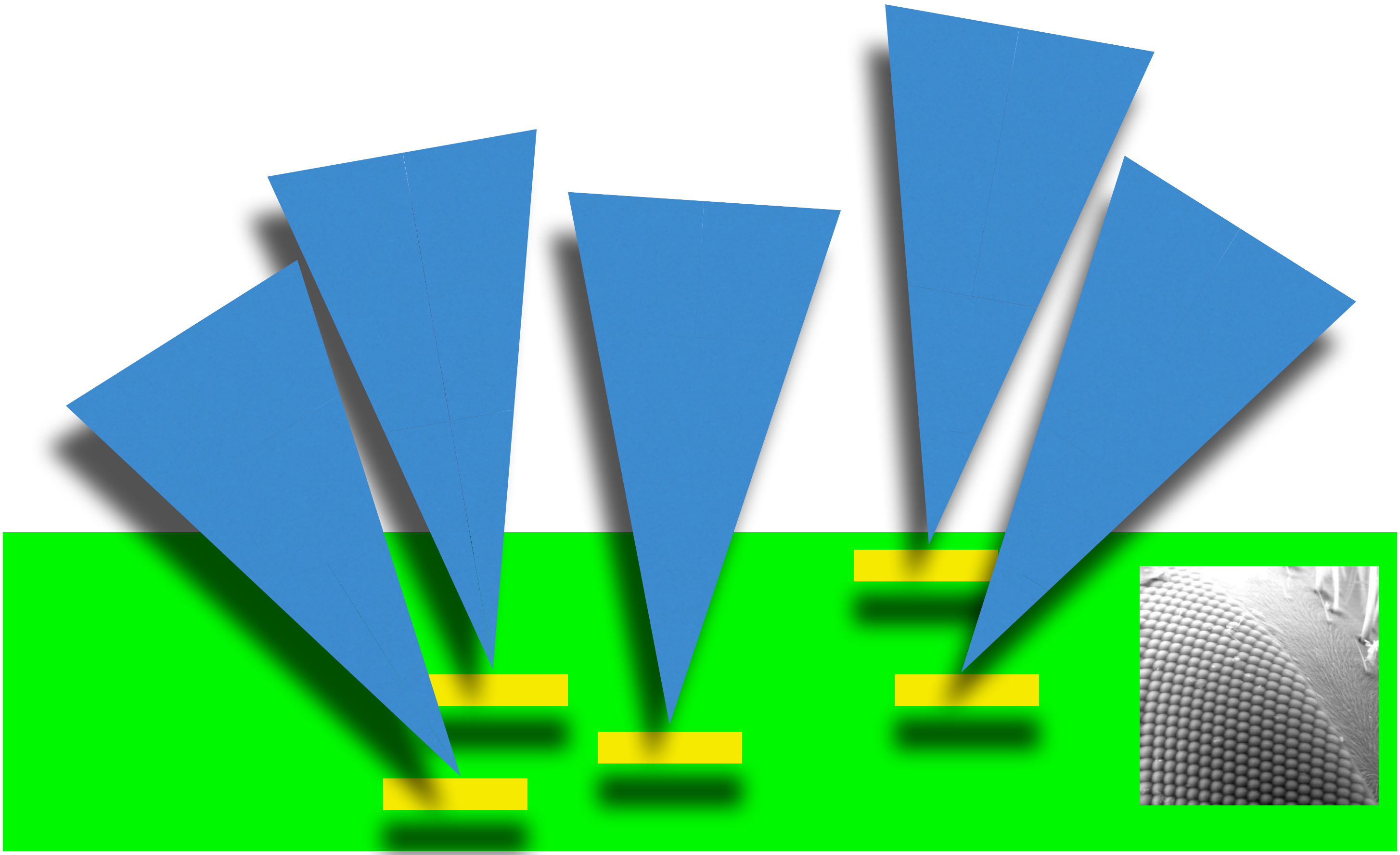
Hessels

- Same idea as previous slide, different representation. Here one sees a histogram showing how adding hundreds and even thousands of individual antennas adds up to a great sensitivity.

Fly’s Eye Observations

- Point each antenna in a different, complementary direction.
- Do *not* sum the individual antenna signals together (i.e. treat them as single dishes).
- Covers a large area of sky at the sensitivity of an individual antenna/station.
- Field-of-view proportional to the number of antennas times the primary beam field-of-view.
- Can employ anti-coincidence to reject interference.

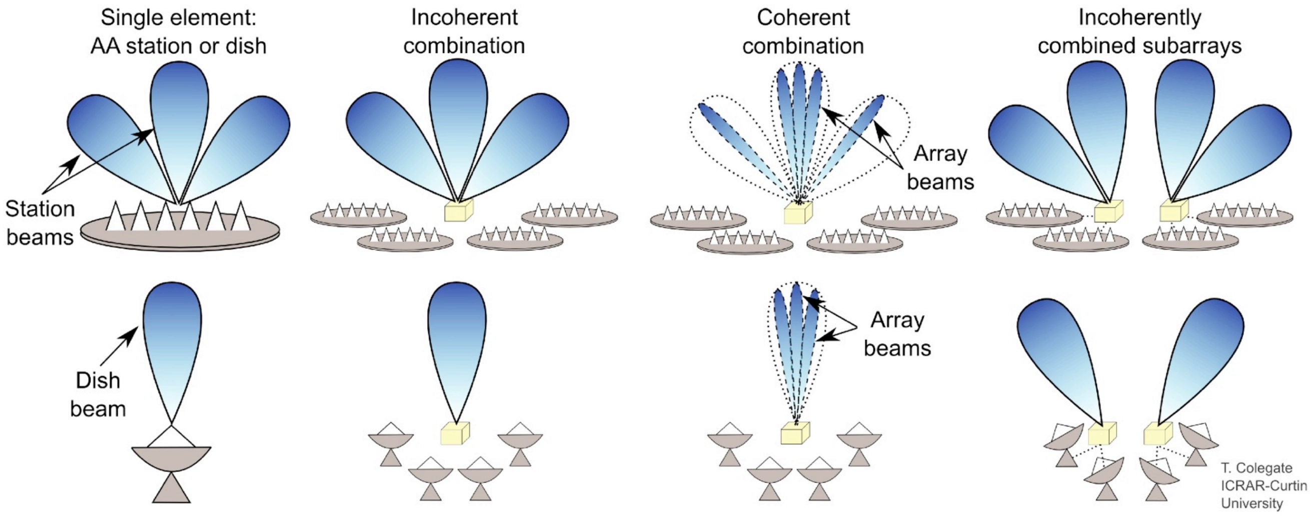
“Fly’s Eye” Observations



• Graphical illustration of a “fly’s eye” observation.
• The yellow rectangles represent the individual stations/telescopes, while the blue triangles indicate the separately pointed beams.
• Bottom right: a real fly’s eye.

Sub-arraying: mixing and matching what you add together

Top: aperture array like LOFAR

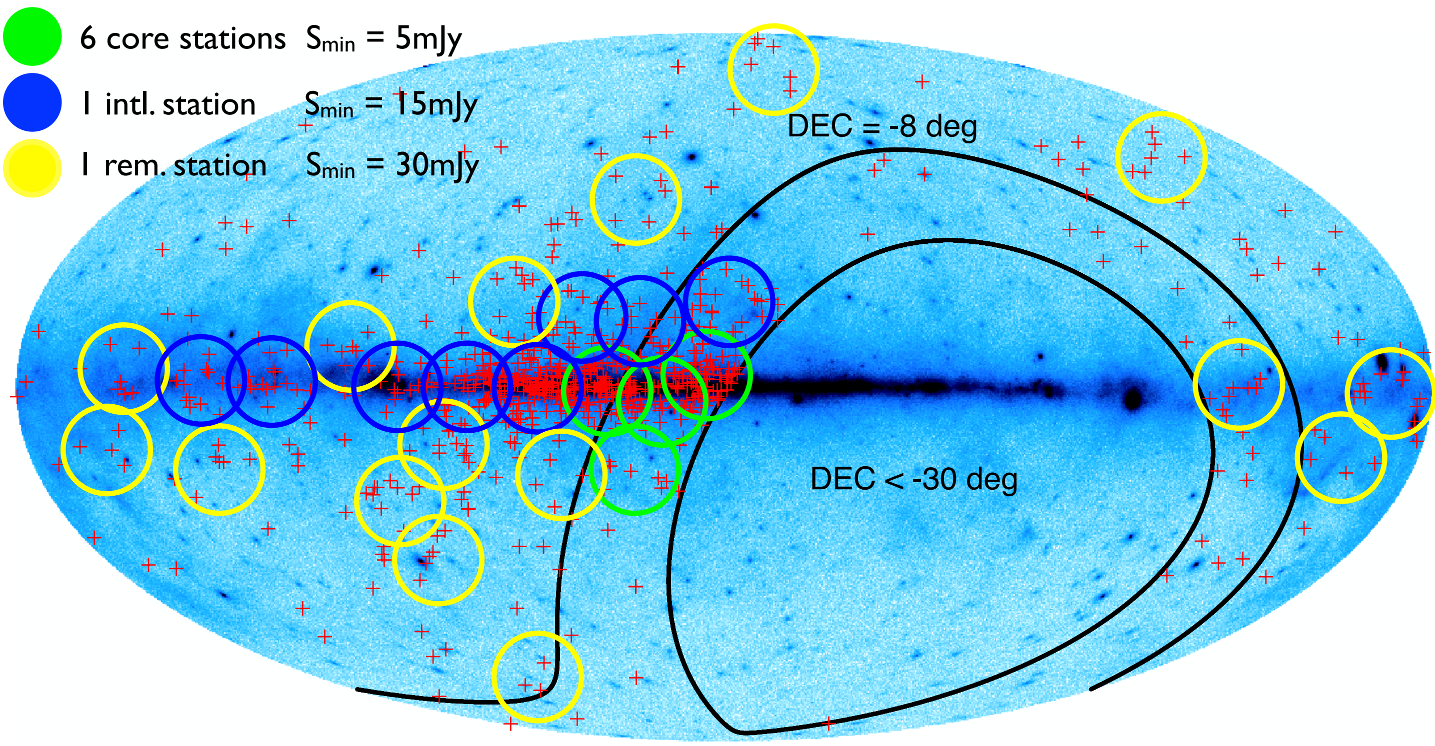


Bottom: dish array like JVLA

Colegate

• Let you imagination go wild... you can also "sub-array" an interferometer, by which we mean that different groups of antennas/telescopes can be combined in different ways at the same time.
• So, you could use the inner core of the telescope array to do one scientific project (one that works well with short baselines) while a different project is running using just the telescopes on the longest baselines.

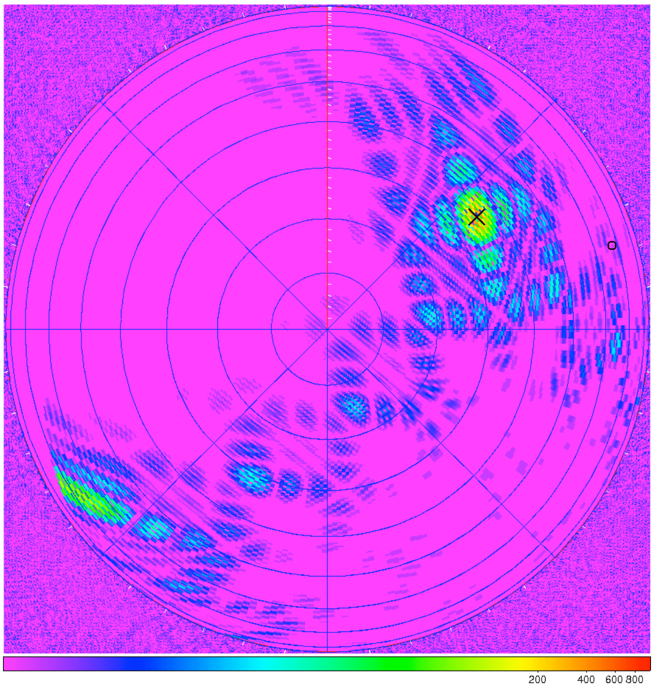
Fully Flexible LOFAR



- For example, in one of my LOFAR projects, we're trying to point the stations separately so we can observe many pulsars at once.
- The circles show the various fields-of-view that would be possible (using different combinations of stations).
- The red crosses are the known positions of radio pulsars.

Careful: beam patterns are sometimes very complicated

LOFAR 4-Tile Beam Pattern

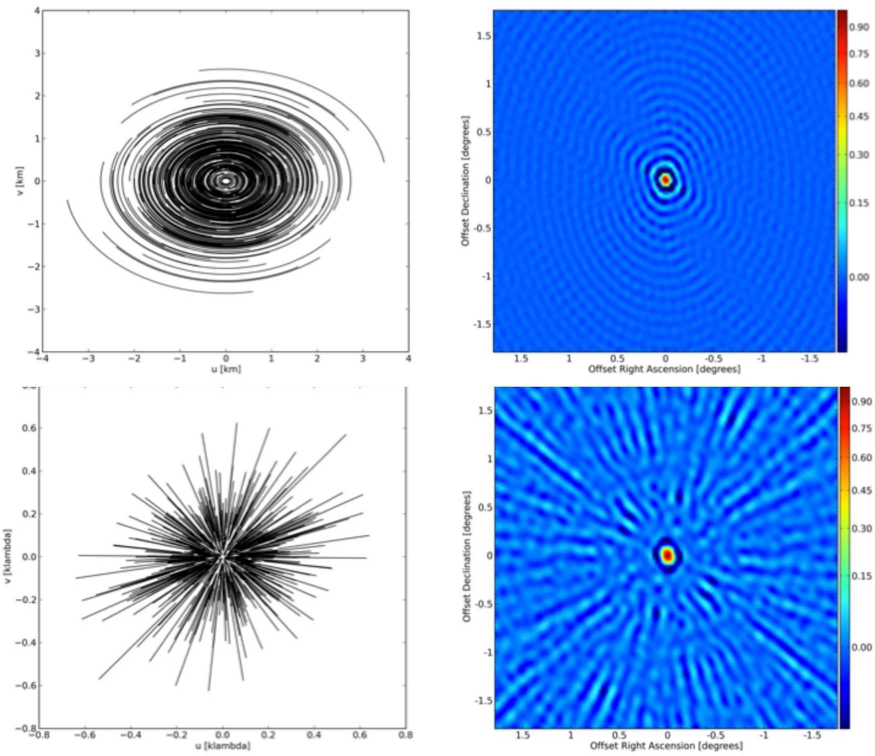


Yatawatta

- Because of sidelobes, there is *some* response *across* the sky.
- Need to be careful with bright sources falling into a sidelobe.
- Potential to misidentify source direction.

• Remember that understanding the full beam pattern across the sky (and not just the main lobe) is important.
• In this example you can see the very complicated beam pattern produce by 4 LOFAR HBA tiles. (you could even simulate this yourself using your code from the first practicum)

LOFAR Instantaneous uv-Coverage



uv-Coverage

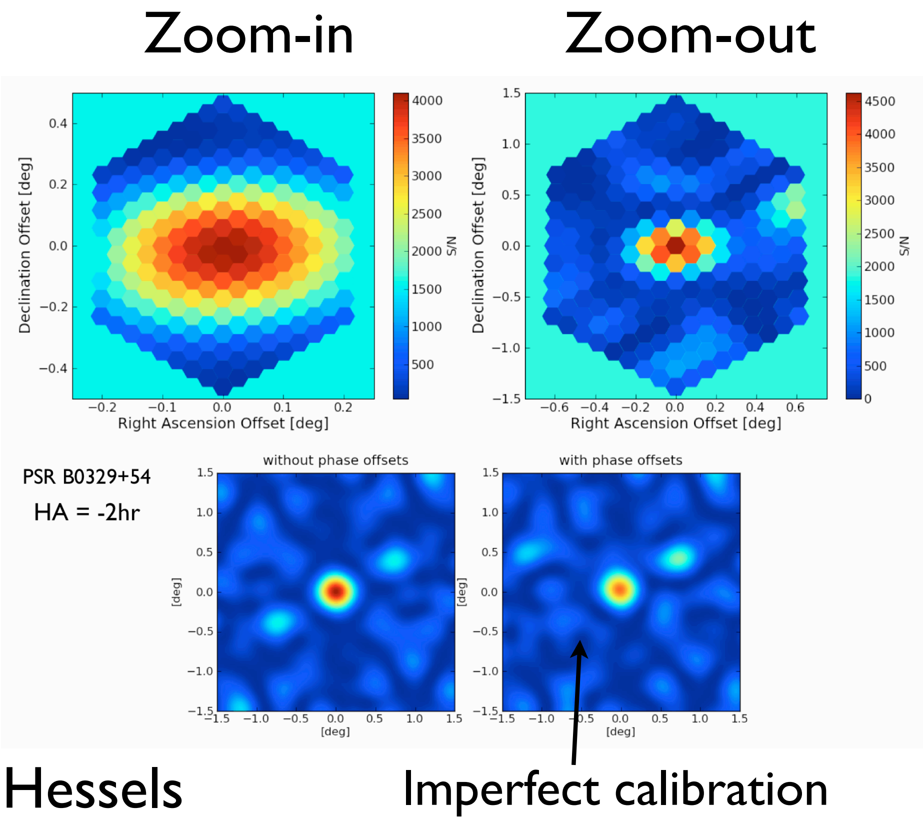
Beam shape

- 2-D array provides good instantaneous uv-coverage.
- Top: 6-hr synthesis with 24-station LOFAR core.
- Bottom: snapshot (1sec) with 24-station LOFAR core.

Heald

- This should be familiar from the first practicum assignment.

Superterp Tied-array Beam



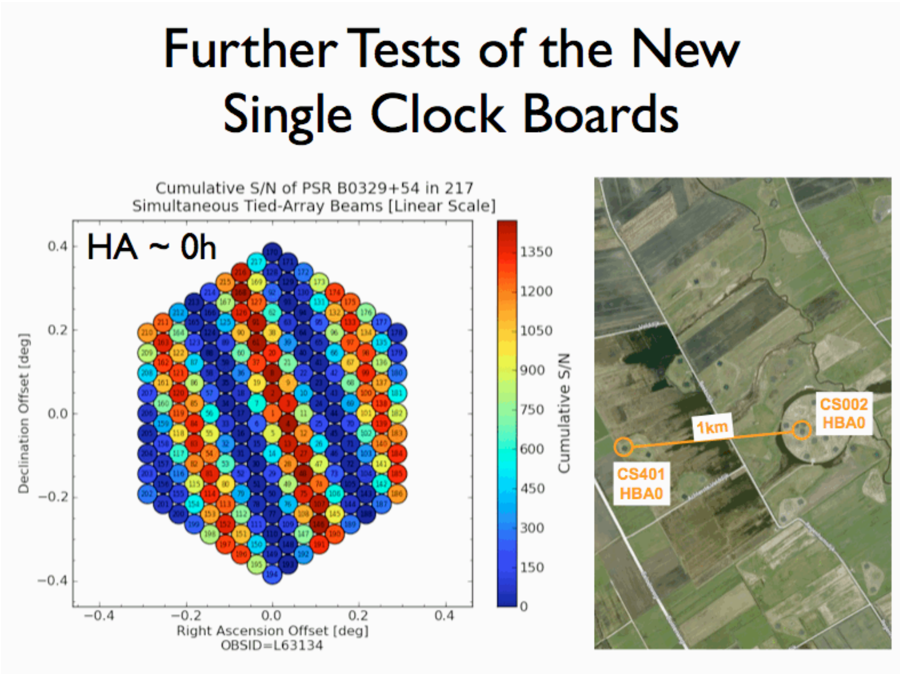
- Top: real data on a bright pulsar (color indicates S/N).
- Bottom: theoretical beam shape both with and without phase offsets.
- Note asymmetric observed beam pattern.

Hessels

UNIVERSITY OF AMSTERDAM

- This figure was also shown in a previous lecture.
- Here one can see that the true beam shape of a tied-array beam can deviate significantly from the expected theoretical shape if the phase calibration use to form the tied-array beam is not perfect. Extra phase offsets can also be introduced because of the ionosphere.

2-element Fringe Pattern

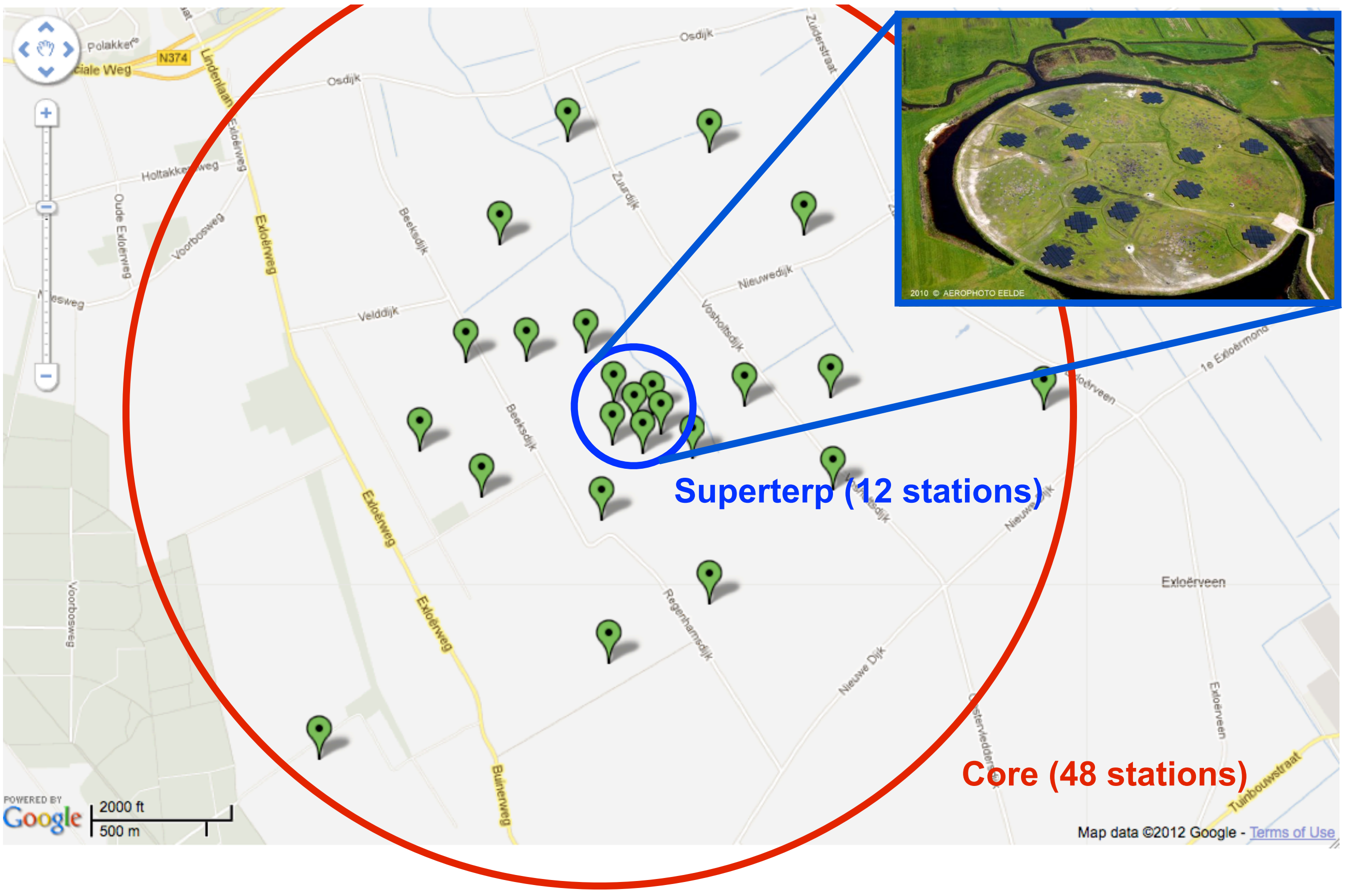


- Late 2012 a distributed clock system was installed on the entire LOFAR core.
- Previously station clocks drifted w.r.t. each other by up to 20ns (several wavelengths).

Hessels

- Here's another example of the beam pattern one gets by coherently combining two station beams.
- Since there are only two stations used in this case, we get a "fan beam" (i.e. 1-D) pattern.

The LOFAR Core



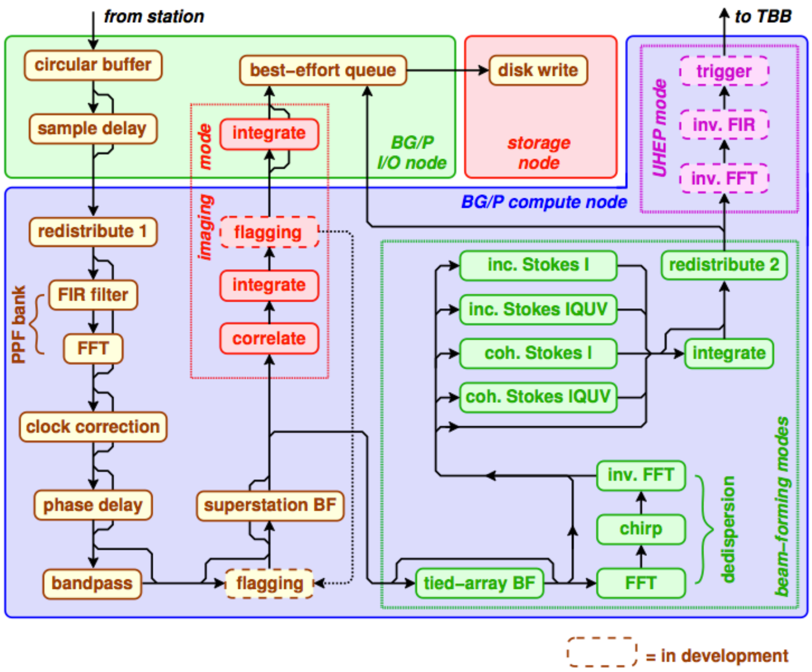
• QUESTION: FOR FORMING TIED-ARRAY BEAMS WITH LOFAR, WE RESTRICT OURSELVES TO USING JUST THE SUPERTERP OR THE CORE, WHY?

• The Superterp has the highest "filling factor" (i.e. density of stations per unit area) and hence gives the best "bang for our buck" when it comes to sensitivity and field-of-view. The full core gives even higher sensitivity, but the beam covers ~40 times less sky per pointing.

• Another important reason: the ionosphere is relatively stable over the 2-km wide area of the Superterp, so we can get away without adding realtime ionospheric phase calibration.

• Another important reason: all the LOFAR core stations are on a single clock such that we don't need to calibrate in real time the clock delays between stations.

Correlator/Beam-former



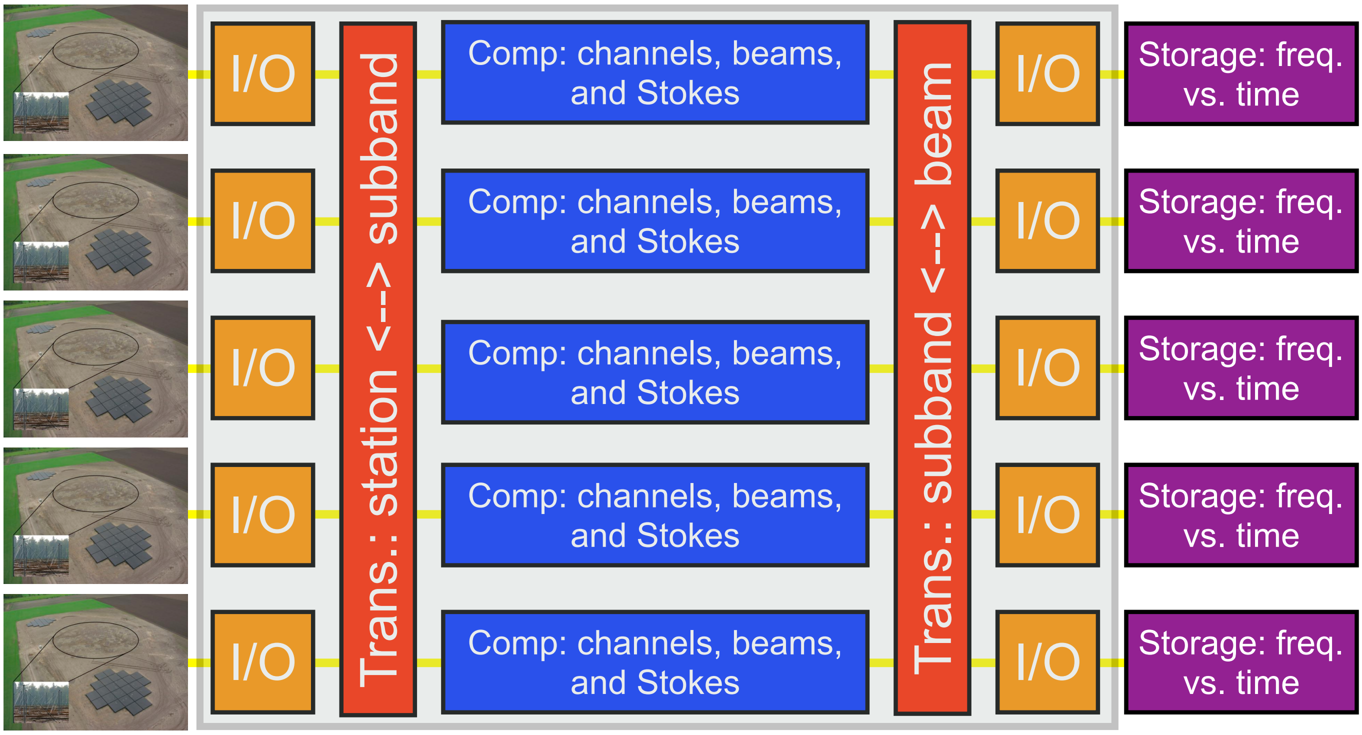
- LOFAR BG/P is both a correlator (imaging) and a “beam-former” (high time resolution).
- Many shared operations between the two main modes.

Romein

- Here’s a chart of what happens on the LOFAR correlator and beam former to produce (optionally) both interferometeric visbilities and “beam-formed” (tied-array or incoherent array beams) data.
- Redistribute1 and 2 refer to steps in which there is a transpose done on the data. First we need to reorganize the data such that for any given frequency subband we have all the stations’s data. At the end we need to reverse this transpose such that we have all frequencies for a particular tied-array beam.
- FFT: Fast Fourier Transform, PPF: Poly-Phase Filterbank, BF: Beam-Former

LOFAR Data Flow

Synthesize 200+ beams



• Here's another representation, but simplified. Note the data transposes at the input and output to the array beam-former. Previously this was the IBM Blue-Gene P supercomputer, now this is a achieved using a cluster of 16 GPU (Graphical Processor Unit) cards.

Filling Factor and Beam-Formed Surveys

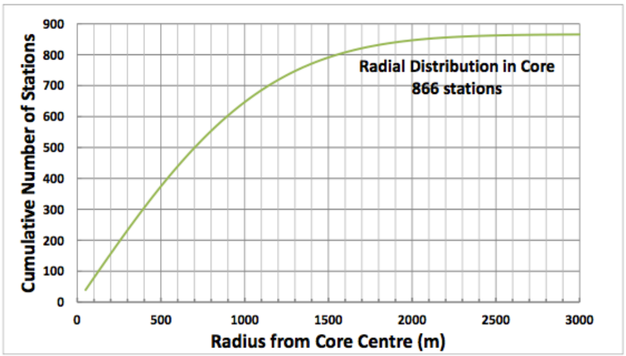


Figure 3 Cumulative collecting area as a function of core radius in the SKA1-low array.

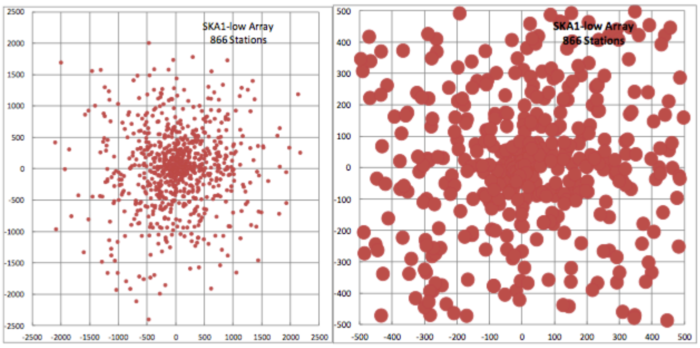


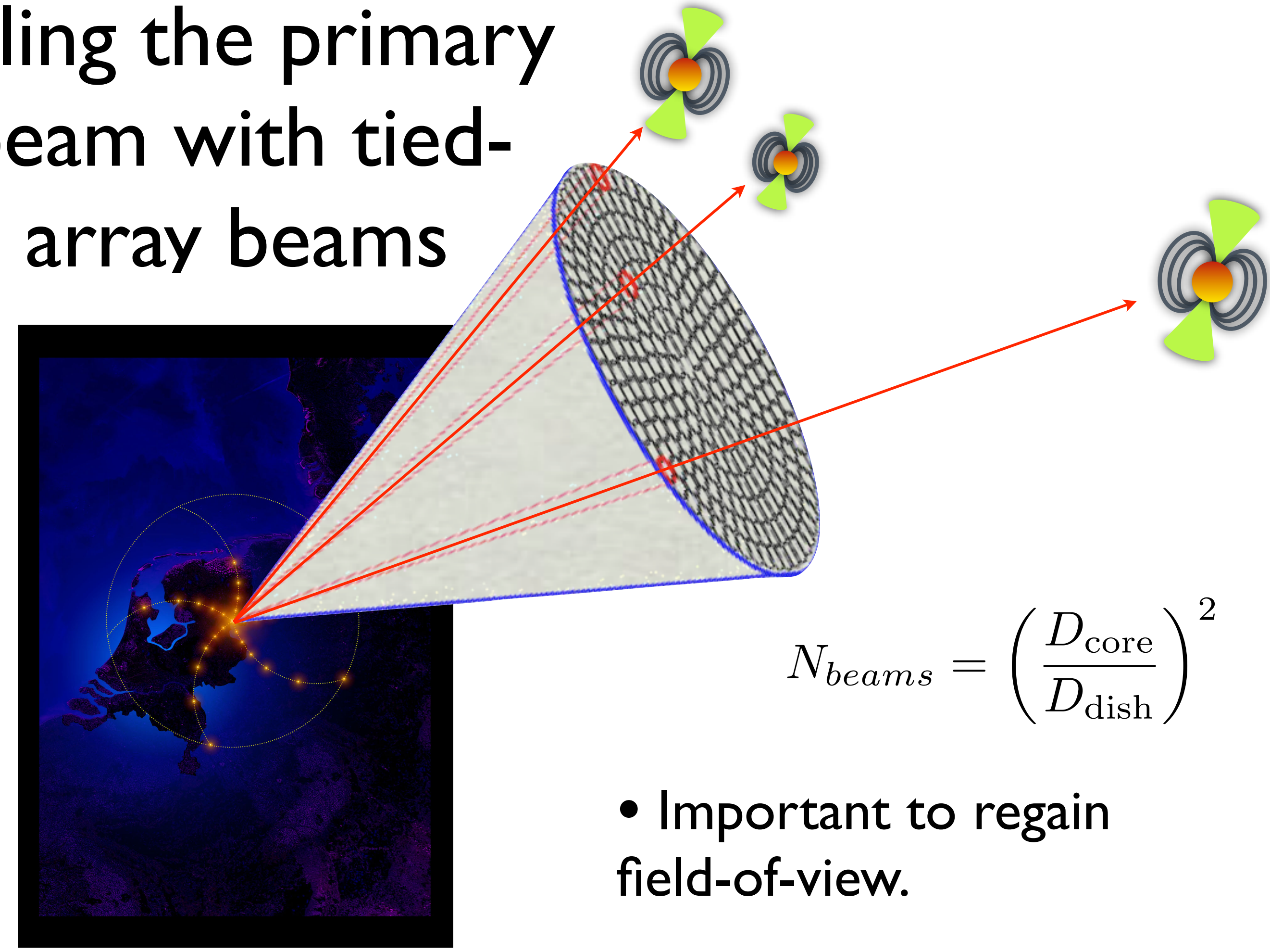
Figure 4 The SKA1-low configuration in the core (35-m diameter stations).

$$N_{ops} = F_c N_{\rm dish} N_{\rm pol} B \left(\frac{D_{\rm core}}{D_{\rm dish}}\right)^2$$

- Filling factor: area within some radius that is covered by antennas.
- Beam-formed surveys: once the filling factor starts dropping then stop including antennas.

• Here we see quantitatively how the number of required operations required to achieve a particular field-of-view using tied-array beams scales quickly with longest baseline. This is why new arrays like the SKA (and also LOFAR) has a centrally concentrated collection of antennas. That's also good for providing the short baselines needed for some imaging projects (e.g. the EOR project in the case of LOFAR).

Filling the primary beam with tied-array beams

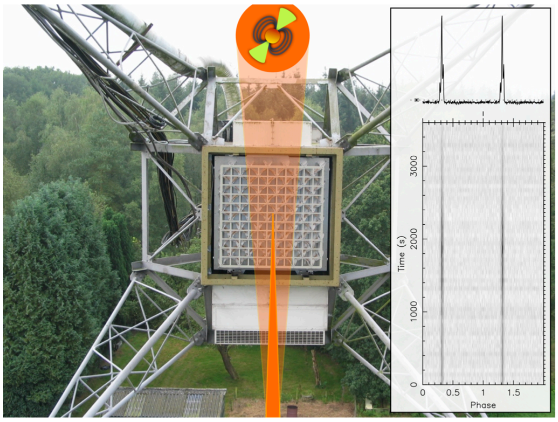


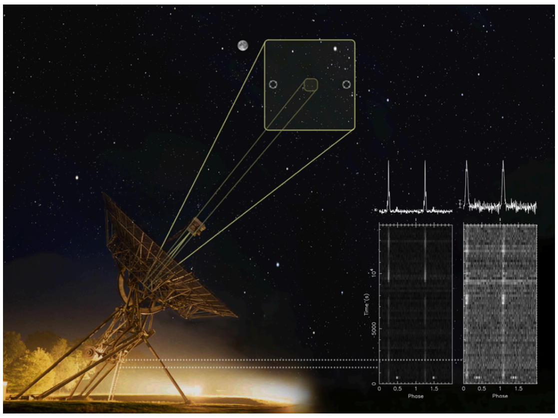
$$N_{beams} = \left(\frac{D_{\rm core}}{D_{\rm dish}}\right)^2$$

- Important to regain field-of-view.

• Here's another representation of filling the primary field-of-view with tied-array beams. Again, the number of tied-array beams required strongly depends on the maximum baseline, represented here by "Dcore" (maximum distance between core stations).

...and add a Focal Plane Array

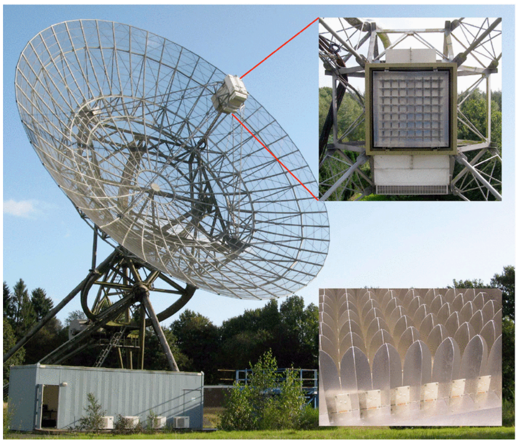




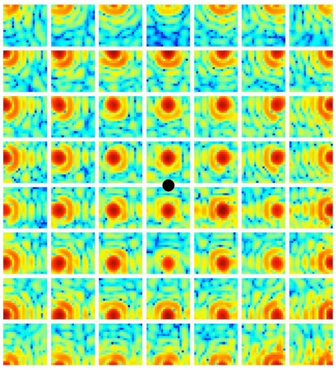
- Focal plane arrays make wide-field surveys with dishes possible.
- APERTIF provides 37 pixels.
- The antenna beams are formed by weighting the 56 dual polarization Vivaldi elements.
- Each of the 37 beams per antenna needs to be cross-correlated and beam-formed!

- For dish arrays like Westerbork, we can even further increase the field-of-view by adding a focal plane array (we saw the APERTIF system during the field trip).
- A focal plane array gives multiple _primary_ beams, and one can form many tied-array beams in each of these.
- The field of view can become enormous, but so is the associated data rate.

...and add a Focal Plane Array



Individual element PSFs before beam-forming

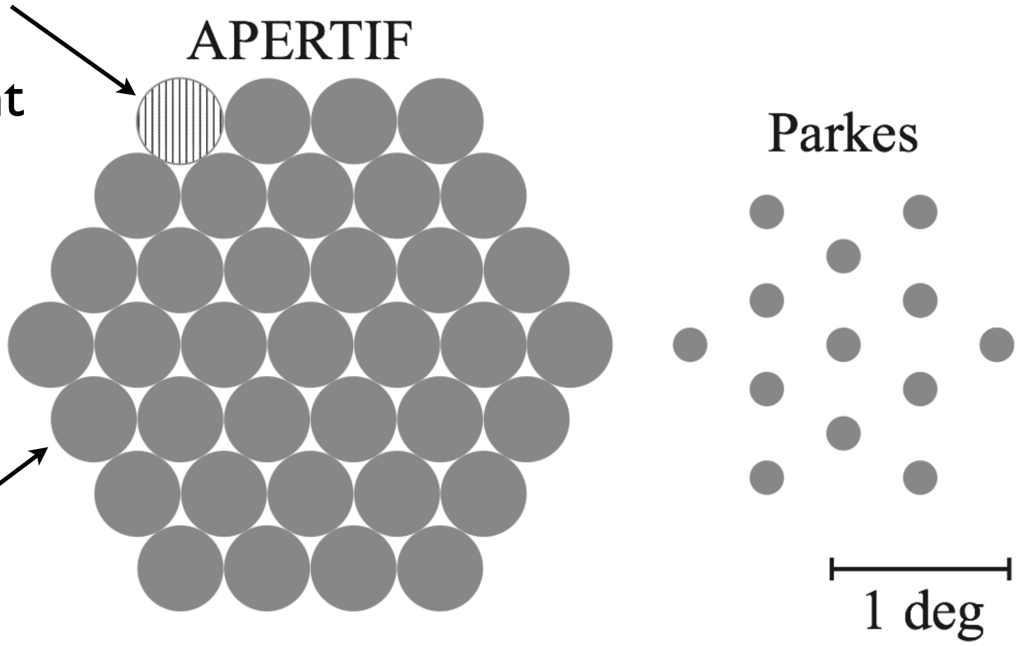


- Focal plane arrays make wide-field surveys with dishes possible.
- APERTIF provides 37 pixels.
- The antenna beams are formed by weighting the 56 dual polarization Vivaldi elements.
- Each of the 37 beams per antenna needs to be cross-correlated and beam-formed!

- Same slide as previously, in the bottom left we see the point-spread-functions of the individual elements of the focal plane array.
- These elements are combined in a weighted way to synthesize multiple primary beams (sampling more of the dishes focal _plane_).

APERTIF vs. Parkes

Form array beams for each element

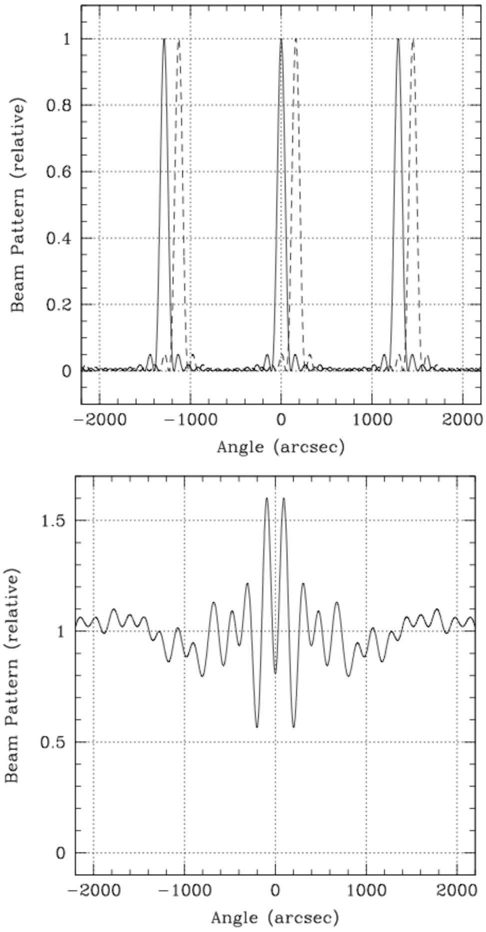


Individual element beam

van Leeuwen

- Here the grey circles indicate the 37 primary beams that the APERTIF system will create.
- Within each of these we can create multiple tied-array beams.
- For comparison, we see the field-of-view achieved by Parkes, where in that case a 13 beam _feed_horn_ (not focal plane array) is used.

WSRT 8gr8

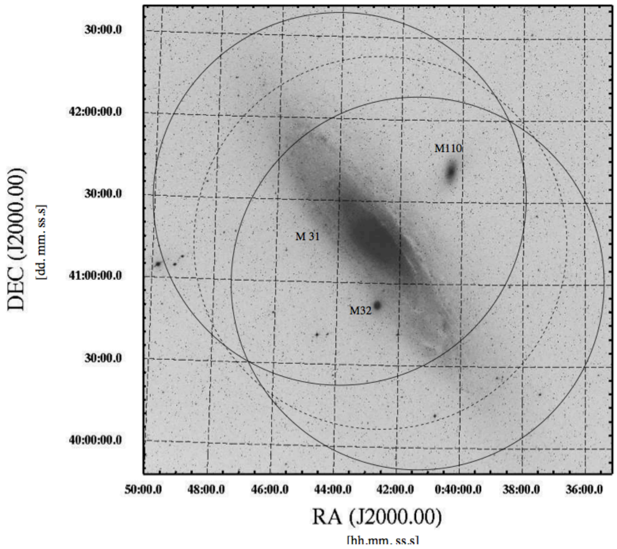


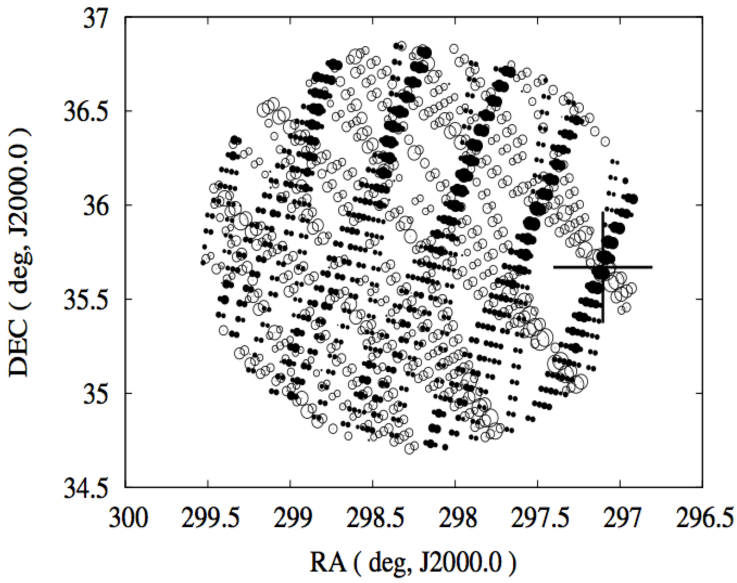
Janssen et al. 2009

- Top: the instantaneous grating fan-beam response of the WSRT telescopes RT0 through RTB, added in phase, when all have a relative baseline of 144 m.
- Bottom: the relative sensitivity across the primary beam field-of-view after a 2 h integration with a total of eight grating fan-beams. The largest oscillations are within a few beamwidths of the overall field centre. These damp out at larger distances to a constant level.

- You simulated Westerbork in the first practicum, so you should already know that the intantaneous synthesized beam looks like the top-left figure.
- One can create multiple such sets of fan beams to cover the whole field-of-view of each dish.

WSRT 8gr8 Andromeda Survey





- Survey pointings: take advantage of large primary beam field-of-view.

- Localization requires detecting bursts at multiple hour angles. Circles show burst strength in the fan beams.

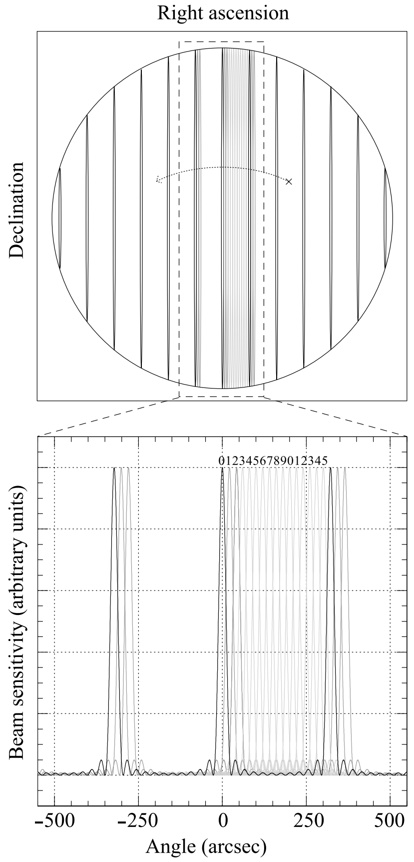
Rubio-Herrera et al. 2013

- This technique was previously used to survey the sky for pulsars with Westerbork.
- The tricky part: you need to detect a source at multiple hour angles before you can localize it.

QUESTION: WHY?

- **ANSWER: DETECTING A SOURCE AT A SINGLE HOUR ANGLE YOU DON'T KNOW IN WHICH OF THE (NEARLY EQUALLY SENSITIVE) SIDE-LOBES IT'S IN, AND YOU ONLY HAVE 1-D INFORMATION ANYWAY (BECAUSE OF THE FAN BEAM SHAPE). DETECTING AT TWO DIFFERENT HOUR ANGLES ALLOWS YOU TO INTERSECT THE FAN BEAMS AND LOCALIZE THE SOURCE.**

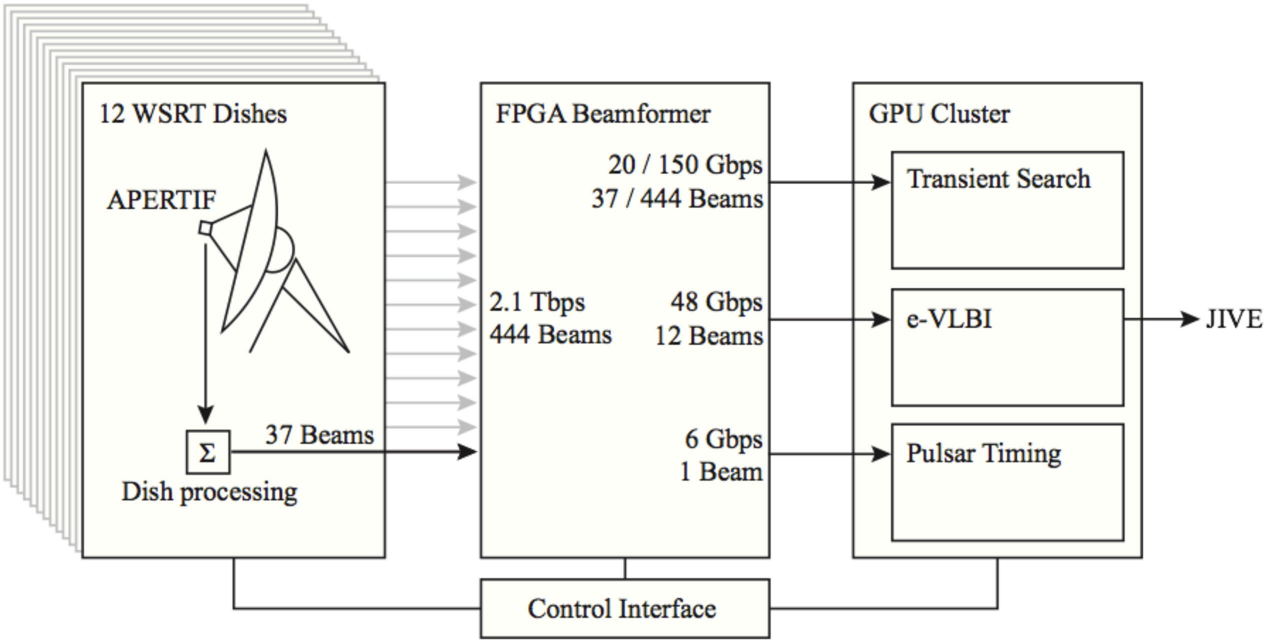
For APERTIF use 16 grating sets



van Leeuwen

- Using all 12 APERTIF dishes, 16 grating sets are required to fill the primary field-of-view.
- These will rotate with hour-angle.
- Sub-beams can be formed by linearly combining the fan beams together.
- This process needs to happen for each of the 37 APERTIF antenna beams!

2-element Fringe Pattern

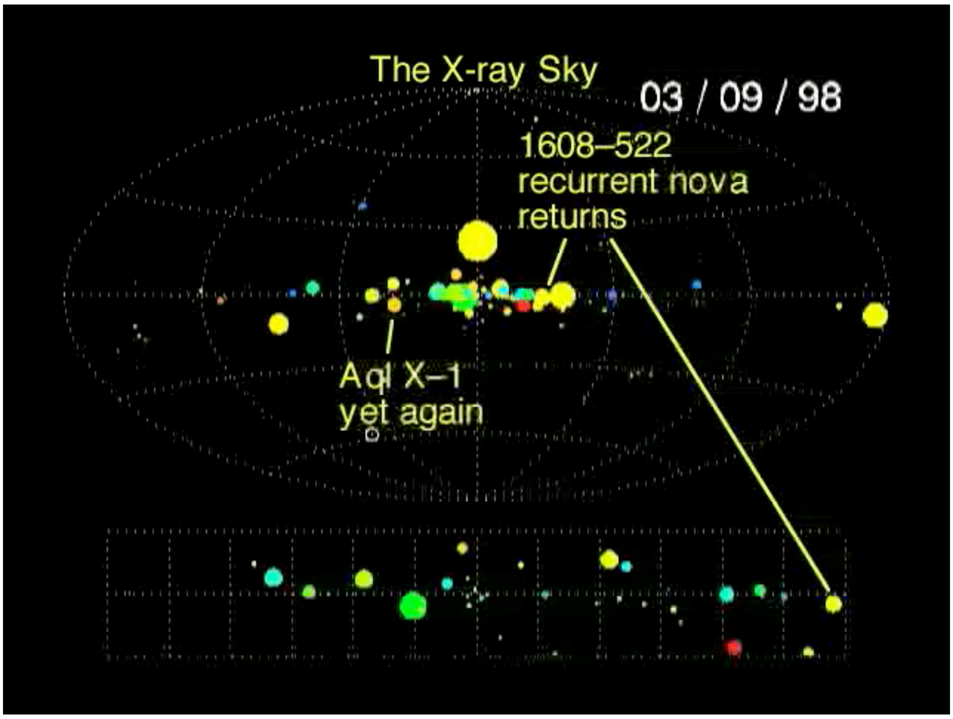


- Data rate of 2Tb/s for 444 beams
- Must form 37 x 16 sets of fan beams and detect transients in real time.

van Leeuwen

Pulsar and “fast transient” searches

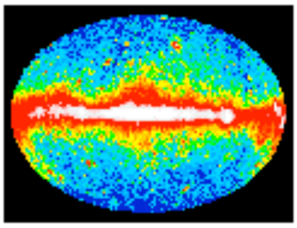
Various types of X-ray transients as seen by All-Sky Monitor onboard RXTE

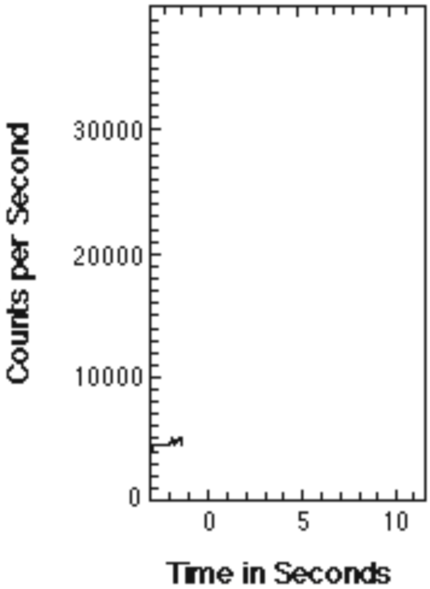


The goal: do the same monitoring at radio wavelengths!

• Radio astronomy has a lot of catching up to do in terms of monitoring the sky as well as has been done in, e.g., X-rays.

Some events are rare, but *very* bright



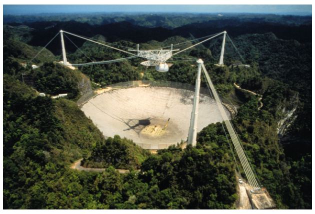


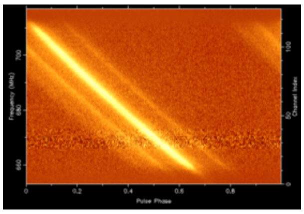
Gamma-ray burst from BATSE (Burst and Transient Source Experiment) on CGRO

• We know that there are very rare, but also very bright transient astronomical sources. Gamma-ray bursts are a great example.
• Is there a radio equivalent to the gamma-ray burst? e.g. the "fast radio bursts" recently discovered are claimed to be of extra-galactic origin.

Transient Radio Sky

The transient sky is a mostly unexplored domain, especially at high time resolution





Difficult to get required sensitivity *and* large field of view.

Difficult to get large field of view *and* good spatial resolution.

Much higher data rates than with photon detectors.

Propagation effects *very* important at short timescales and at low frequencies.

- F.O.M. $A^*(\Omega/\Delta\ \Omega)^*(T/\Delta T)$ should be large.

• So why isn't there already a useful radio all-sky monitor. Above we list some of the technical challenges that first need to be tackled.

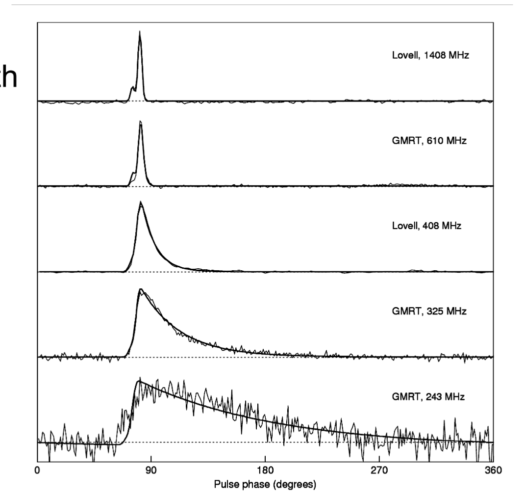
Propagation effects in the ionized interstellar medium

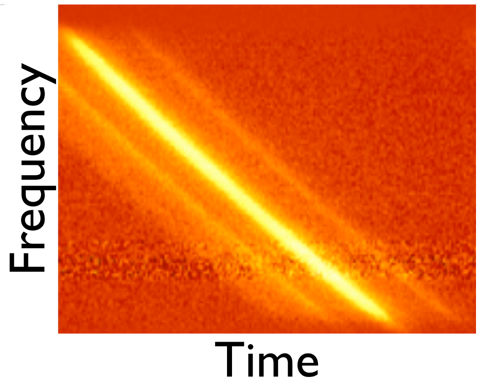
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference





Not pure evil: show that the signal is astronomical

• Also, propagation effects in the intervening material mean that we have to do a lot of processing and search a larger parameter space before we can detect short-duration radio signals.
• For example, scattering central figure will broader any impulse towards toward frequencies and dispersion will cause the signal to arrive at later times at lower frequencies.

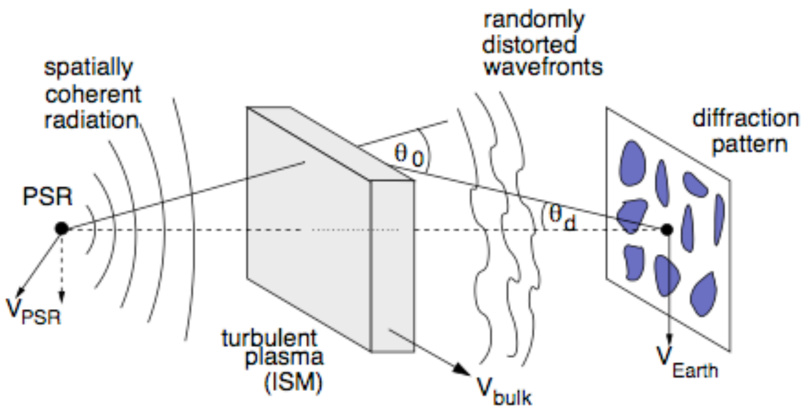
Propagation effects in the ionized interstellar medium

$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference

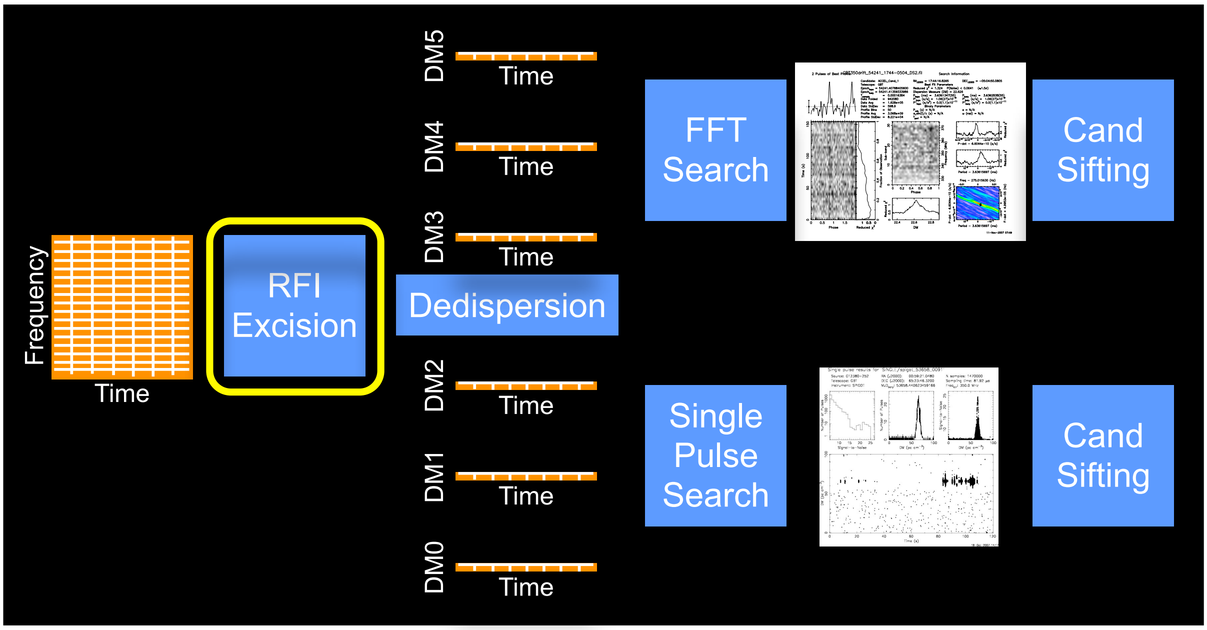


Kramer, Lorimer

Not pure evil: show that the signal is astronomical

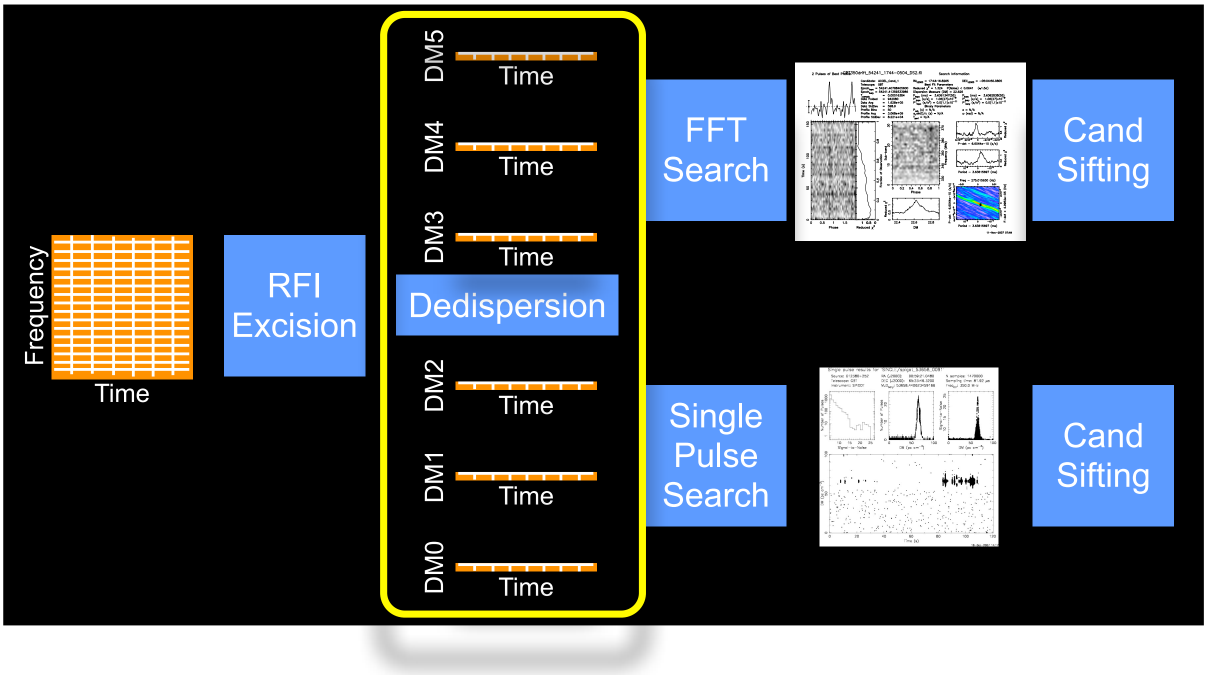
• We often model the interstellar medium along any particular line-of-sight as a thin screen which distorts the origin wave front of the source and creates a diffraction pattern at Earth. This causes scintillation, which means that the source brightness can increase and decrease on characteristic time and frequency scales.

Standard Pulsar/Fast Transient Search



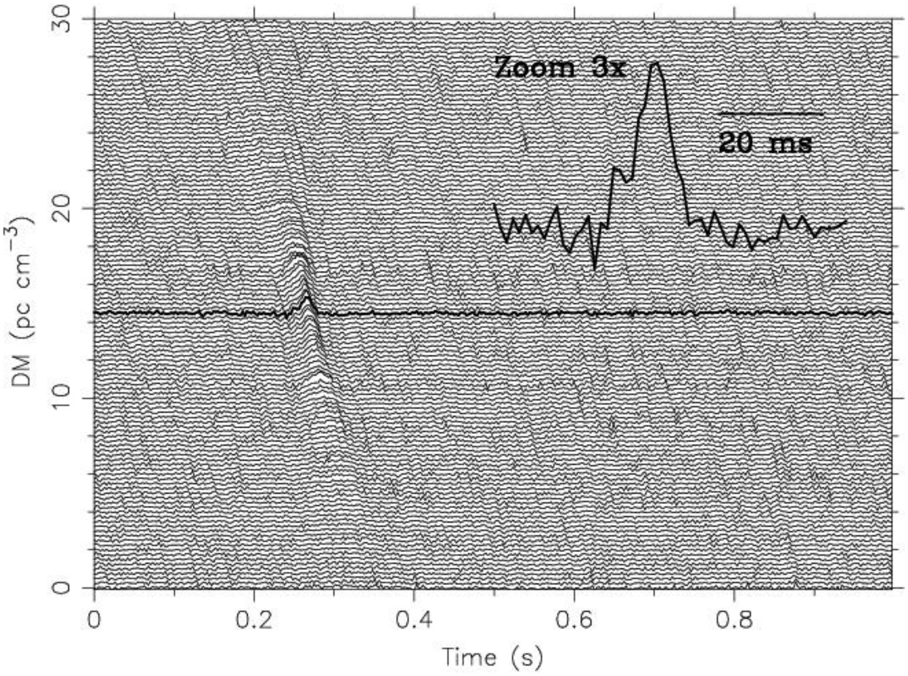
• So how do we do a search for short-duration pulsations? (we'll be doing this in the last short practicum)
• Each tied-array beam we start with gives us data in a particular direction of the sky as a function of frequency (channelized) and time (in time samples).
• First we need to remove interference. This means flagging some of the frequency channels and/or time intervals.

Standard Pulsar/Fast Transient Search



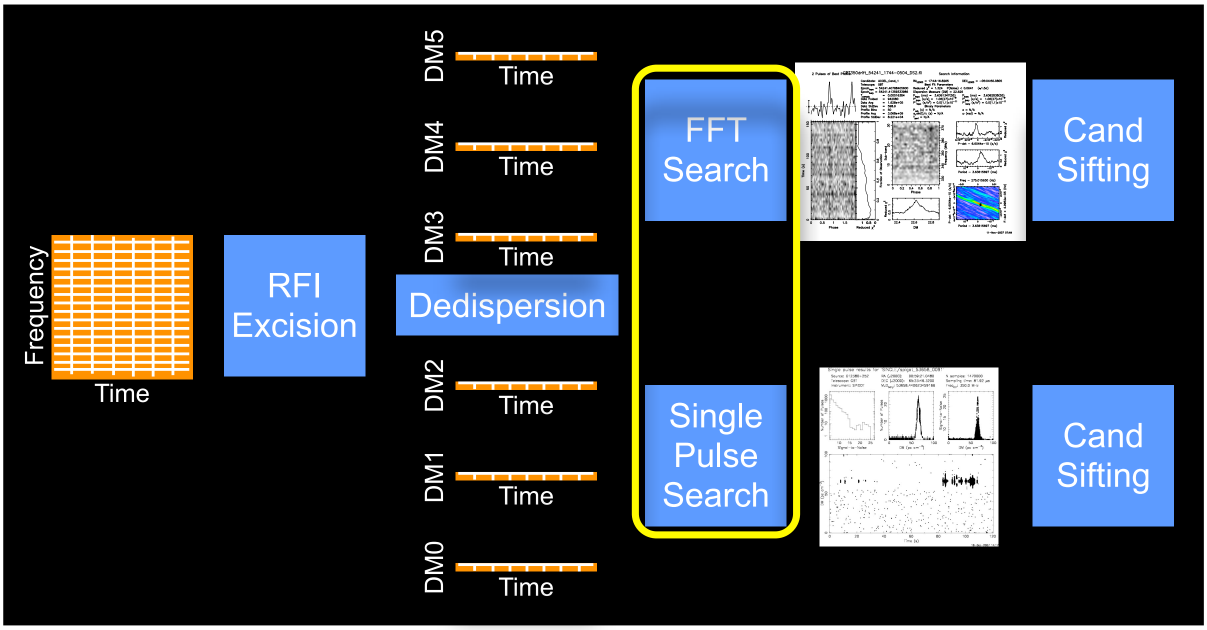
• Next we need to "dedisperse" (remove dispersion) from the data.
• In the simplest sense this means trying various guesses for how much dispersion there is to the source (the so-called dispersion measure) and then collapsing the data in frequency for each of these guesses. This process produces many "timeseries" (data as a function of time for a certain dispersion measure), each of which needs to be search for either periodic or single pulses.

Searching over Dispersion Measure



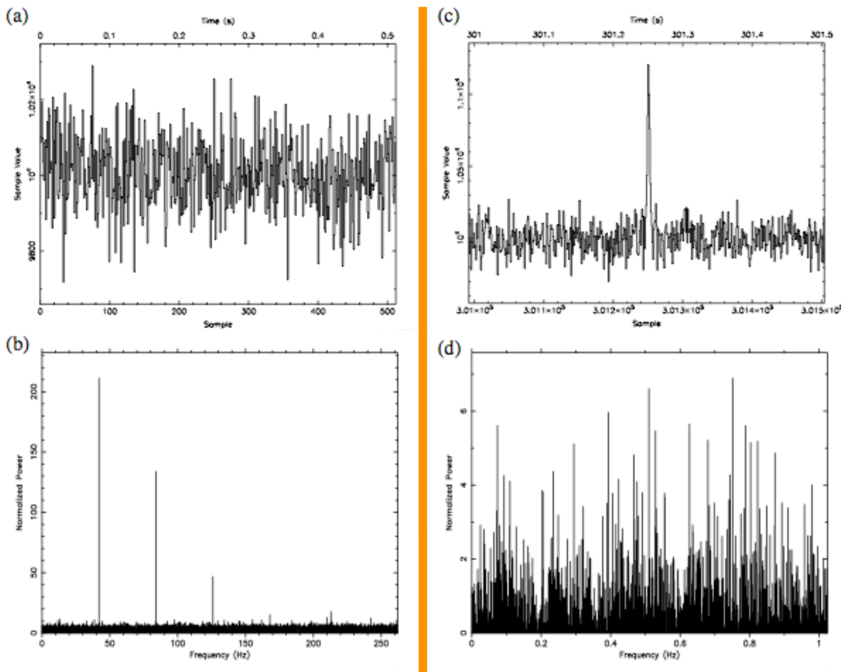
• Here we see how the signal strength of an individual pulse increase as our guess about the dispersion measure (shown on the y axis) comes closer to the right value.

Standard Pulsar/Fast Transient Search



• We perform both FFT (Fast Fourier Transform) search for periodicities in the data as well as single-pulse search (searches of isolated, individual bursts).

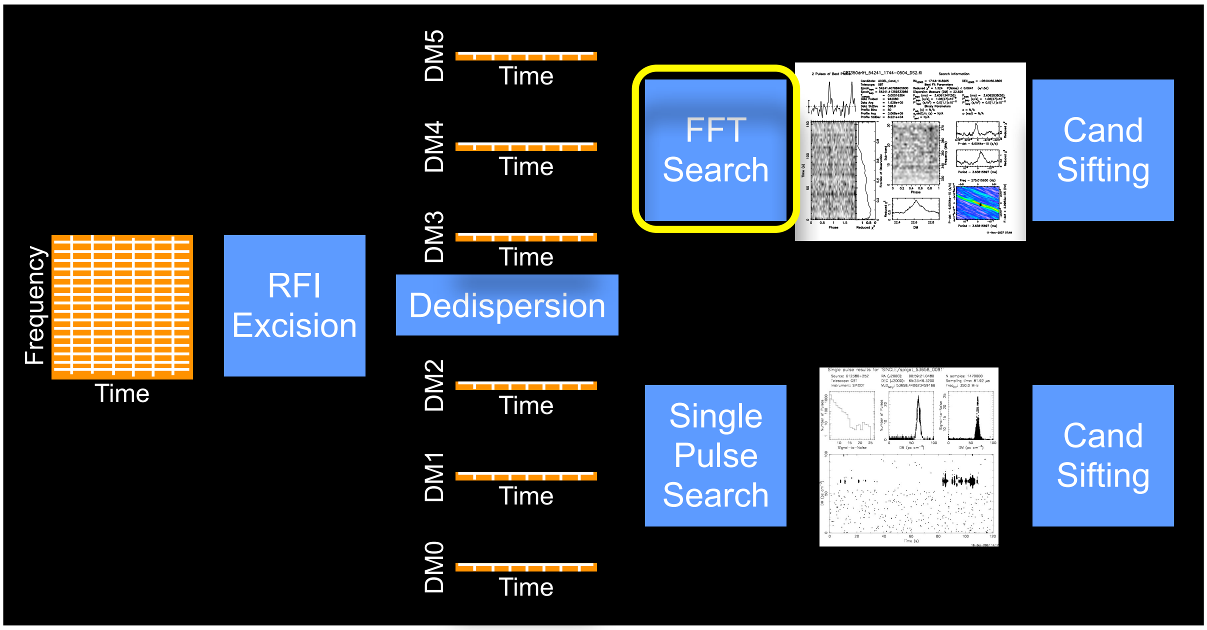
Periodic Signals vs. Bursts



Fourier techniques | Time-series techniques

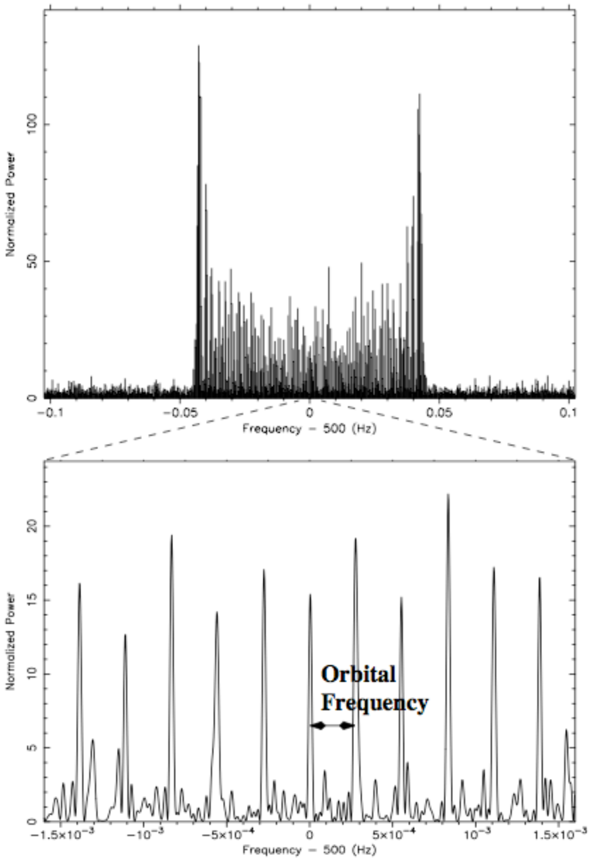
- Some signals are better found in a periodicity search; others in a single-pulse search.
- Panel a): this is how the timeseries looks in the "time domain" (signal as a function of time). There is a periodic signal, BUT it's buried in the noise.
- Panel b): this is how the same signal in Panel a) looks when you make a Fourier transform of the data. In the "frequency domain" one sees obvious peaks (harmonically spaced) which show that the data is modulated at a very specific frequency (in this case the spin frequency of a pulsar in the data).
- Panel c): in this time series, the signal comes in a single isolated burst which is clearly visible above the noise.
- Panel d): same data as in Panel c) Fourier transformed; now there is no signal in the frequency domain, which is simply because there is no steady periodicity (just a single burst)

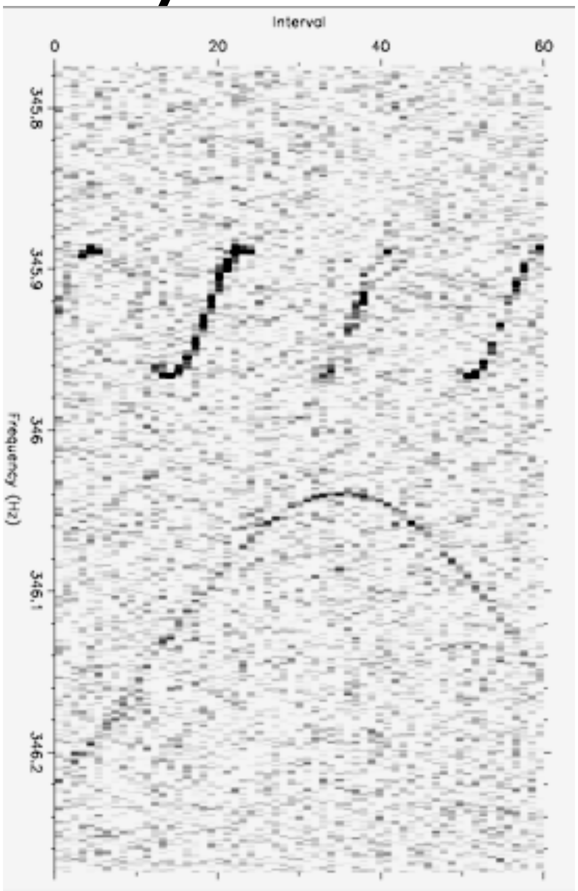
Standard Pulsar/Fast Transient Search



- Now the FFT (periodicity search) in a little more detail.

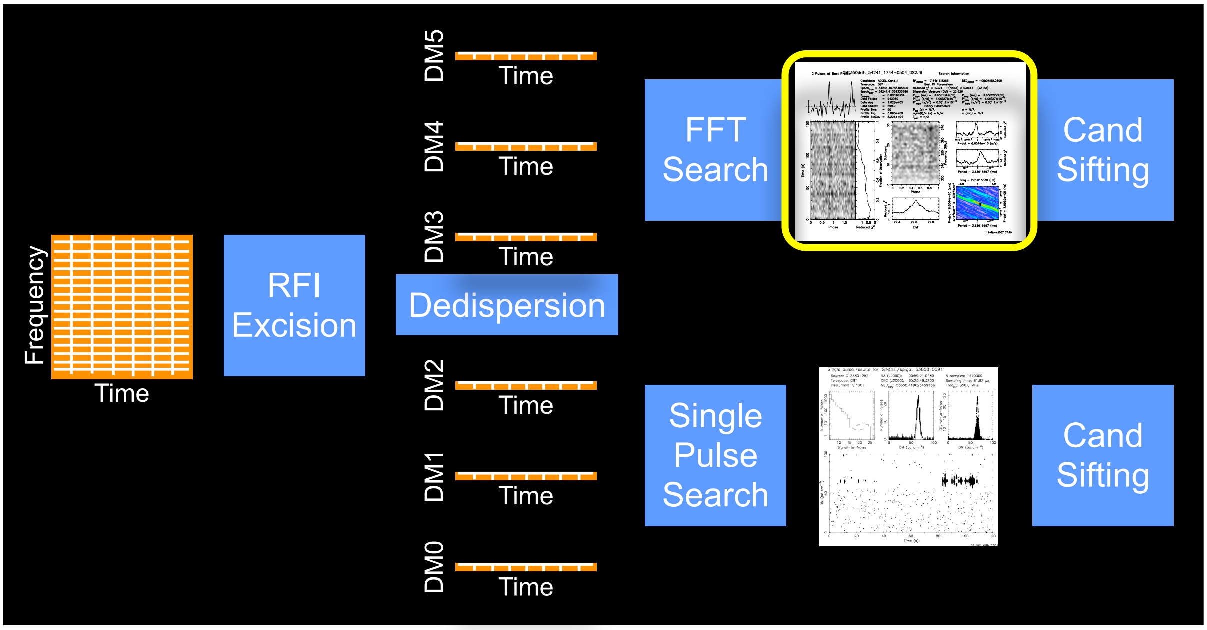
Detecting Binary Pulsars





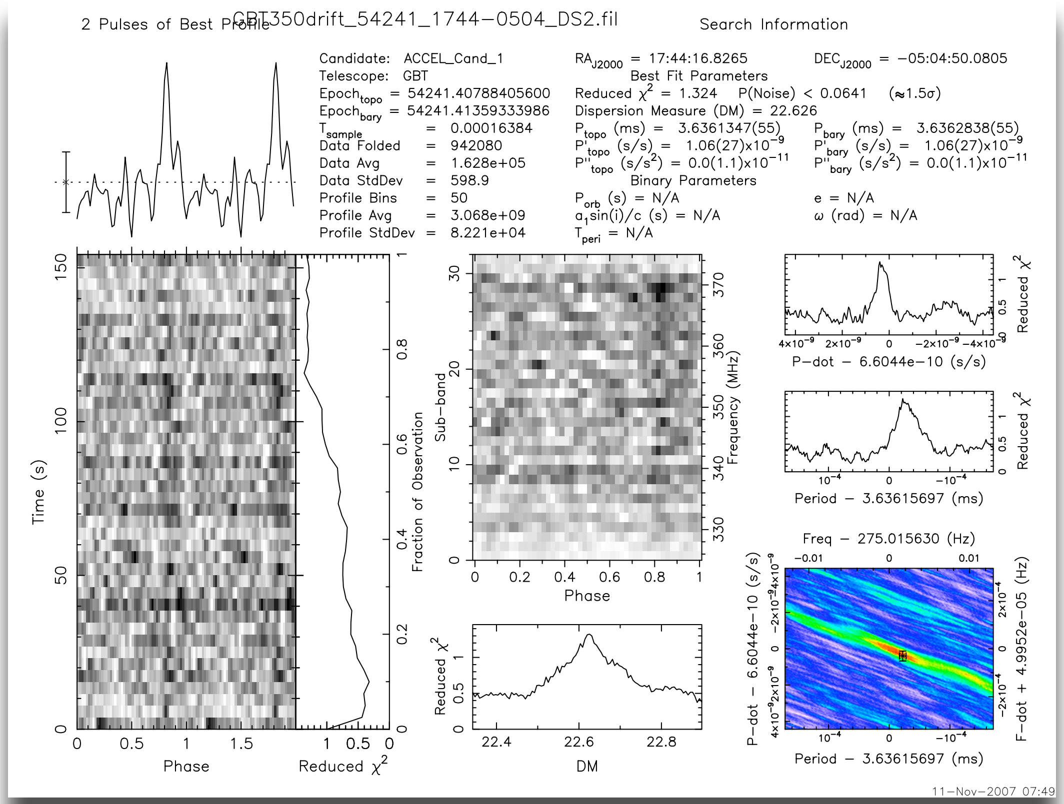
• Detecting periodicities of pulsars in binary systems is tricky because the Doppler shift causes the _observed_ pulsar periodicity to change during the observation.
• The left-hand figure shows how the orbital motion smears the signal in the "power spectrum" (square Fourier transform).
• The right-hand figure shows a bunch of short Fourier transforms during a long observation, stacked on top of each other. Here you can seen the sinusoidal modulation of the pulsar's observed pulse frequency.
• Why is one of the two pulsars only visible roughly half the time? Because it eclipses when it goes behind its companion star!

Standard Pulsar/Fast Transient Search



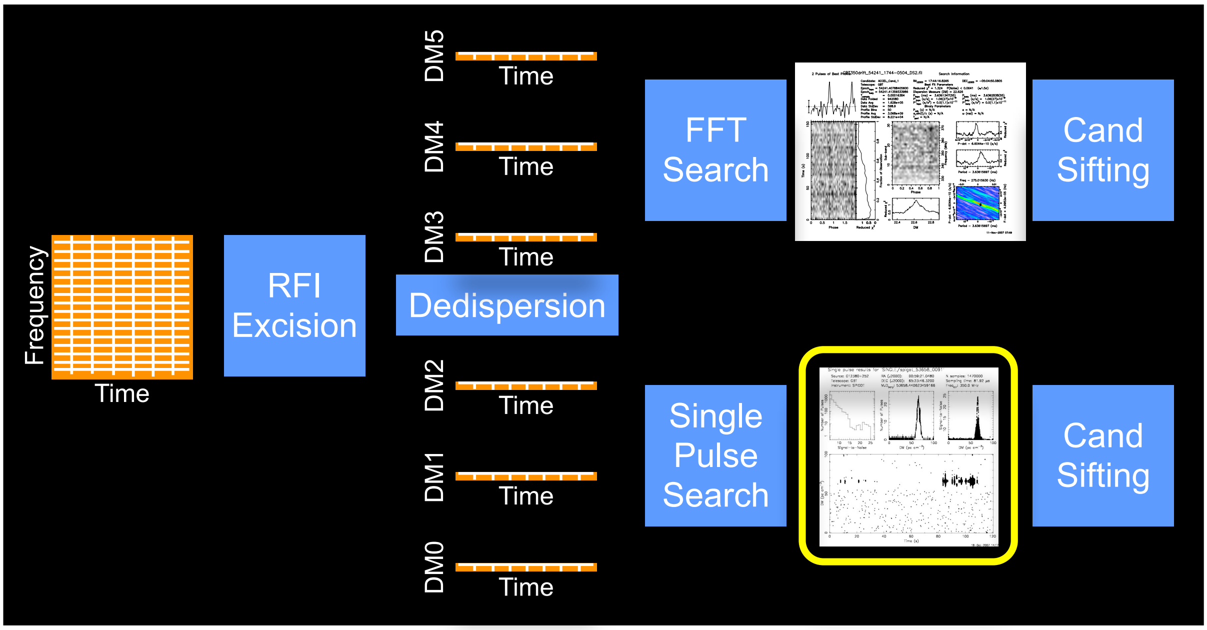
• In the practicum you will search for a pulsar using LOFAR data and the PRESTO software suite. Let's take a look at what PRESTO produces.

FFT (acceleration) searches



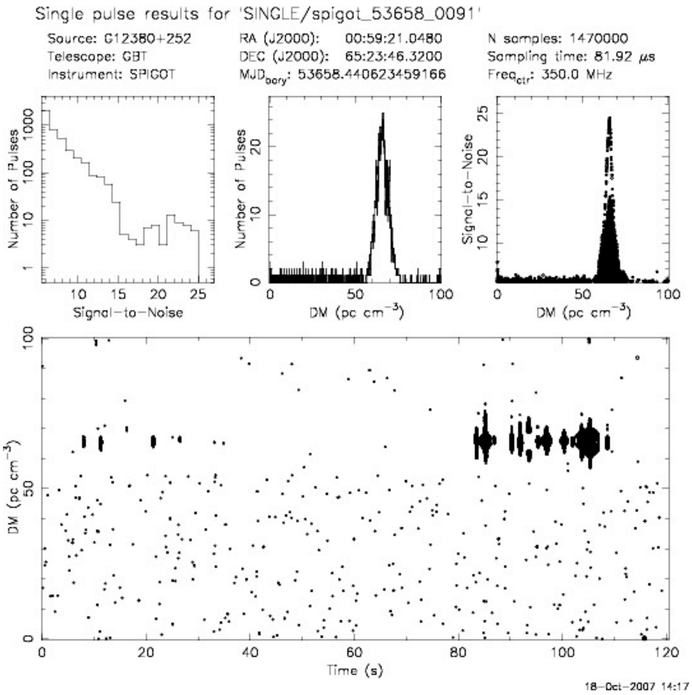
- This is one of PRESTO's diagnostic plots for judging the quality of a candidate pulsar signal.
- Left-hand the pulsar signal as a function of time. The full rotational phase is repeated twice and the summed signal over the whole observation is shown at the top.
- Central figure: the signal as a function of frequency. Below this we see how the signal-to-noise of the detection depends on the chosen dispersion measure.
- Right hand figures: the program tries to optimize the signal by tweaking the period and period-derivative that are used to "fold" the data (remember from previous lectures, the data in time is cut into chunks that are equal in length to the pulse period and then added to each other)

Standard Pulsar/Fast Transient Search



- We can also search for individual bursts (though we won't do this in the practicum).

Single-Pulse Search

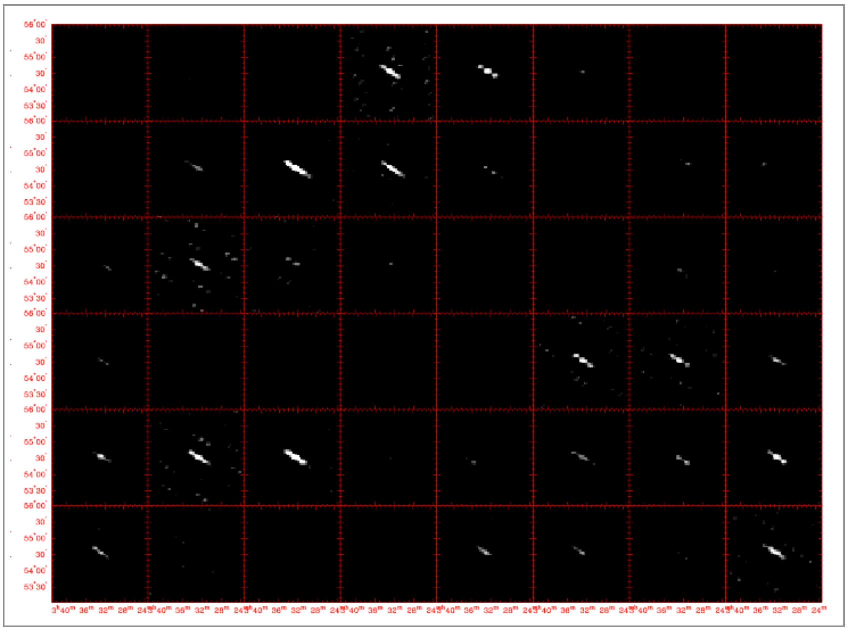


• This is a diagnostic plot showing what bursts were detected in a particular observation. The bottom panel shows signal strength as a function of dispersion measure and time.

Fast imaging and uv-plane techniques

• We said earlier that we used tied-array beams because imaging at 1-ms timescales was unfeasible. That's not completely true, and as computing power advances we're more and more able to do this.

Fast Imaging: B0329+54

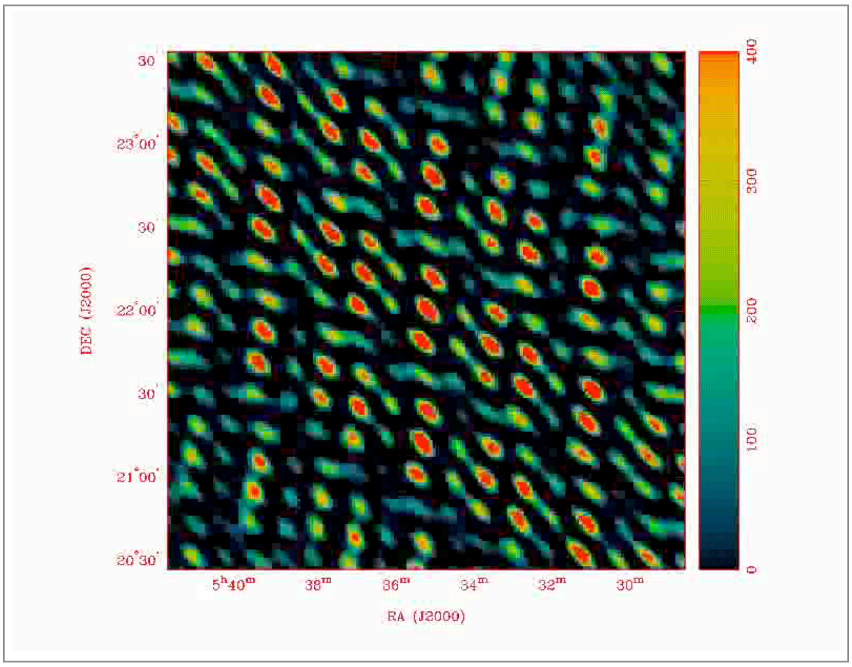


- Series of 100-ms images made with the Allen Telescope Array.
- Repeating, pulsed signal from B0329+54 can be seen.

Law

• For example, each of these panels is a 100-ms slice in time which show the pulsed signal from the pulsar B0329+54. (sometime we see nothing, this is when the pulsar beam is pointed away from us)

Fast Imaging: Crab Giant Pulse

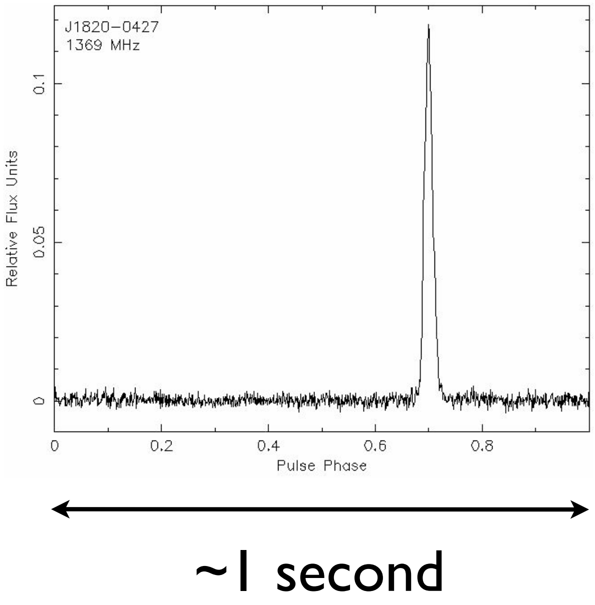


- Movie showing imaging of a Crab giant pulse at 1/40th of the actual speed.
- Dedispersion required.

Law

- Here's a movie showing an image of a giant pulse from the Crab pulsar.
- **QUESTION: WHY DON'T WE JUST SEE A POINT SOURCE? ANSWER: THE REPEATING POINTS ARE DUE TO THE INSTANTANEOUS SYNTHESIZED BEAM PATTERN (THE SIDE-LOBES) OF THIS TELESCOPE. YOU CAN IMAGINE HOW HARD IT WOULD BE TO LOCALIZE THIS SOURCE IF YOU DIDN'T KNOW ITS POSITION.**

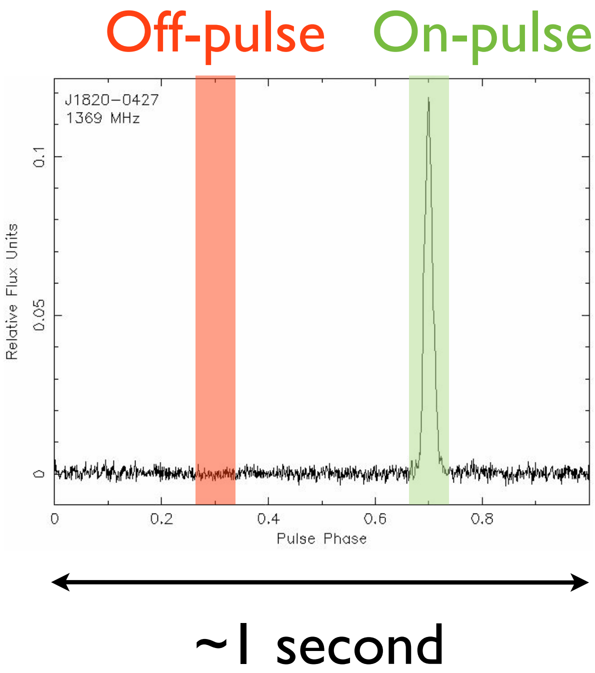
Pulse Gating



- Pulsars typically have narrow duty cycles (~5% for slow pulsars, ~20% for millisecond pulsars).
- Need tsamp < spin period in order to see pulsations.
- S/N is also poor if pulse is not resolved.
- Problem: can't dump correlator fast enough. Also, lots of the data is uninteresting because the pulsar is mostly off.

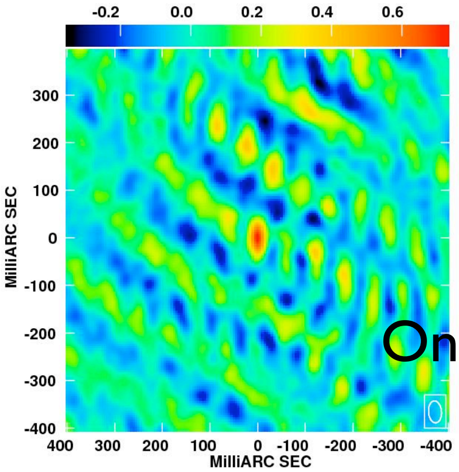
• Another useful trick is "gating"; here we just store the data during the part of the pulsar rotation in which there is a signal.

Pulse Gating

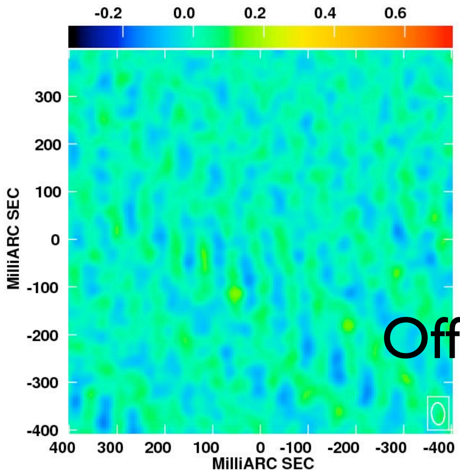


- Solution: use the pulsar timing ephemeris to predict which bits of data the pulsar is on and only write out those integrations.
- Can also use binning to give a coarse image of the pulse with time.

- You can also record an off-pulse window for comparison.



On-pulse



Off-pulse

Pulse Gating

- Preliminary images of PSR J2032+4127 obtained with 6 stations of the EVN at 1.6 GHz. The data were correlated with the new DiFX correlator in Bonn using pulsar gating, which improved the signal-to-noise ratio by a factor of 2. The left image corresponds to the data correlated during on-pulse (0.1 phase bin), and the right image during off-pulse (for a 0.1 phase bin as well).

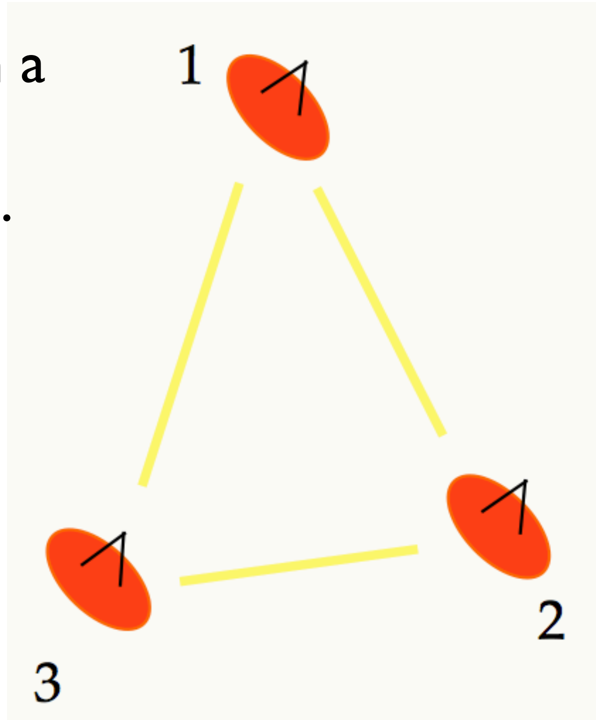
- Here we see images of the on-pulse (pulsar pointed towards us) and off-pulse (pulsar pointed away from us) regions.

Closure quantities

- Combination of visibilities on a closed loop is independent of source location and calibration.

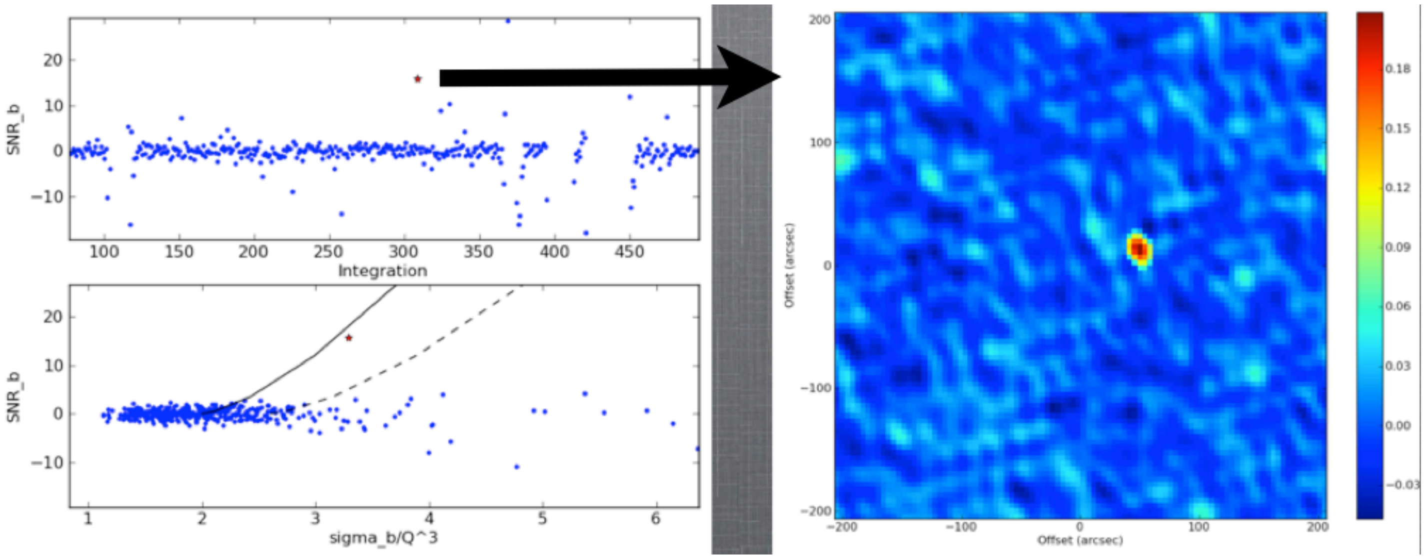
$$\Theta_{12} + \Theta_{23} + \Theta_{31}$$

$$V_{12} * V_{23} * V_{31}$$



- We also don't necessarily need to image the data at high time resolution. Instead we can look at the statistic of the raw visibilities at high time resolution in order to see if a transient event has occurred (if it has then we can record the visibilities at high time resolution for a short period of time).
- One trick is to use the fact that the product of the visibilities on a closed triangular loop should be a constant quantity and to use this to look for sudden transients.

Bi-spectrum detection method



- Transient astronomical signal sticks out like a sore thumb.
- Save those data and image the pulse.

Law

- Can use a statistical quantity called the "bi-spectrum" on the raw visibilities (at high time resolution) to tell you when to trigger a high-time-resolution recording of the visibilities for subsequent imaging.

Astrometry and pulsar distances

- Precise positions are important for multi-wavelength associations as well as proper motion studies.
- Precise distances are important for the interpretation of many observed quantities.
- Interferometers can help a lot with both astrometry and even distances (through parallax measurements).

Astrometry

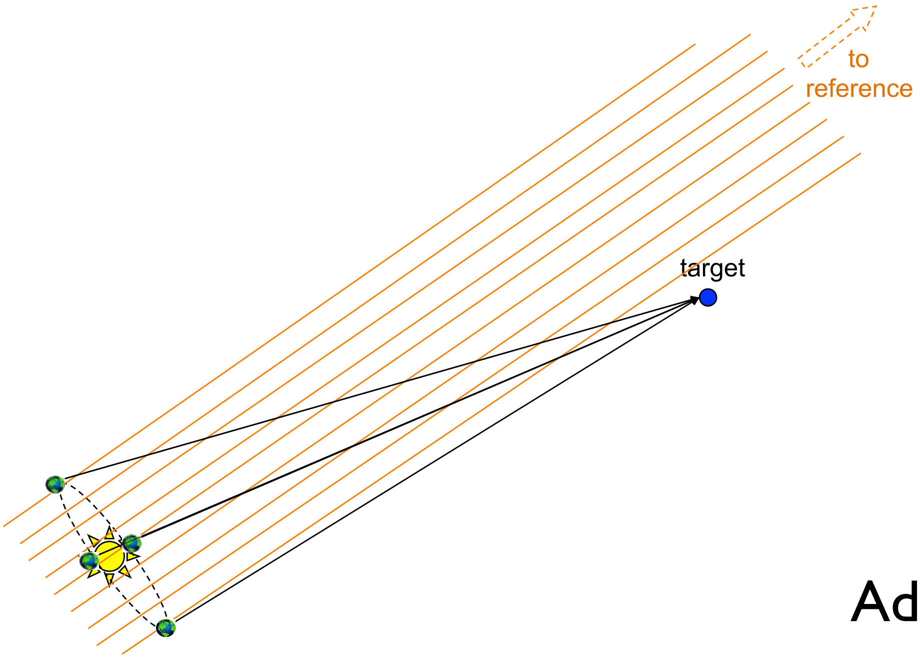
• Astrometry is the concrete base supporting all distance models.

• Distance ladder reaches from precision parsec-level measurements in our Galaxy out to inferred Gpc cosmological distances.

• Incredibly important because the scientific consequences of distance are far-reaching (e.g. luminosity is proportional to distance squared).

• Distance scales are critical in astronomy, and linking varies astrometric and distance scales is an important part of this.

Distance and Velocity via Astrometry



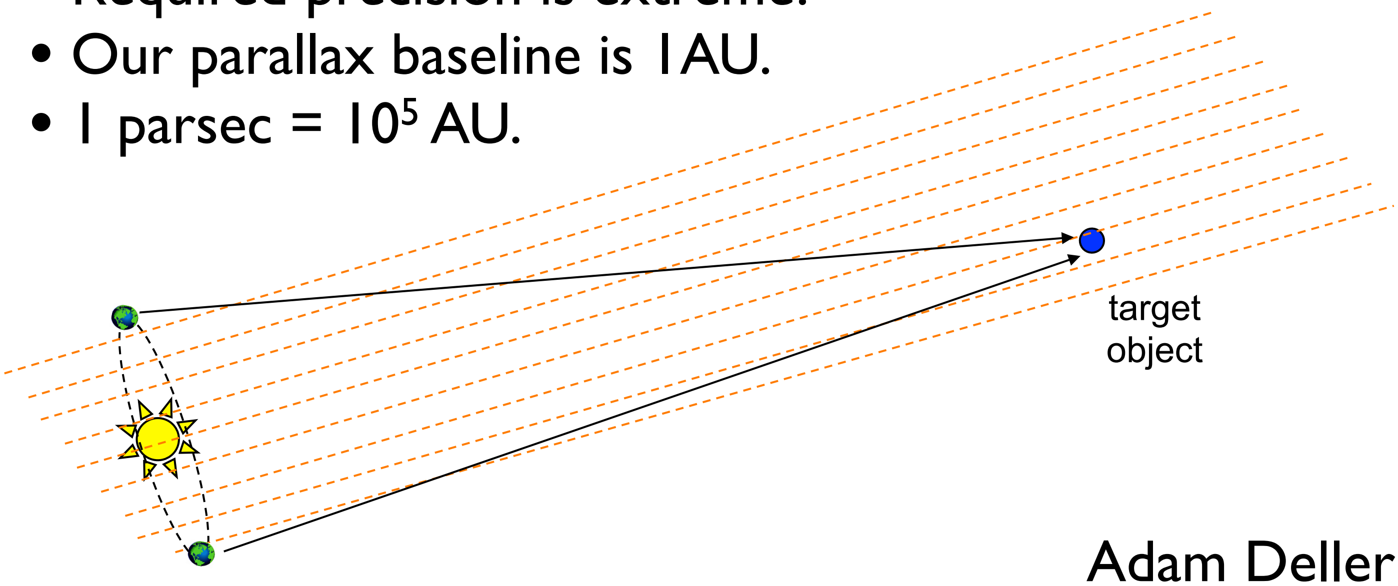
Adam Deller

- Measure positions over time with respect to a fixed reference frame.

- We can get extremely high angular resolution using long interferometric baselines, but this is only useful if we can relate this to a reference frame.
- The motion of Earth around the Sun allows us to view the target source from various angles. It should shift in position with respect to more distant sources. (surely you've seen the concept of parallax in other areas of astronomy as well)

Distance and Velocity via Astrometry

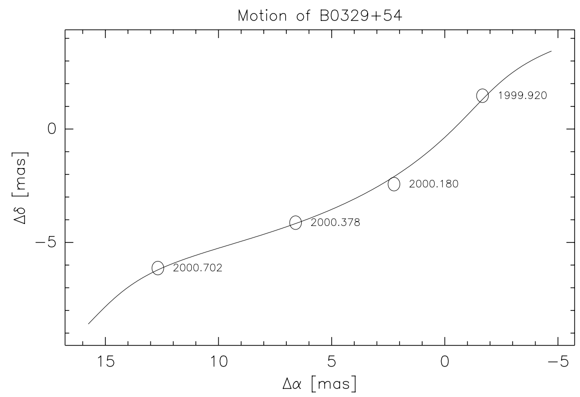
- Required precision is extreme.
- Our parallax baseline is 1AU.
- 1 parsec = 10^5 AU.

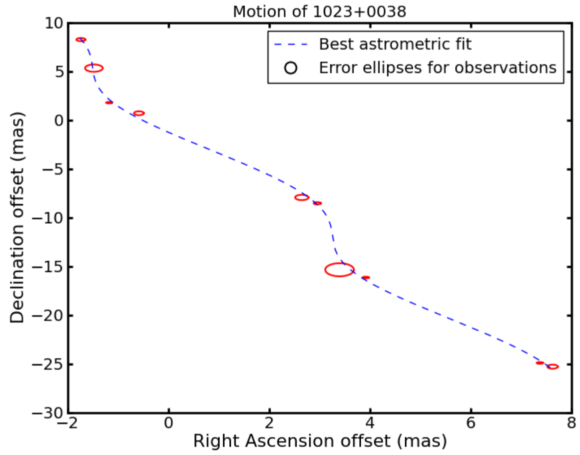


Adam Deller

- Distance scale in Galaxy (~kpc) is foreshortened by a factor of 10^8!

Pulsar Astrometry with VLBI





- Very Long Baseline Interferometry (VLBI) has the precision to measure both the proper motion and distance to pulsars given multi-year monitoring campaigns.
- Linear trend is the proper motion. Extra “squiggle” is from parallax.

Chatterjee, Deller

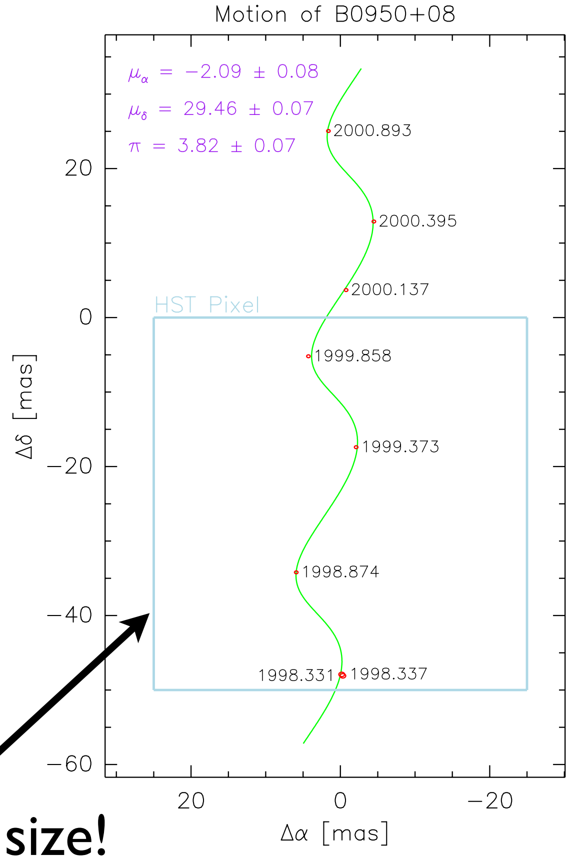
Pulsar Astrometry with VLBI

Distance (kpc)	Velocity (km/s)	Parallax (mas)	Proper motion (mas/yr)
0.1	10	10	21.1
10	200	0.1	4.2
770	100	0.0013	0.027

Current Galactic applications

Tiny fractions of a resolution element, even for e.g. Hubble (50+ mas)

- Need 10's-100 *micro*-arcsecond precision on the position at each epoch.



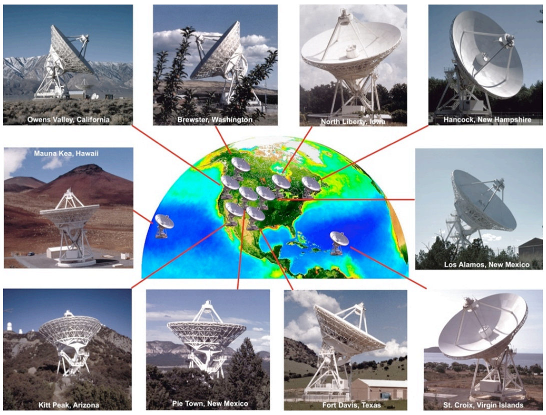
Adam Deller

Hubble pixel size!

Astrometry with VLBI

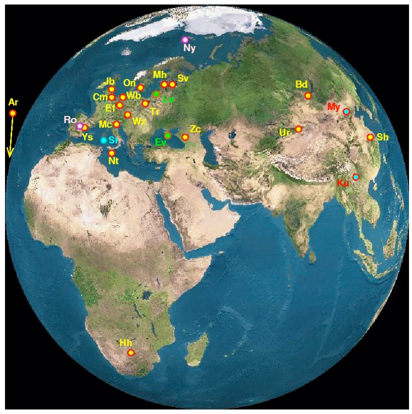
$$\Theta = \frac{\lambda}{D}$$

$$\lambda \sim \mathrm{cm}$$
$$D \sim 1000\mathrm{km}$$
$$\Theta \sim \mathrm{mas}$$



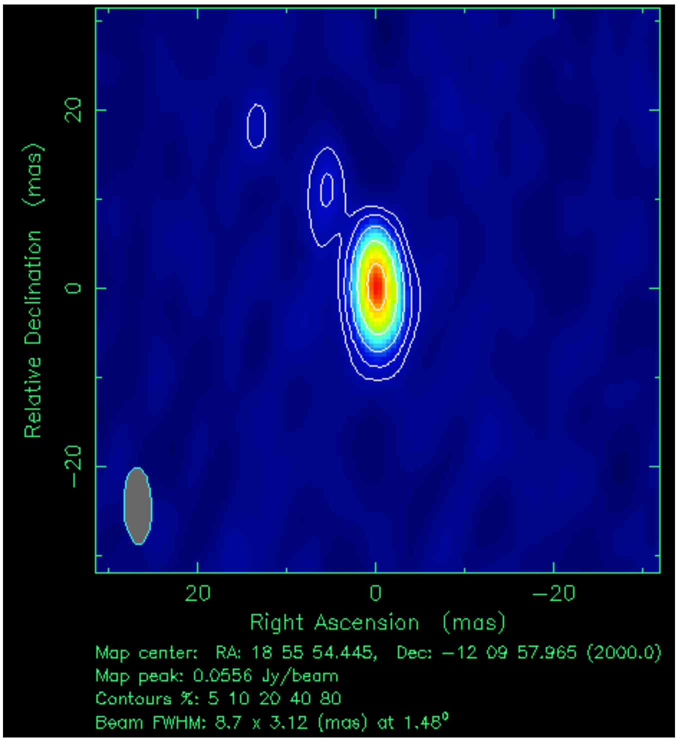
VLBA, USA

EVN, Europe



Global VLBI

Astrometry with VLBI



$$\delta(\text{Position}) \sim \frac{\text{PSF}}{2 \times \text{S/N}}$$

- With proper calibration the beam size (PSF) is very stable and depends only on the antenna positions.

- Need to do better than just the beam size (PSF).

Astrometry with VLBI

Ideal situation

Take a short observation with the VLBA @ 8 GHz, with 1.25 hours on target:

- Beam size is 1 x 2 mas
- Image sensitivity is 35 Jy
- Say your source is 1 mJy (faint!), giving you a modest S/N ~ 30
- Your limiting positional accuracy will be
  1/60 mas = **16 micro-as**!
- With more integration time/more sensitive arrays/brighter sources it is trivial to do many times better

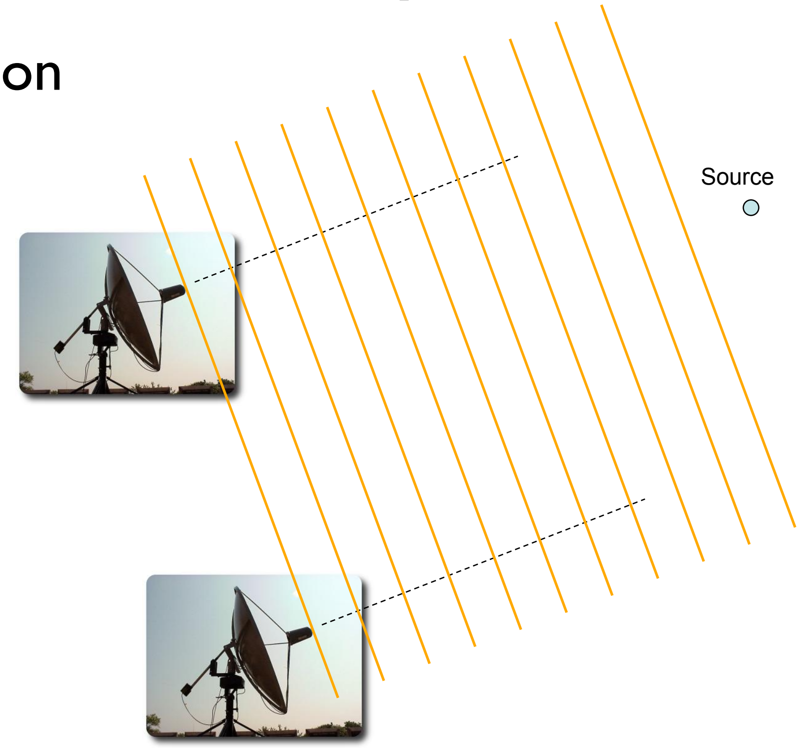
…in theory

Real world situation

Anything which causes relative delays in the arrival time of the signal will lead to errors in positional estimation

Astrometry with VLBI

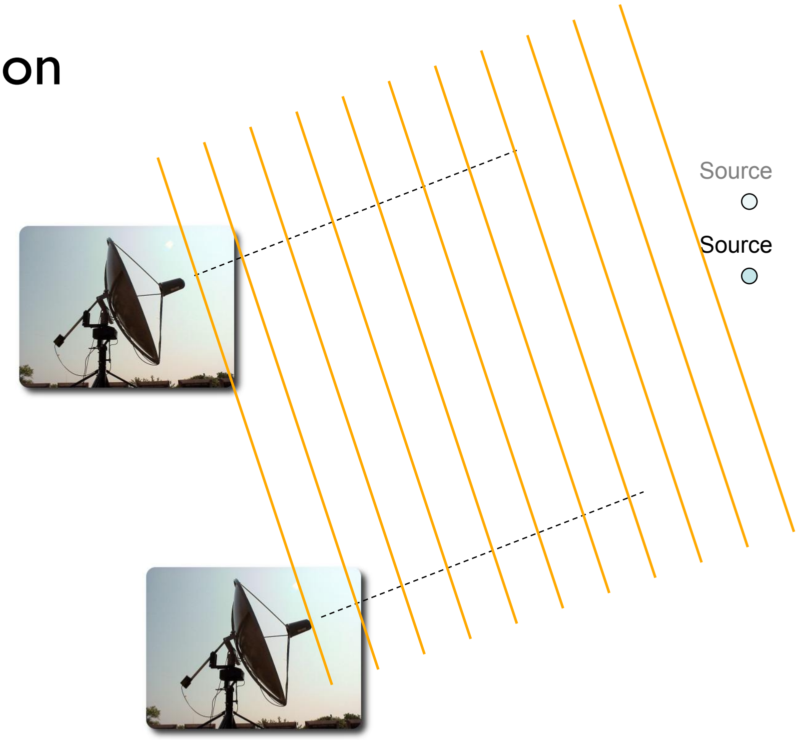
Ideal situation



Minute change in source position will cause a minute but measurable differential arrival time

Astrometry with VLBI

Ideal situation

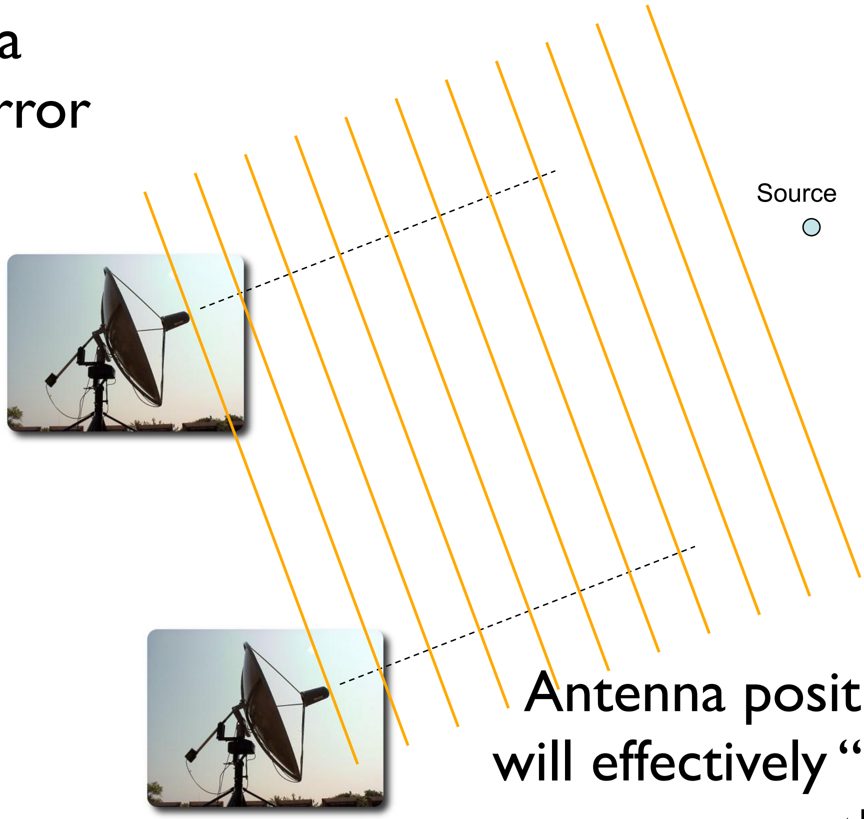


Long baselines are critical for getting the "lever arm" necessary to see the small position change

Astrometry with VLBI

Antenna position error

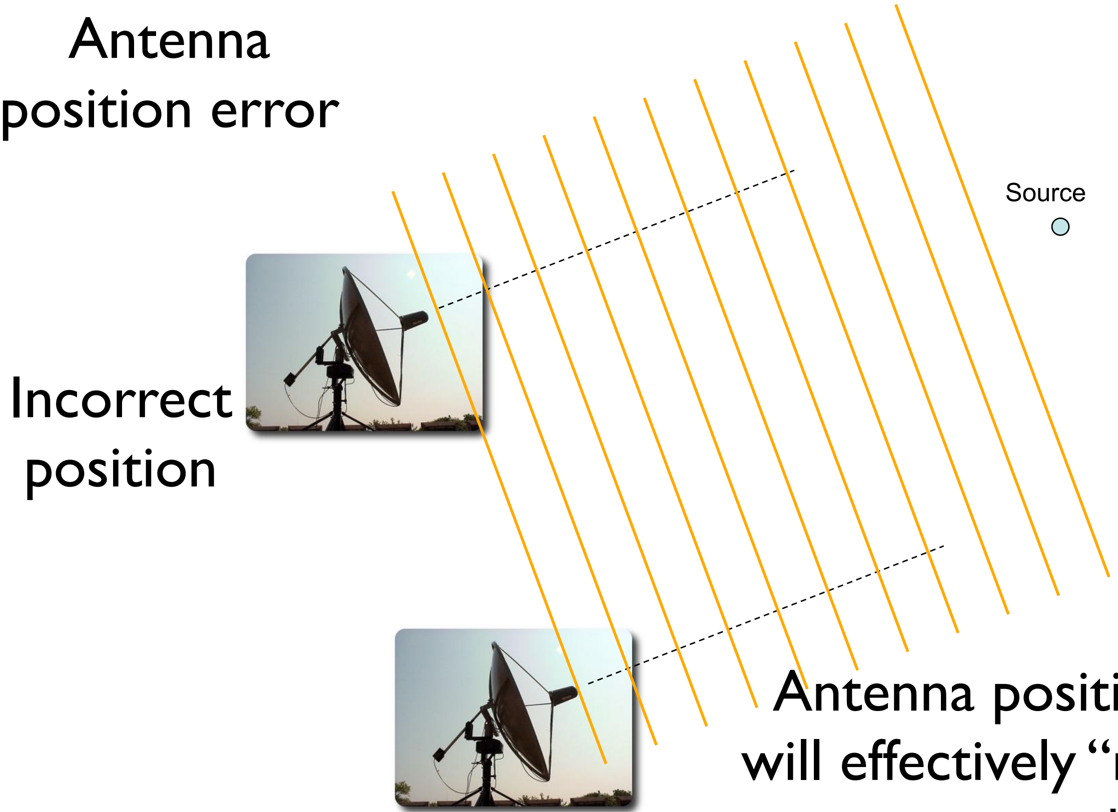
Correct position



Antenna position error will effectively "move" the source on the sky!

Astrometry with VLBI

Antenna position error

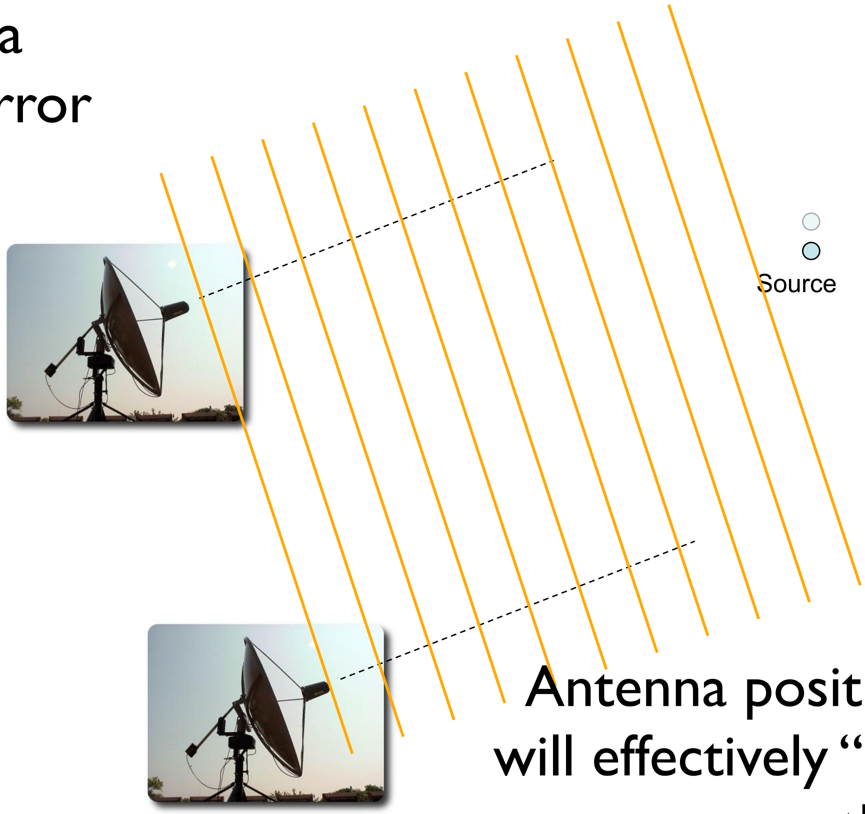


Antenna position error will effectively “move” the source on the sky!

Astrometry with VLBI

Antenna position error

Incorrect position



Incorrect source position

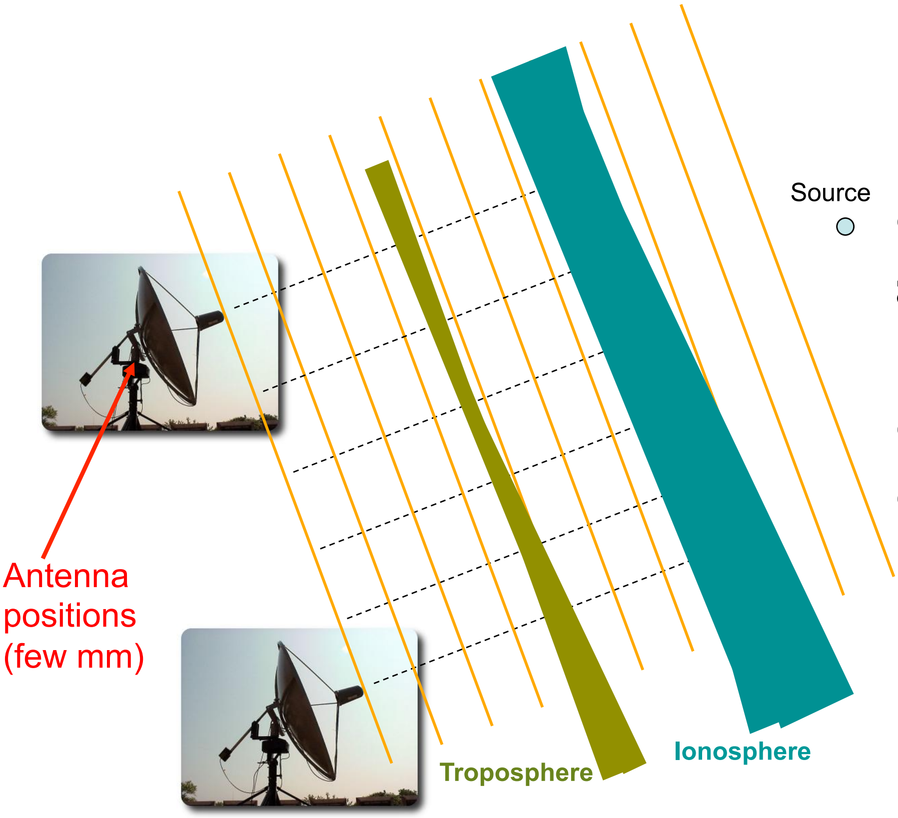
Antenna position error will effectively “move” the source on the sky!

Astrometry with VLBI

Real world situation

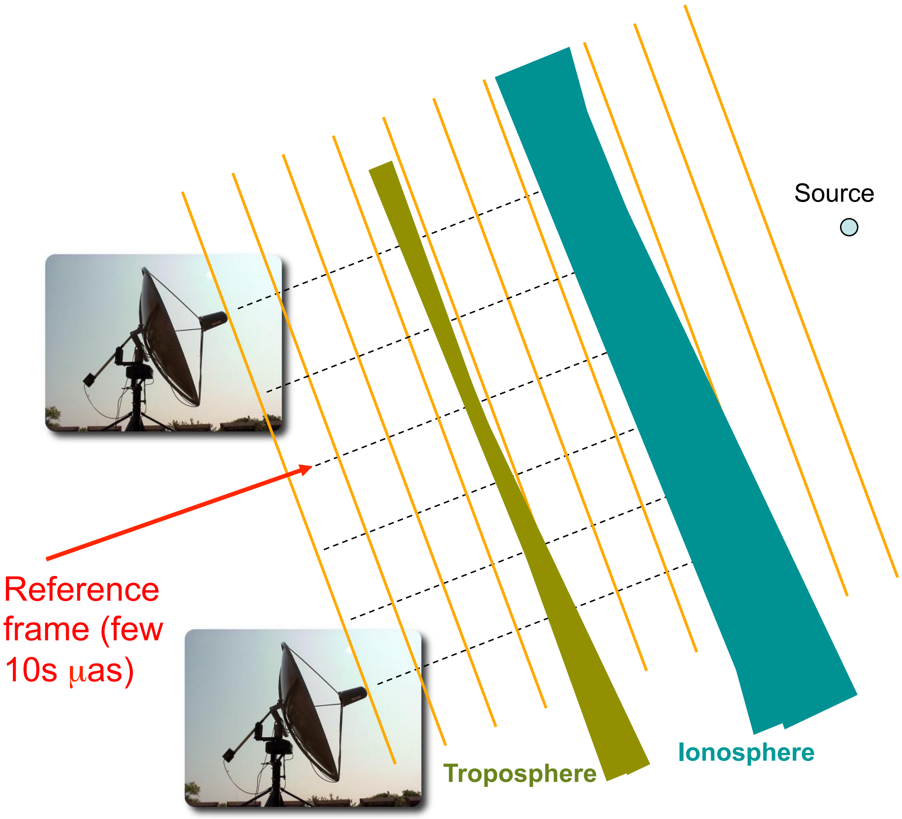
- **Anything** which causes relative delays in the arrival time of the signal will lead to errors in positional estimation
- The control of systematics has to be phenomenal:
  - 10 as angular change (5 x 10^{-11} radians) induces differential delay ~ **1 picosecond** on a 5000 km baseline
  - Equivalently, a path length error of 0.3 mm

Astrometry with VLBI



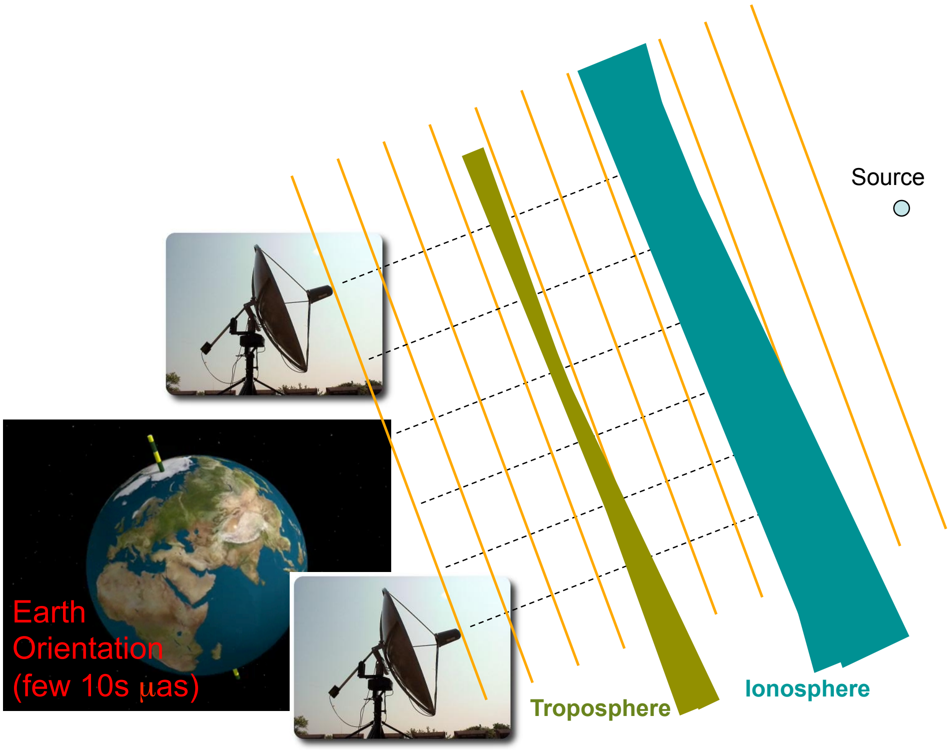
- Relative antenna positions (w.r.t. each other) are known to a few mm precision.
- These are constantly changing due to continental drift.

Astrometry with VLBI



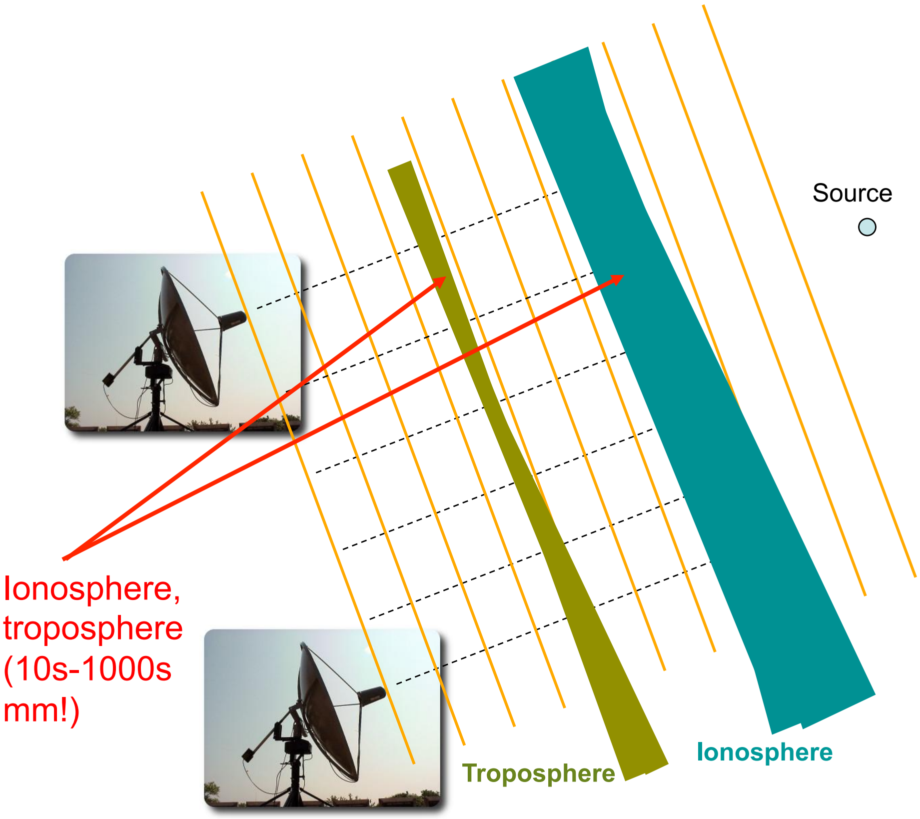
- Reference frame (e.g. J2000) itself is good to ~10s microarcseconds.

Astrometry with VLBI



- Earth orientation changes with time due to precession and nutation. This also introduces inaccuracies on the 10s microarcsecond level.

Astrometry with VLBI



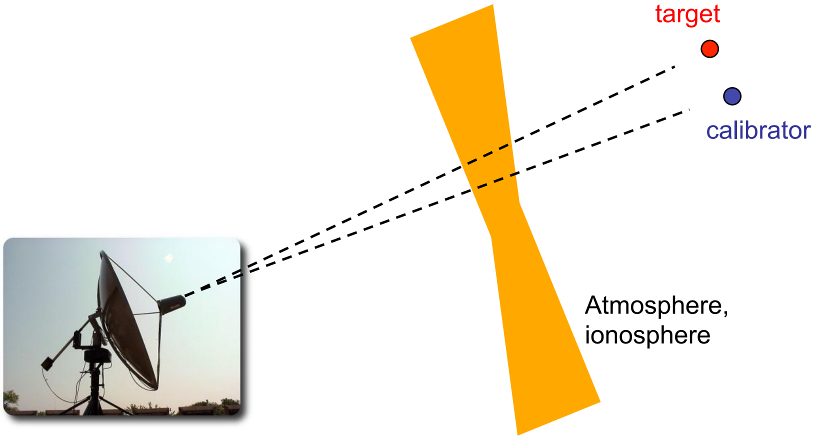
- Ionosphere and troposphere are highly dynamic, even on a few minute timescale.
- Depends on latitude, season, time of day, Solar activity, etc.
- Ionosphere a big problem at low frequencies.

Atmospheric Effects

Troposphere: bulk of atmosphere mass
- Non-dispersive (freq. independent) delay
- Depends on latitude, weather etc but predictable; with good model error ~50 mm

Ionosphere: charged particles, higher
- Ionised -> dispersive delay
- Highly dependant on solar weather, much less smooth than troposphere
- 1.6 GHz, good model + good day, error ~500 mm!

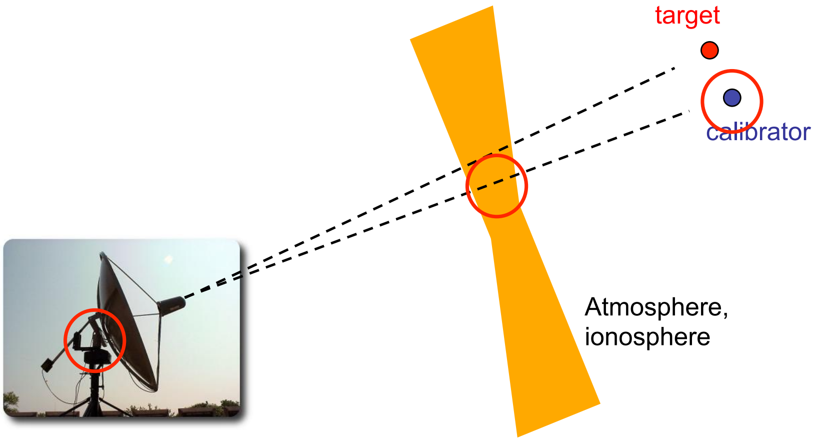
Relative Astrometry



Calibrate: nearby astronomical source

- Solve for and remove sum of all delays; residual will be of order sin(separation).
- Accuracy is seriously limited if a good nearby calibrator cannot be found.

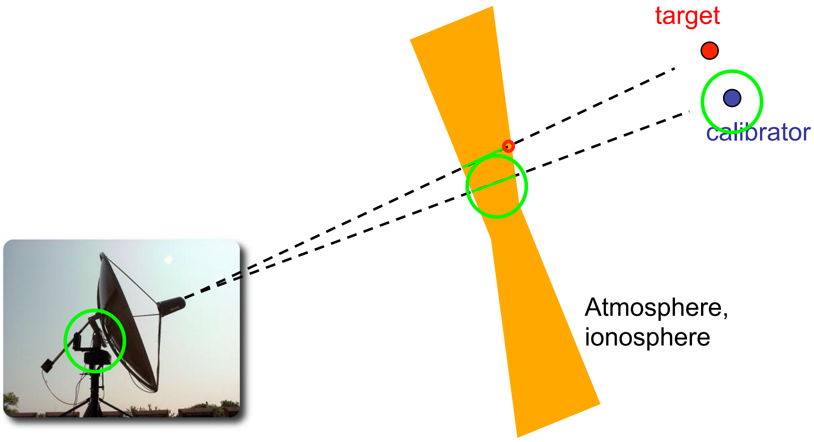
Relative Astrometry



Calibrate: nearby astronomical source

- Solve for and remove sum of all delays; residual will be of order sin(separation).
- Accuracy is seriously limited if a good nearby calibrator cannot be found.

Relative Astrometry



- Very important that the calibrator is unresolved and stable. It's the reference point after all...

Relative Astrometry

Getting ultimate positional accuracy of 20 microarcsec requires each measurement to have an accuracy of ~50 microarcsec

Corresponds to a path length of ~1.5 mm

High frequency (≥ 8 GHz, troposphere dominates):

Need a calibrator source within ~2°

Low frequency (~1.6 GHz, ionosphere dominates):

Need a calibrator source within ~10’

Pulsar Astrometry

Radio pulsars tick every box as interesting astrometric targets:

1) Compact
2) Hugely scientifically interesting: as gravitational wave detectors, probes of strong field gravity, dense nuclear matter, high energy emitters…
3) And: mostly, distance precision is appalling!

Pulsar Astrometry

(Refine distances to) the
same objects we search for

Exotic objects
Triple system,
pulsars with PWN…

Population analysis
Shklovskii corrections,
velocities…

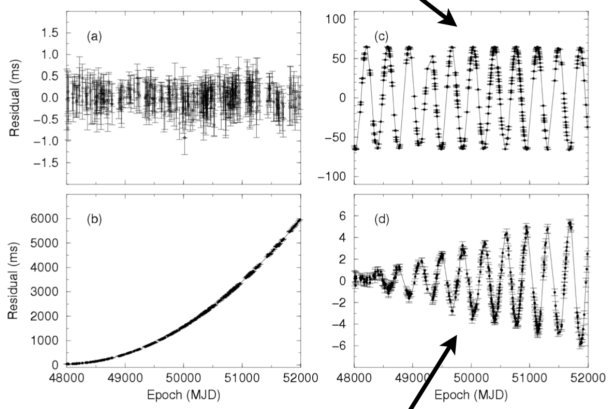
Multiwavelength observations
Get an accurate luminosity
(e.g. FERMI sources)

Tools for fundamental physics
PSR B1913+16

- Accurate and precision distance aids almost all areas of pulsar science.

Pulsar Astrometry

Signature of incorrect position

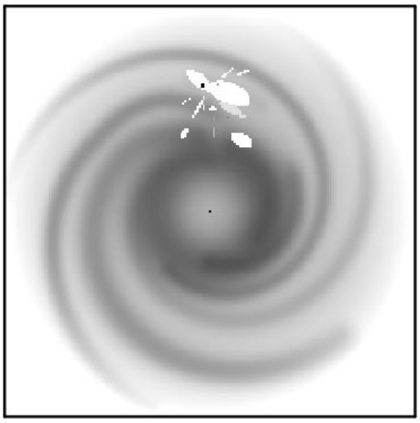


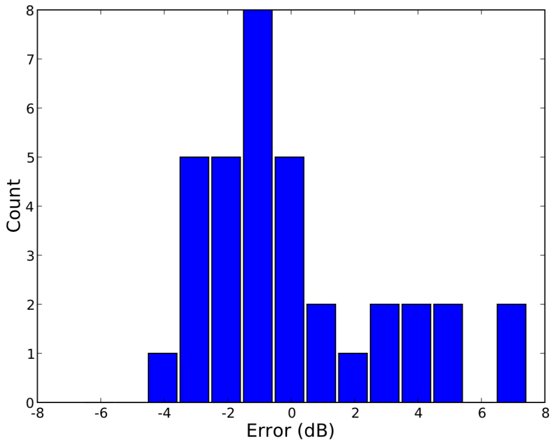
Proper motion signature

Pulsar timing residuals

- Recall that pulsar timing can give milliarcsecond positions and proper motions.
- Getting distance is only possible in a few extreme cases (need to see the curvature in the wave front from the arrival times!).

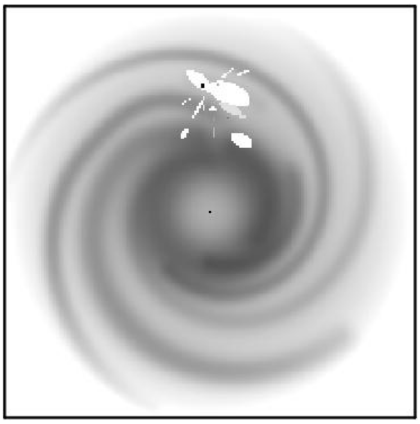
Pulsar Distances





- Top: the NE2001 electron density distribution model (Cordes & Lazio, 2002).
- Given a pulsar DM, can use NE2001 to get the distance.
- Problem: these are good to only about a factor of 2.
- Bottom: NE2001 distance errors compared with accurate astrometry measurements.

Pulsar Distances



The NE2001 model is anchored by just **112** distance measurements (plus some scattering measurements)

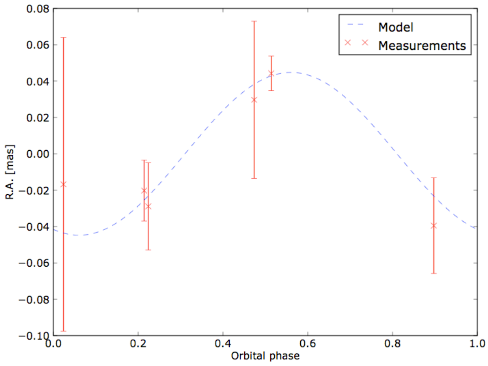
- Heavily concentrated in the solar neighbourhood
- Many are themselves model-dependent
  (HI plus Galactic rotation)
- Many are low quality - just **8** are model-independent with error of 10% or less

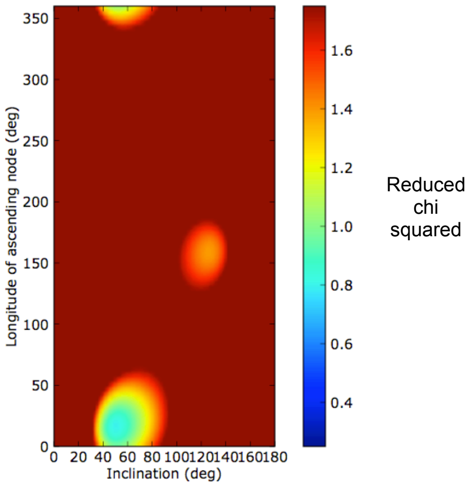
Binary Pulsar Astrometry

Example: PSR J1022+1001

Observed by PPTA and EPTA
7.8 day binary, recycled (P=16 ms)
Massive WD companion
DM distance: relatively near (~600 pc)
   Projected orbital motion ~ 50 microarcsecond
Observational details:
   7 epochs (of 9 total) in hand
   Pulsar is moderately bright, ~3 mJy

Binary Pulsar Astrometry





Full orbital solution:
- 39deg < inclination < 63deg
- -5deg < Omega < 40deg

Parallax 1.438 +/- 0.010 milliarcsec
- Distance 695 +/- 4 pc
- Transverse velocity 52.5 +/- 0.3 km/s

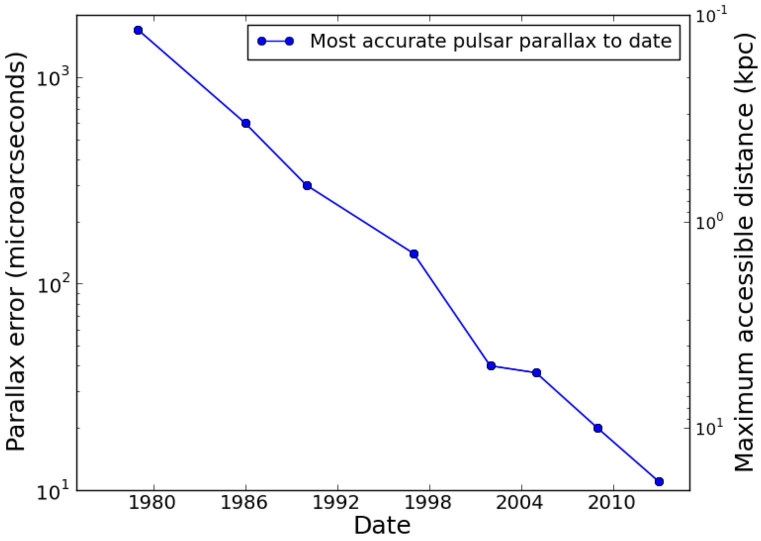
Needed just ~10 hours of VLBA time

Refined timing solution to come

Precise white dwarf constraints

Similar results for J2145-0750

VLBI Precision



- VLBI astrometry with the SKA will likely be a big business.

Sources

Figures from Adam Deller, Casey Law, and other (cited on slide)

Other course slides (see links on course wiki page):

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2015