SKA AFRICA
SQUARE KILOMETRE ARRAY

Radio Astronomy:

SKA-Era Interferometry and Other Challenges

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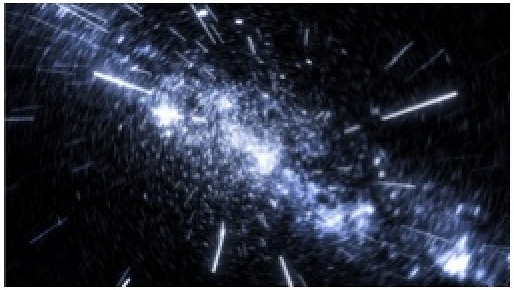
(and Dr Oleg Smirnov, Rhodes and SKA SA)

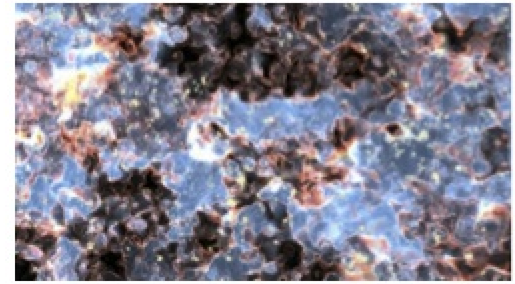
ASSA Symposium, Cape Town, Oct 2012

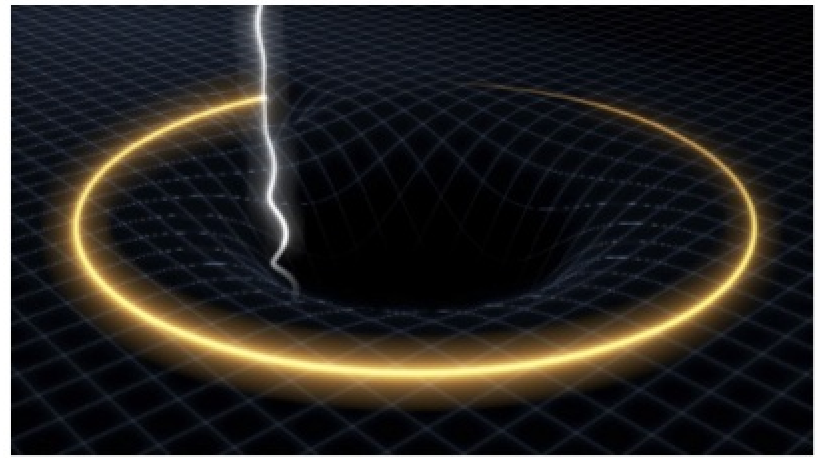
Scope

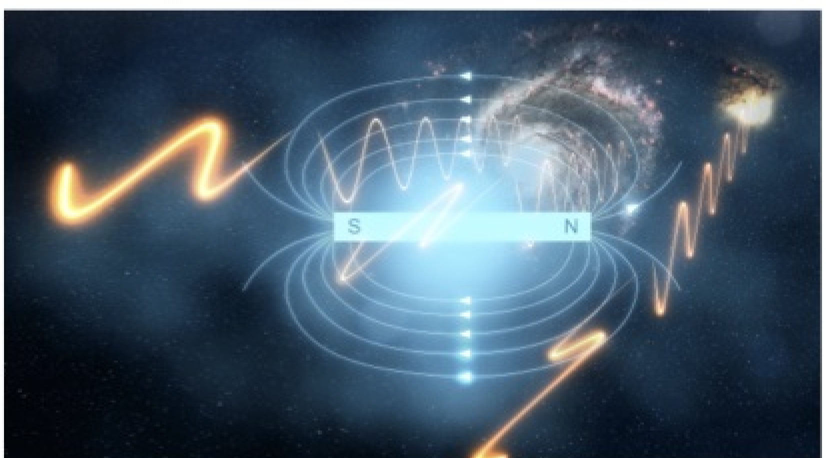
- SKA antenna types
- Single dishes and time domain signals
- Beyond single dishes: arrays
- Making radio images from arrays
- Making (better) radio images from arrays
- Making better radio images from arrays (quickly)
- Data rate considerations
- Conclusion

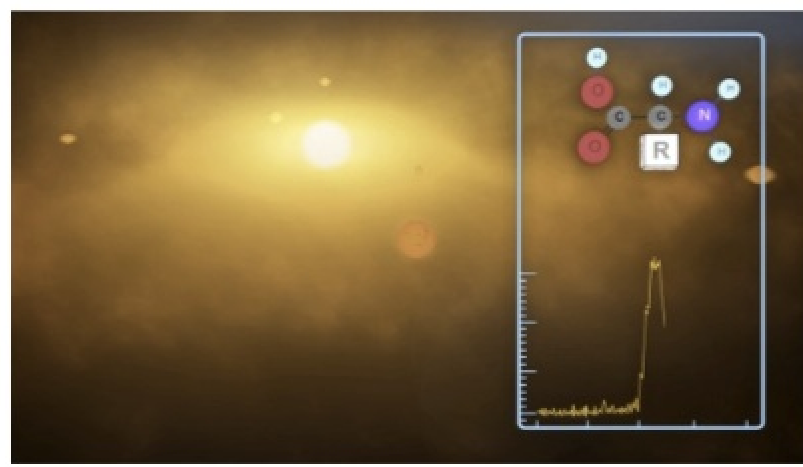


SKA Science

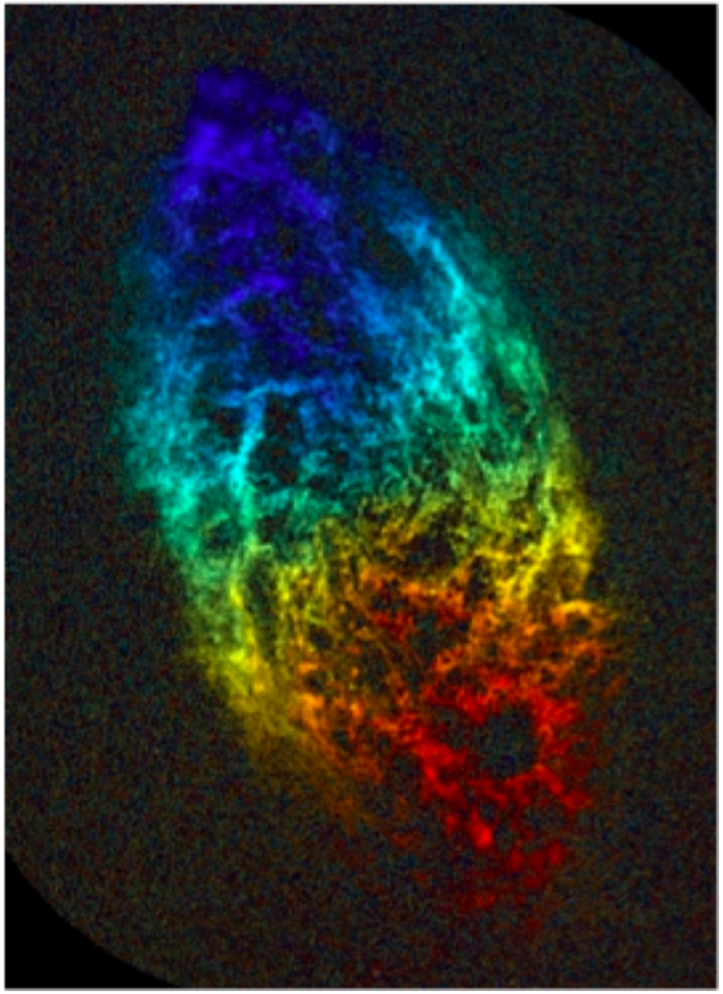








Radio (and Optical) Images



M33
Image courtesy of NRAO/AUI

NGC1316 / Fornax A
Image courtesy of NRAO/AUI and J.M. Uson

Radio Astronomy: Antennas

- Radio -> Detecting light not sound!
- Think car radio aerial as a start
- Looking for radio signals from space - mostly "naturally" generated
- Signals are typically (very) weak and buried in instrument noise

Our "Aerial": MeerKAT L-Band Feed

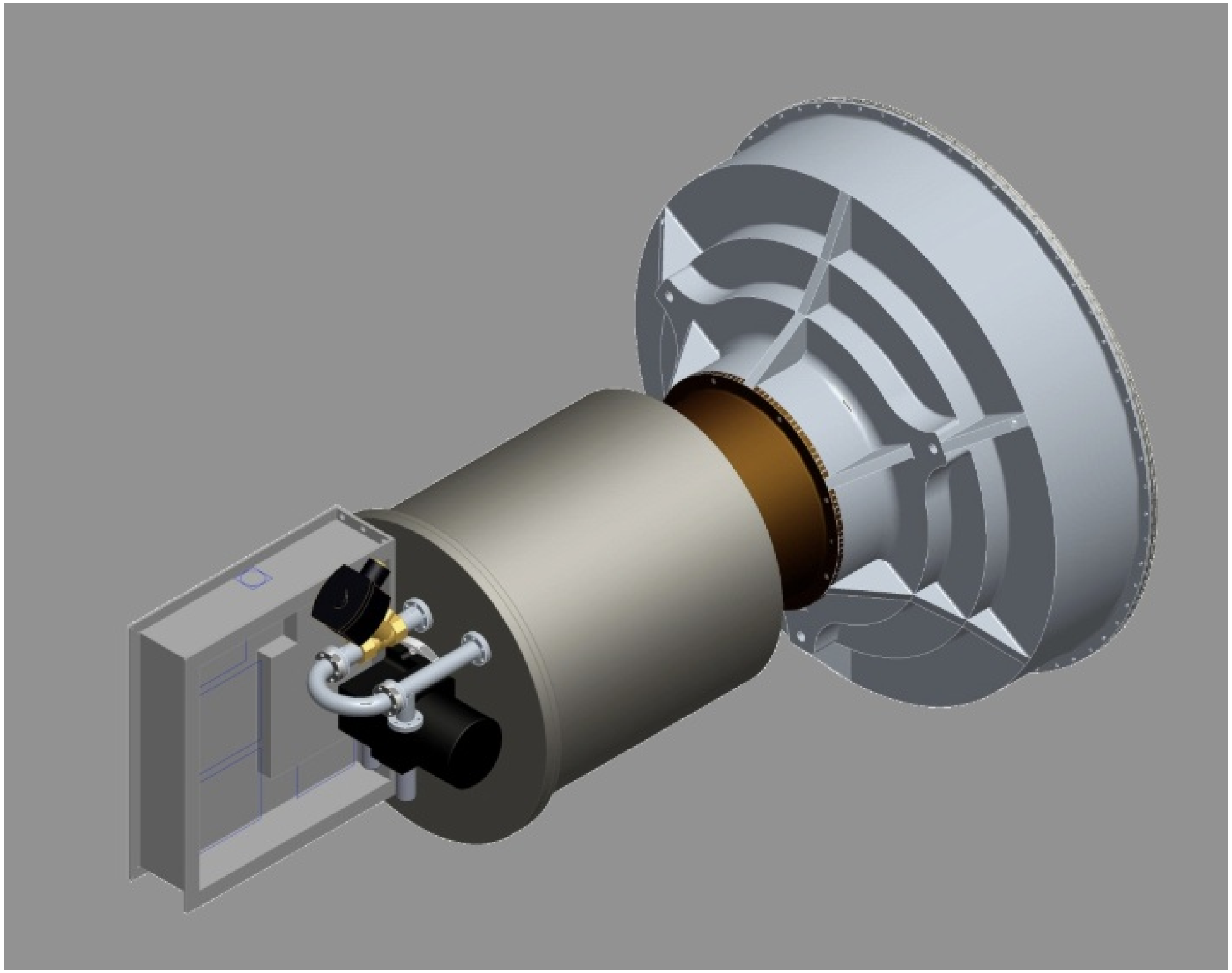


Image credit: EMSS Antennas

MeerKAT Horn, OMT and Coupler

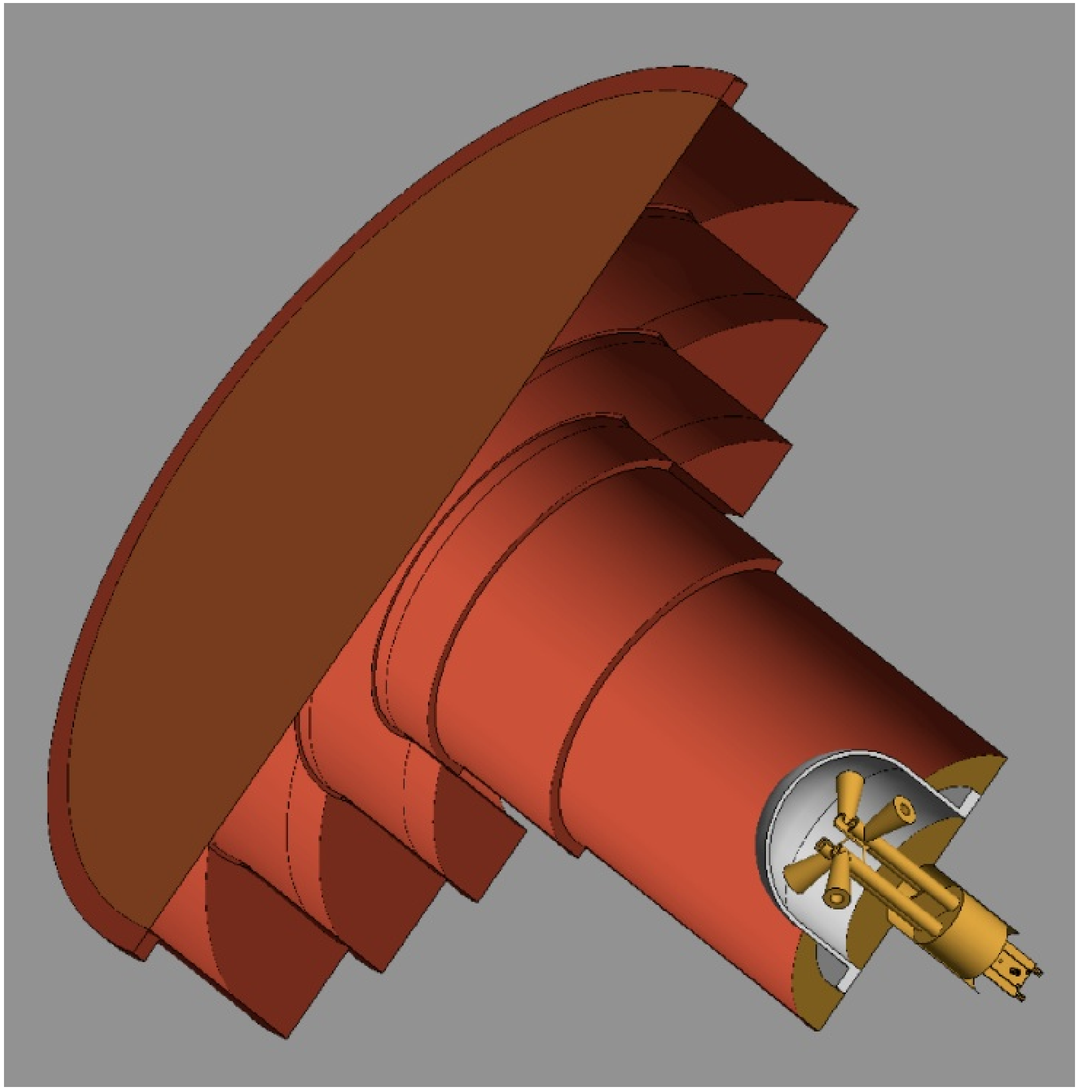


Image credit:
EMSS Antennas

OMT

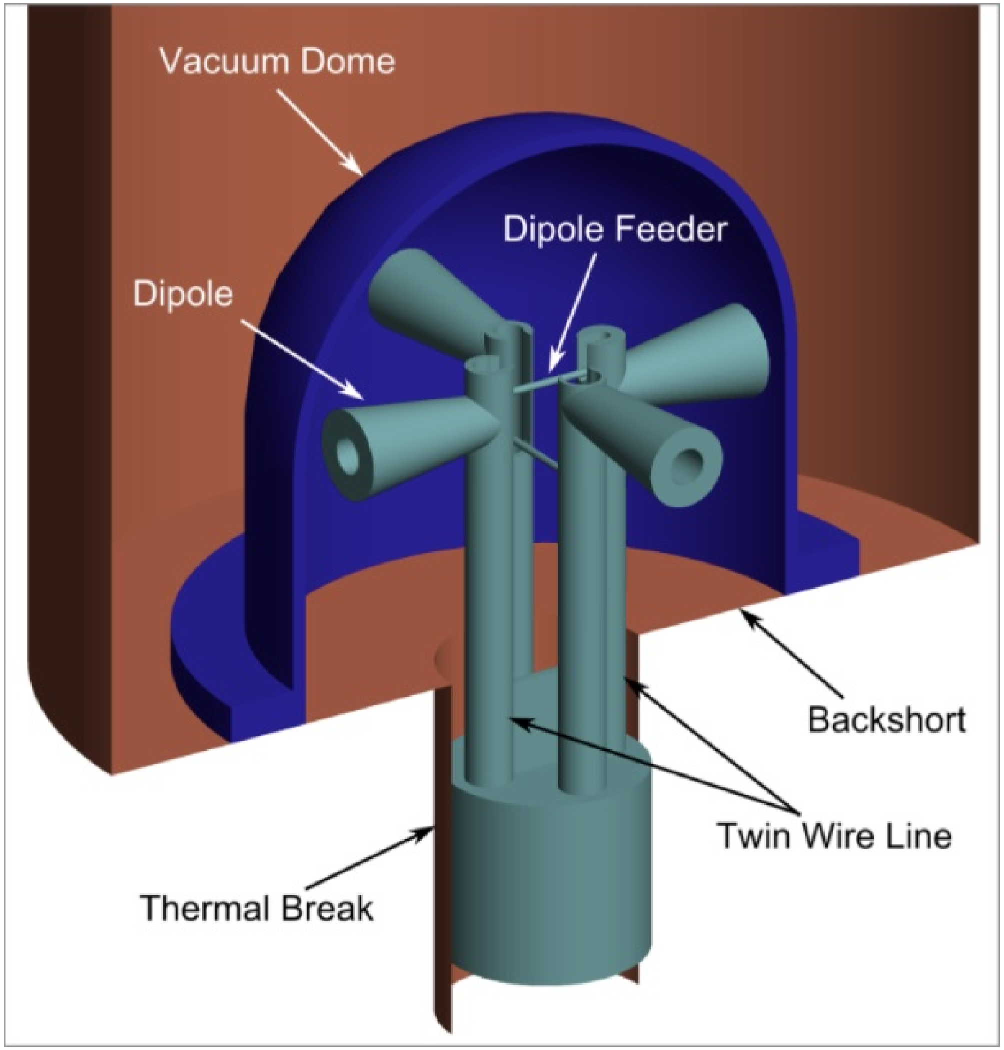
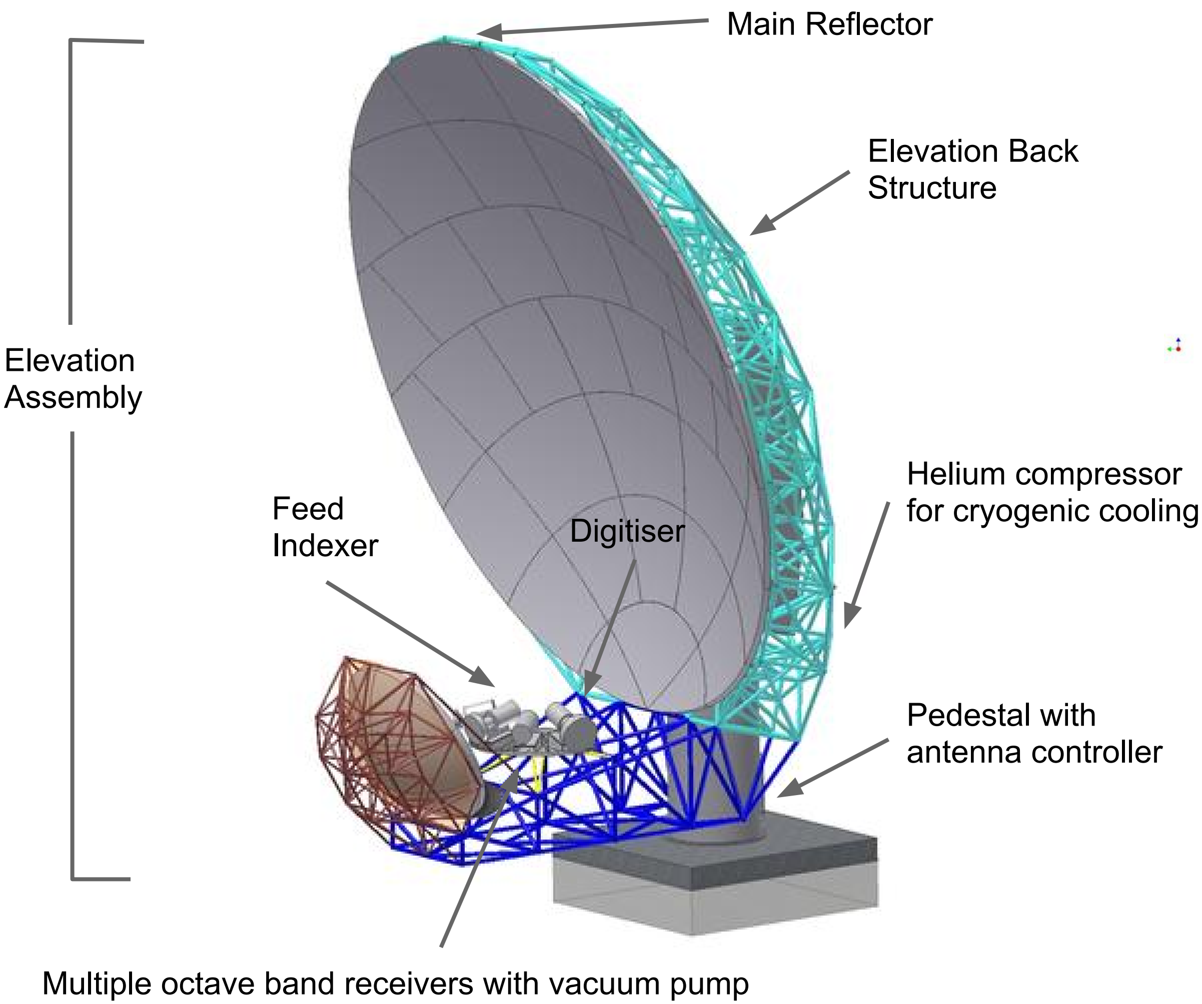
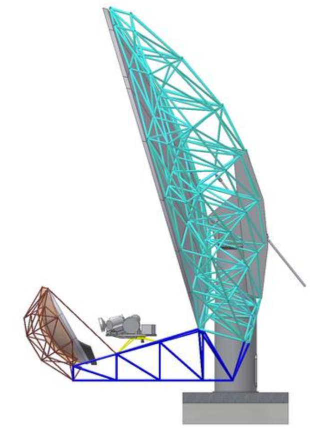


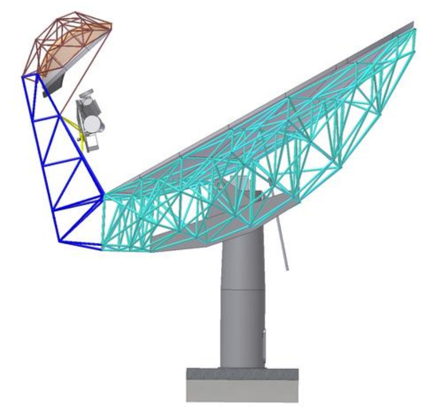
Image credit:
EMSS Antennas

Feeds with Dishes: KAT-7 Prime Focus Antennas

MeerKAT Offset Gregorian Antenna







Prime Focus vs Offset Gregorian Patterns

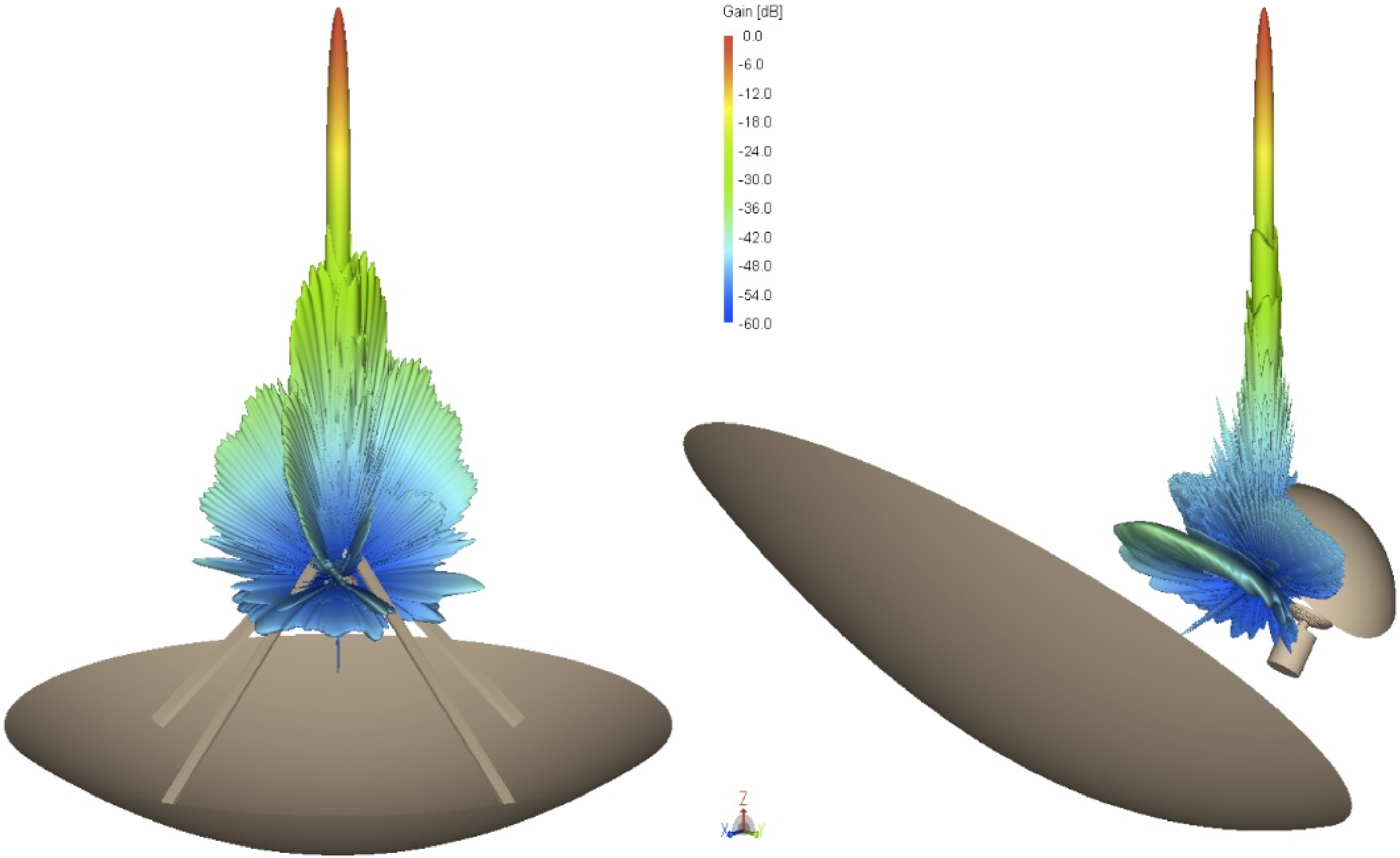


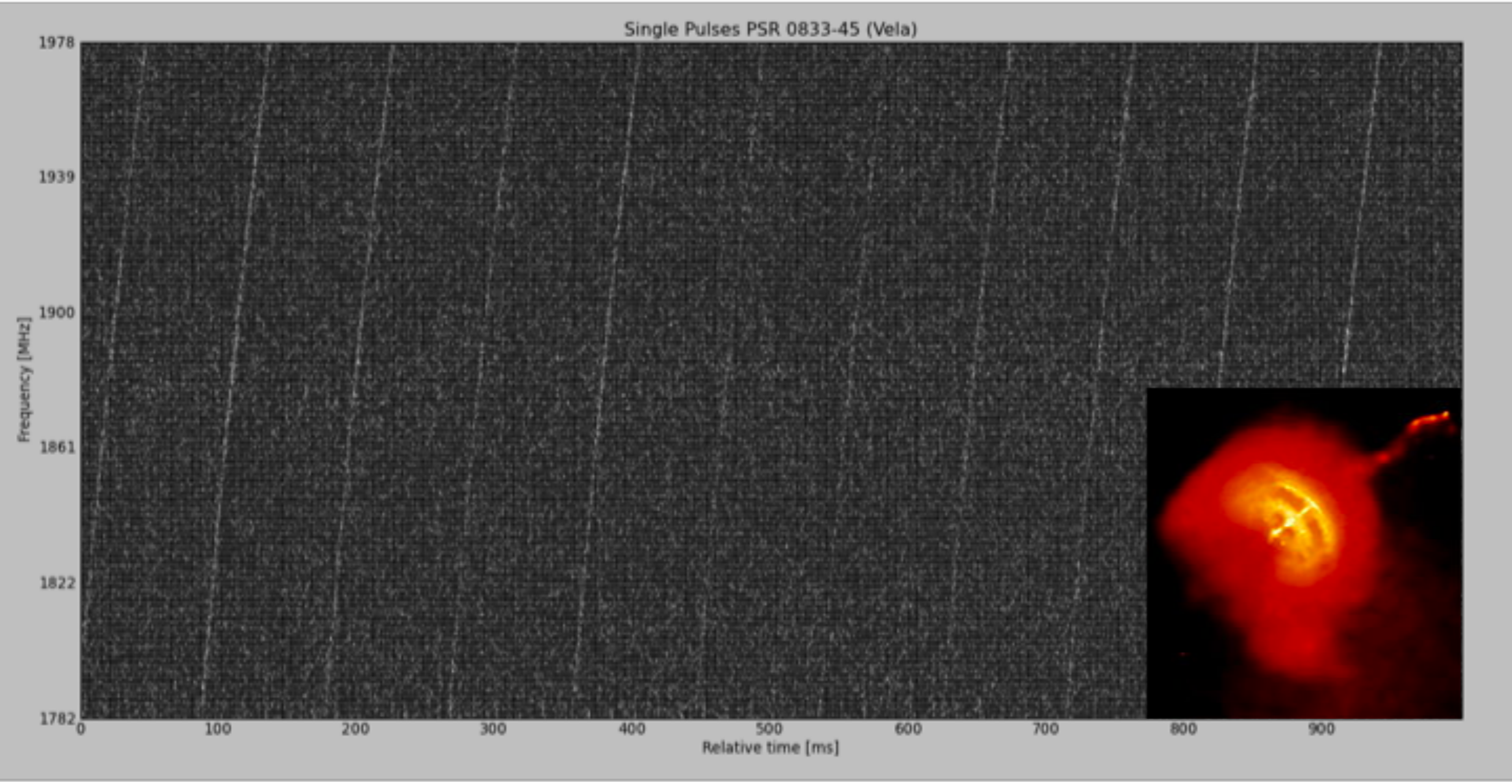
Image credit: EMSS Antennas

SKA Dishes (artistic)

SKA Dense Aperture Arrays (artistic)

SKA Sparse Aperture Arrays (artistic)

Time Domain Signals - Vela Pulsar

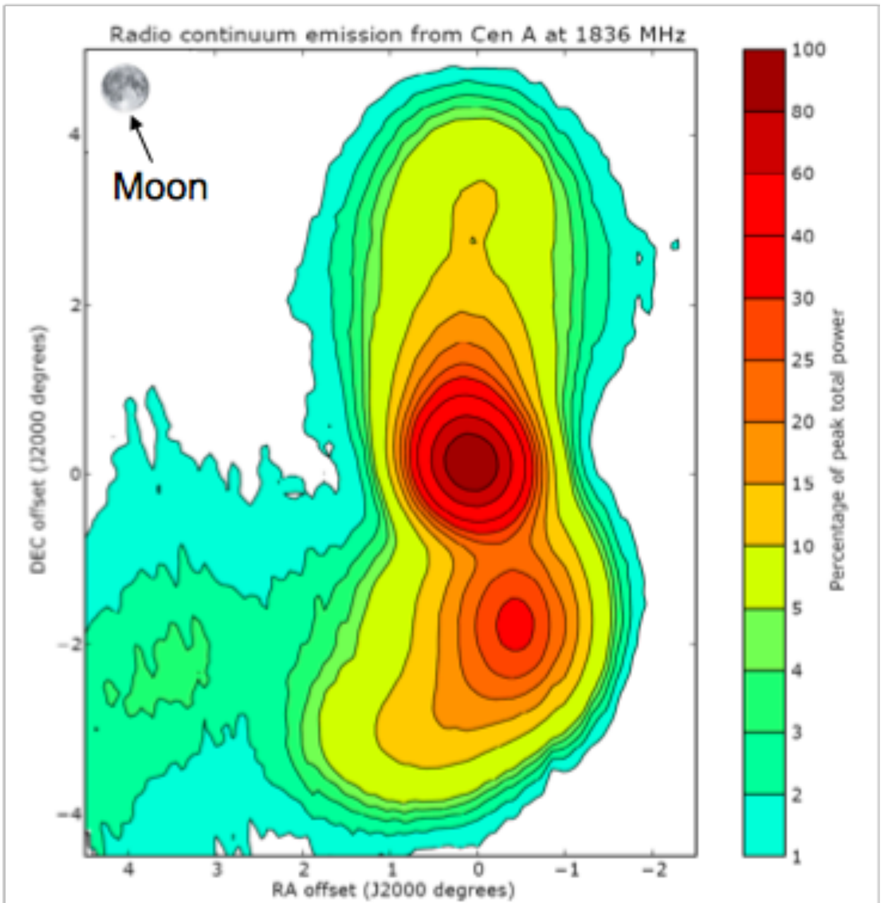


(Note frequency axis reversed)

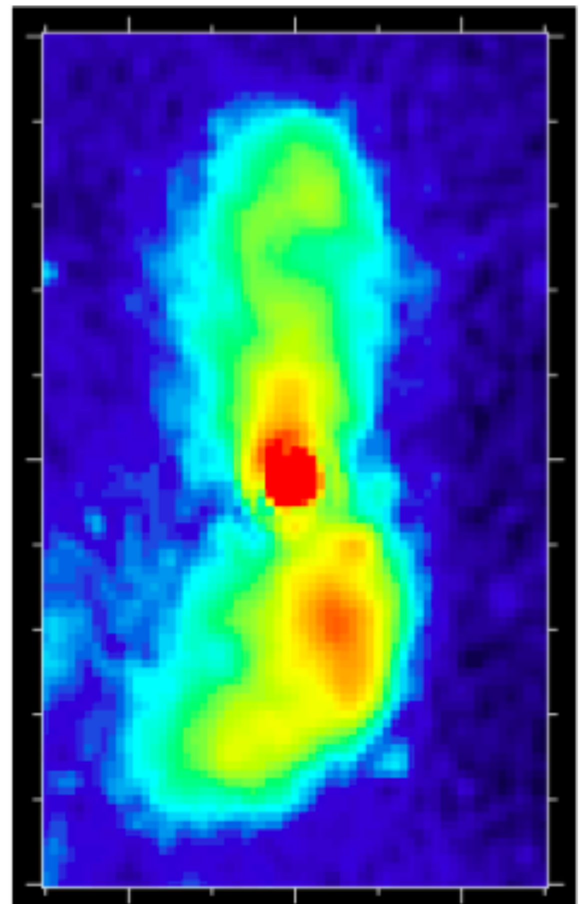
(Chandra X-Ray image insert)

Single Dish Images : Centaurus A

KAT-7 Dish @ 1836 MHz

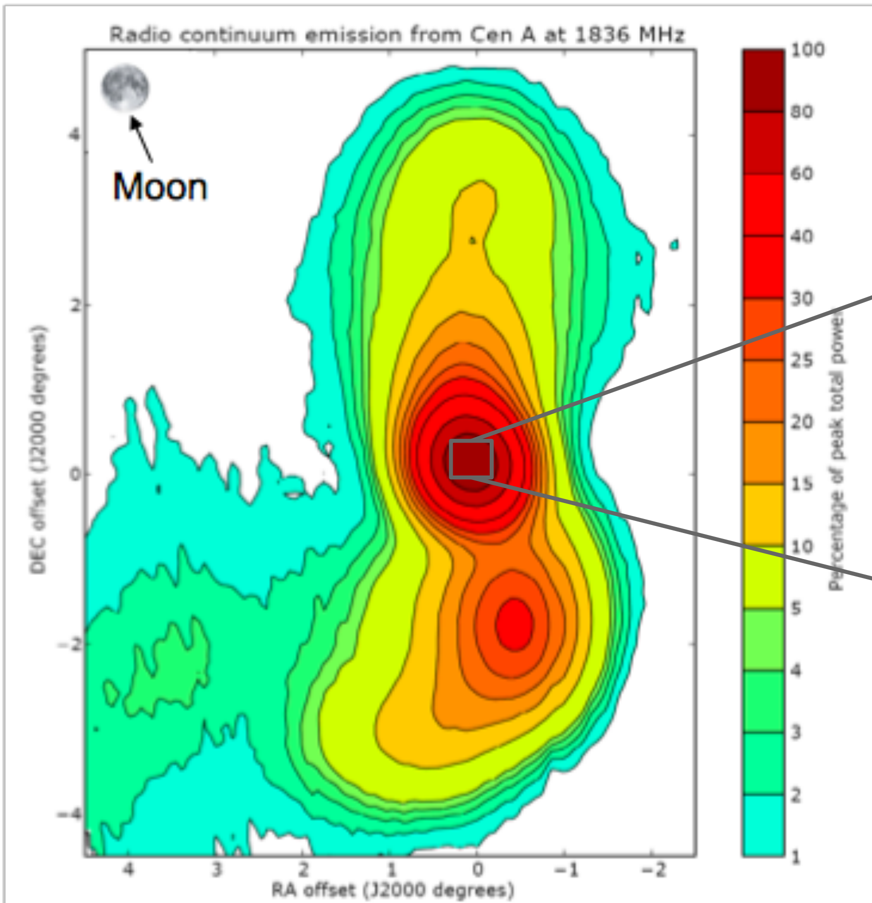


Rhodes/HartRAO @ 2326 MHz

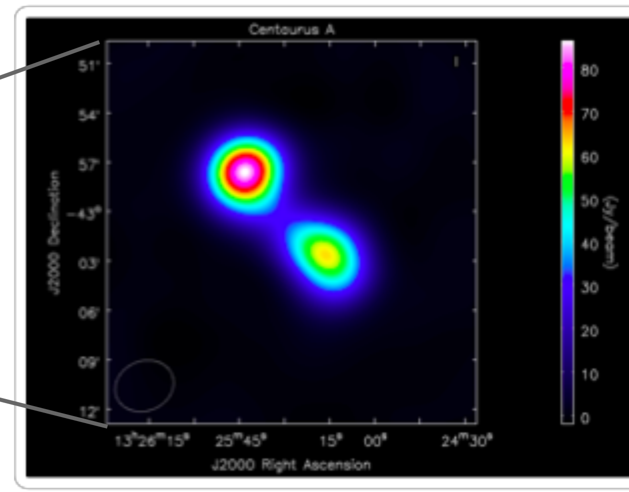


Beyond Single Dishes : Interferometric Image (Centaurus A)

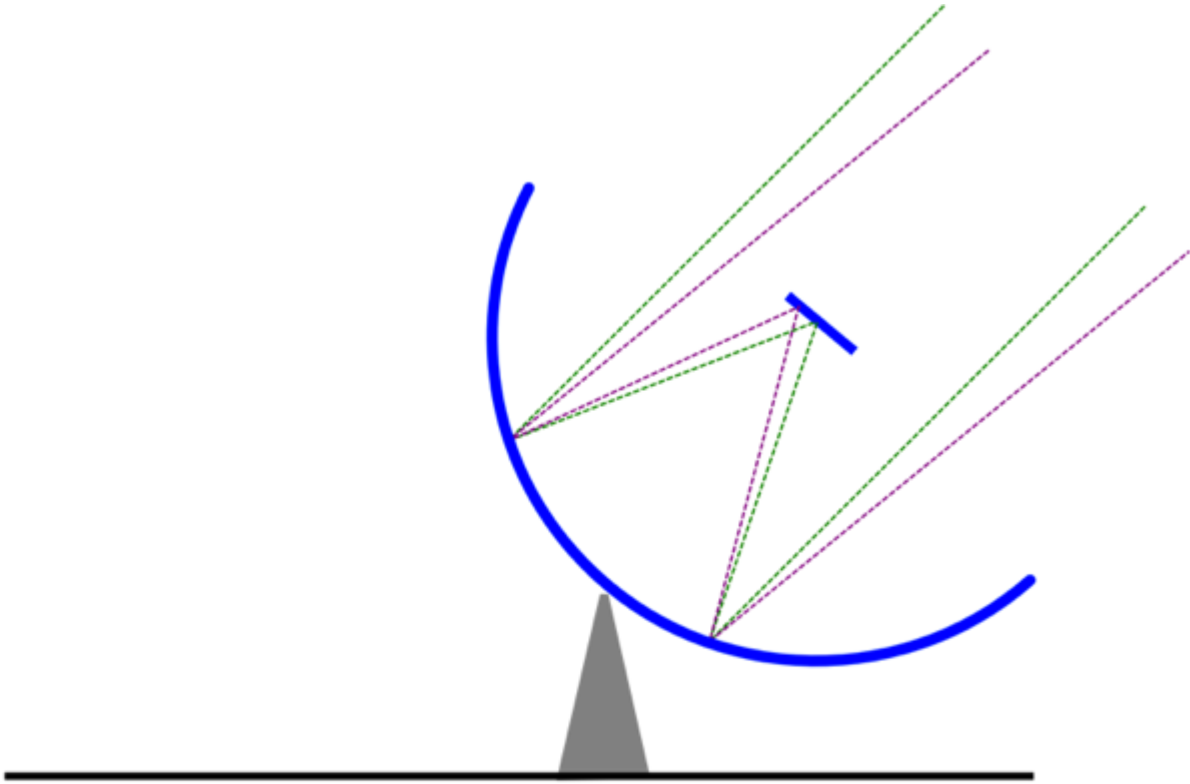
KAT-7 Dish @ 1836 MHz



KAT-7 interferometric image

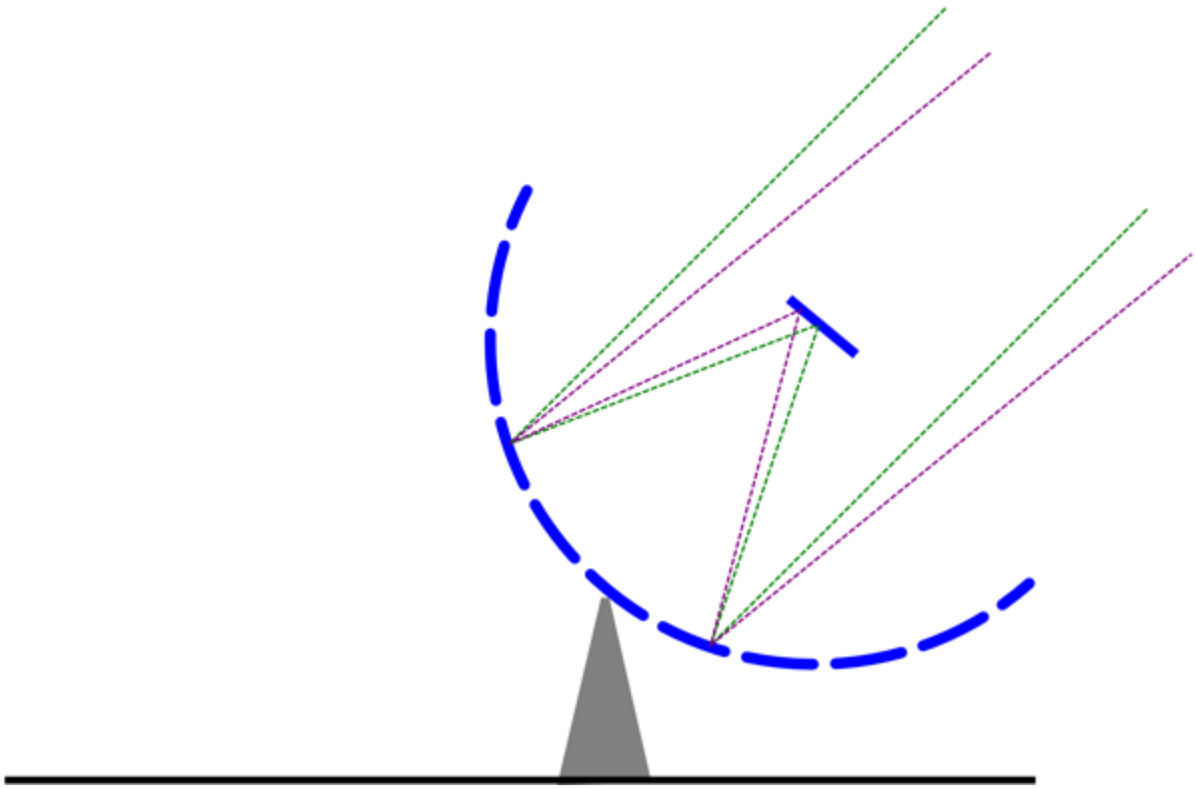


How To Make An Interferometer 1



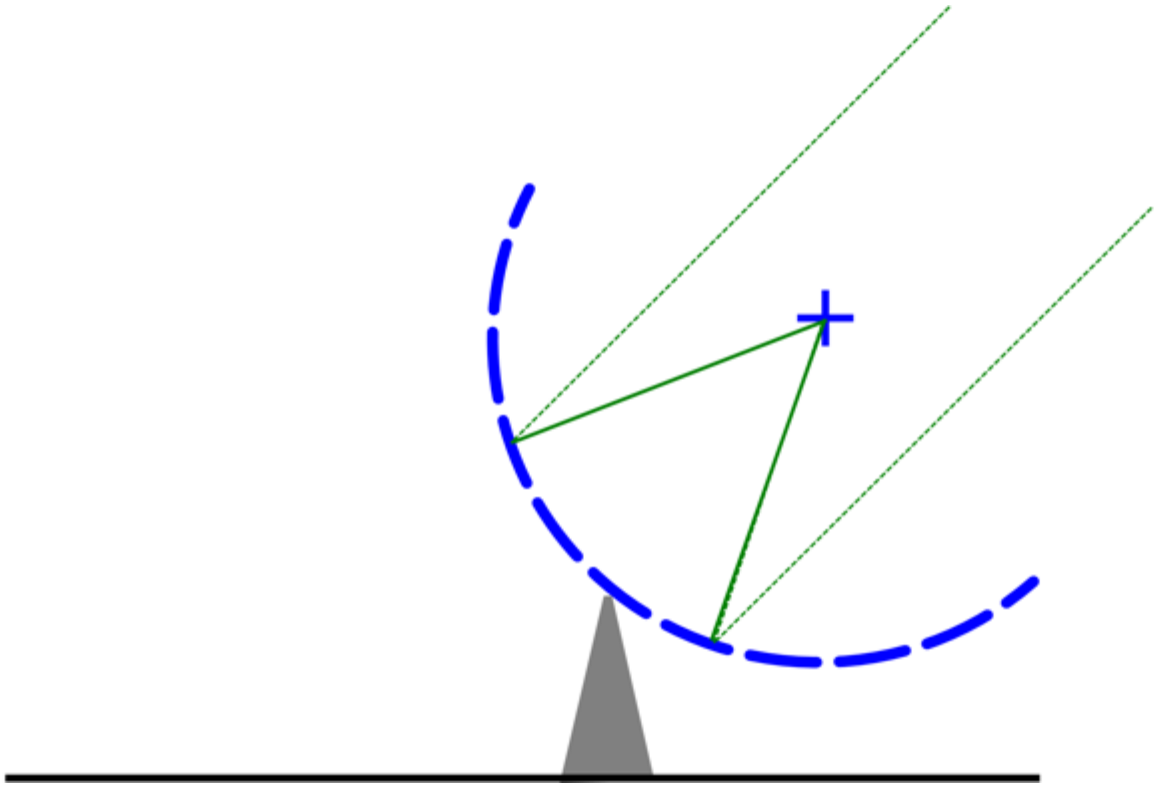
- Start with a normal reflector telescope...

How To Make An Interferometer 2



- Then break it up into sections...

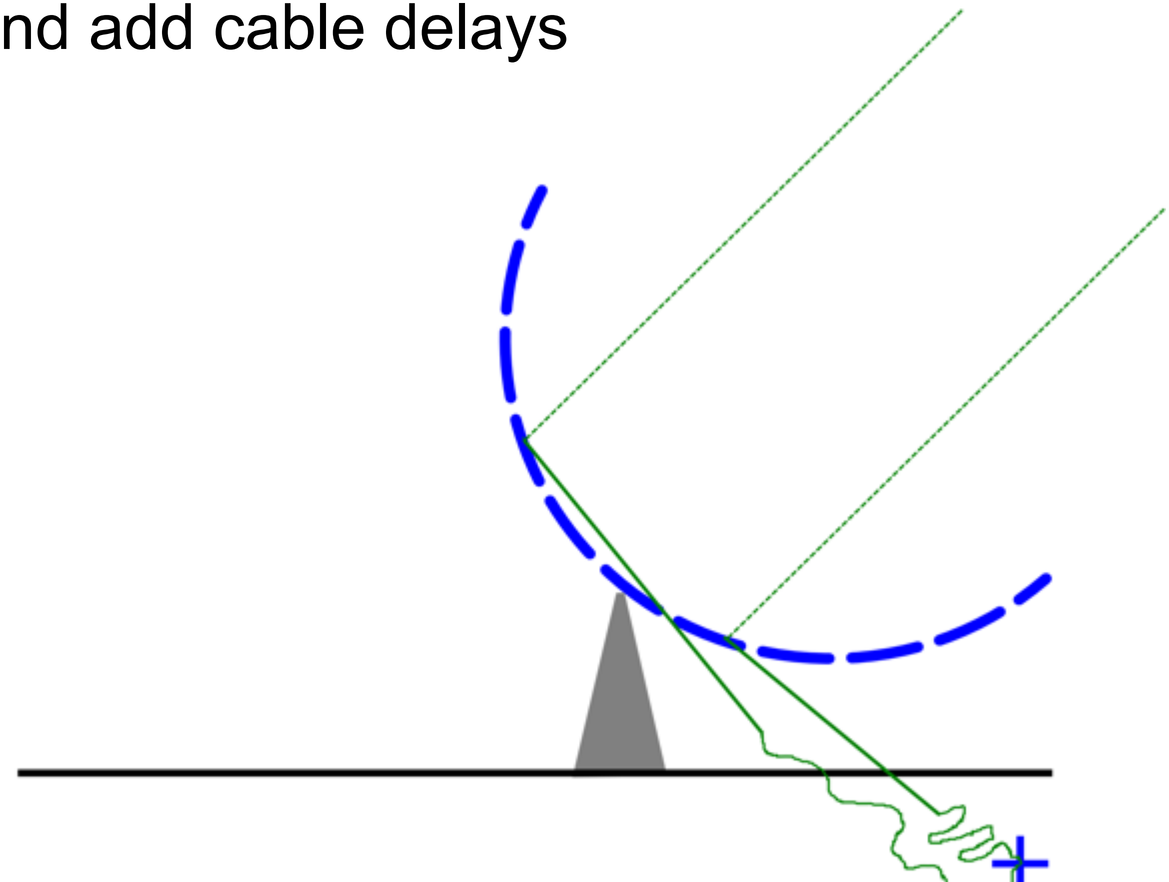
How To Make An Interferometer 3



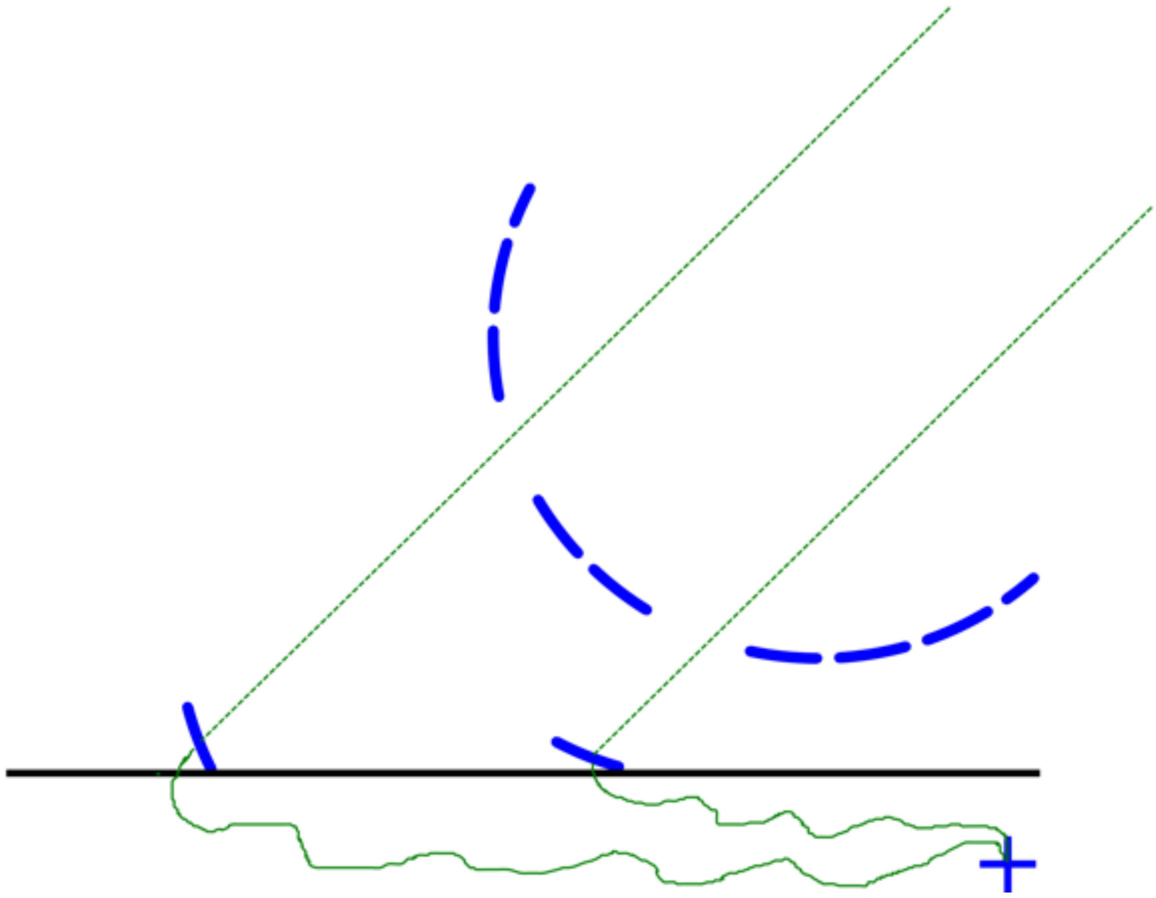
- Replace the optical path with electronics...

How To Make An Interferometer 4

- Move the electronics outside of the dish
- ...and add cable delays

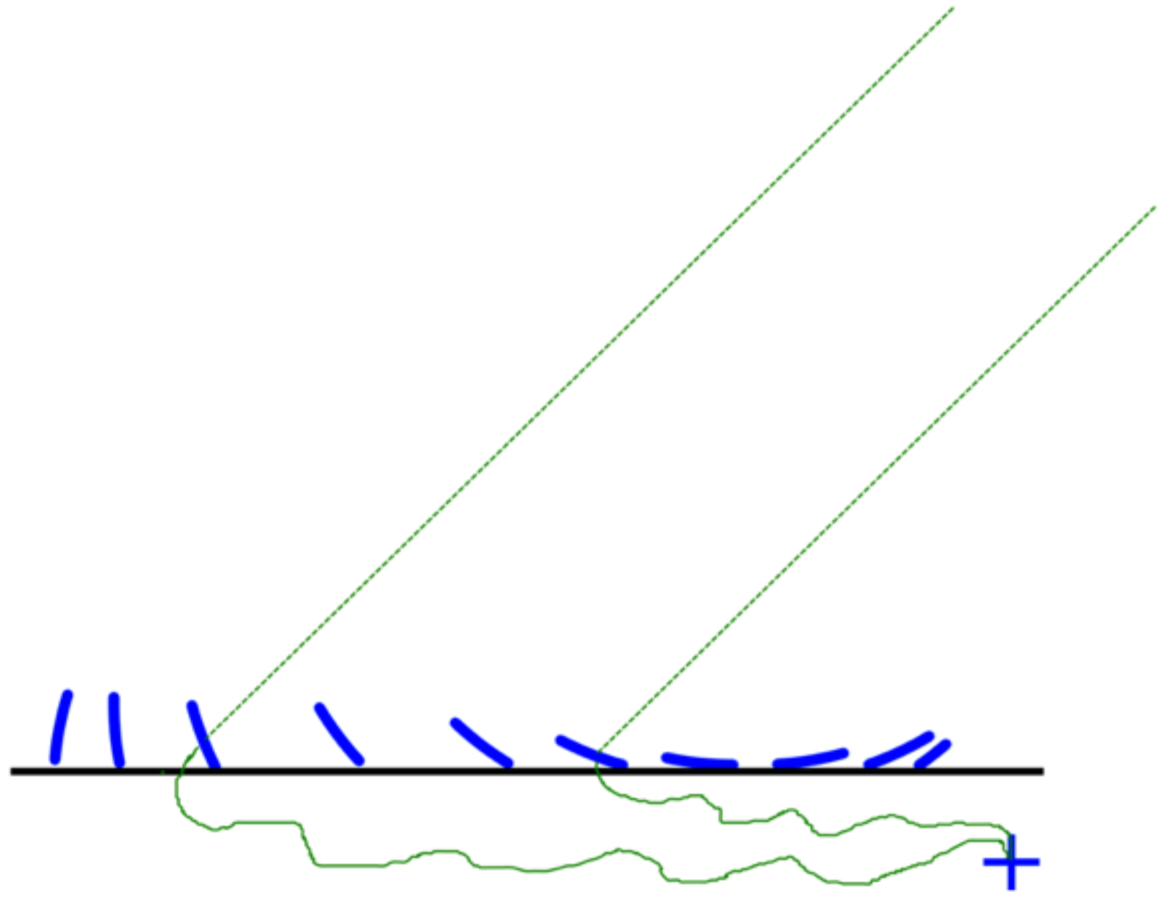


How To Make An Interferometer 5



- Why not drop the pieces onto the ground?

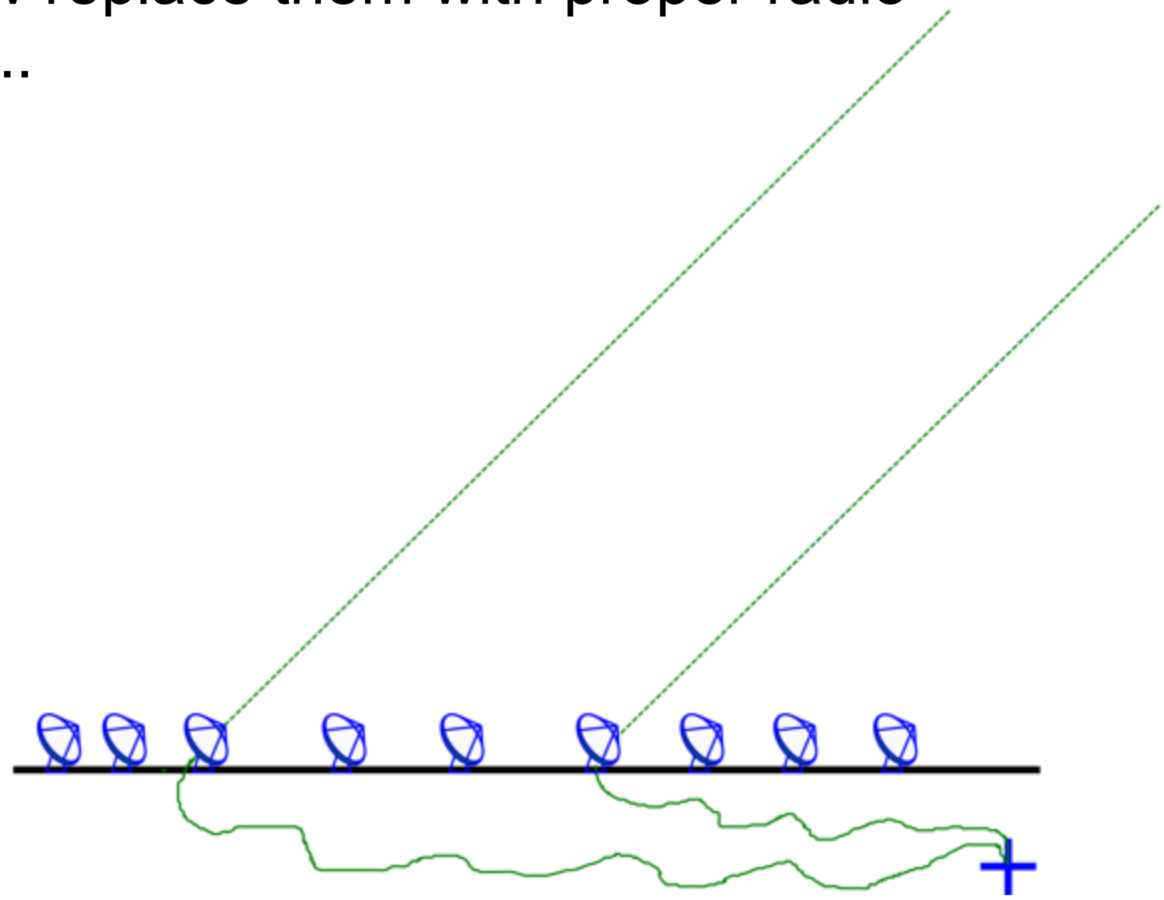
How To Make An Interferometer 6



- ...all of them

How To Make An Interferometer 7

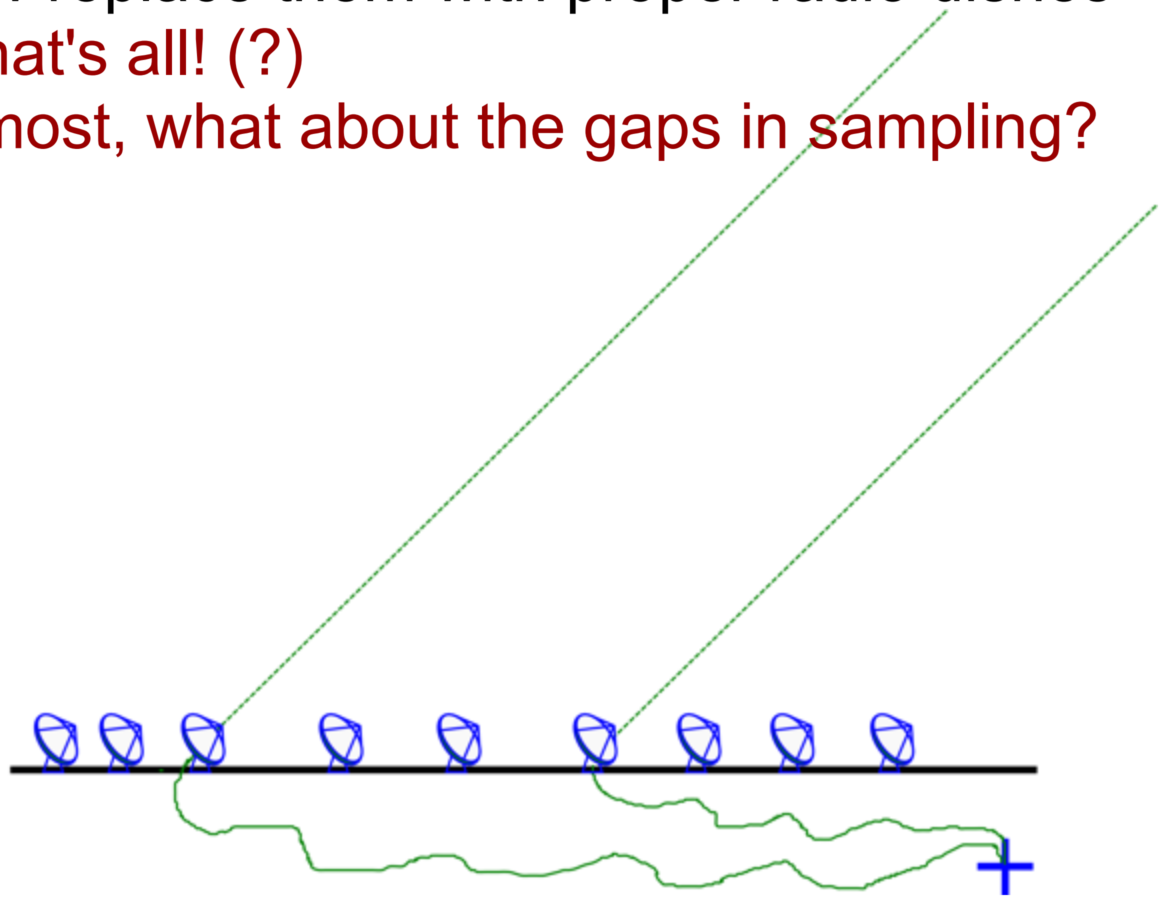
- And now replace them with proper radio dishes....



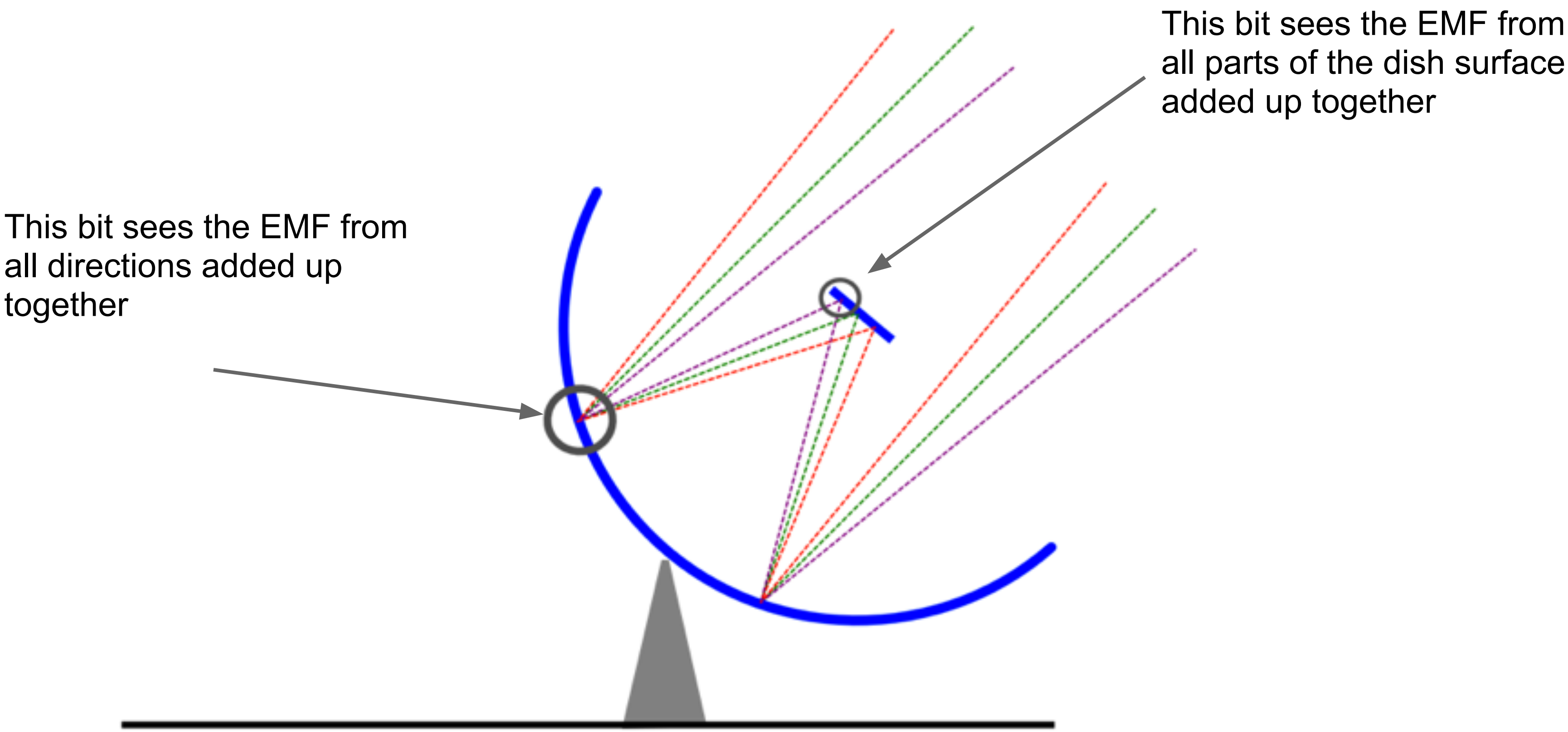
Voila! The KAT-7 Array

How To Make An Interferometer 7(b)

- And now replace them with proper radio dishes
- ...and that's all! (?)
- Well almost, what about the gaps in sampling?

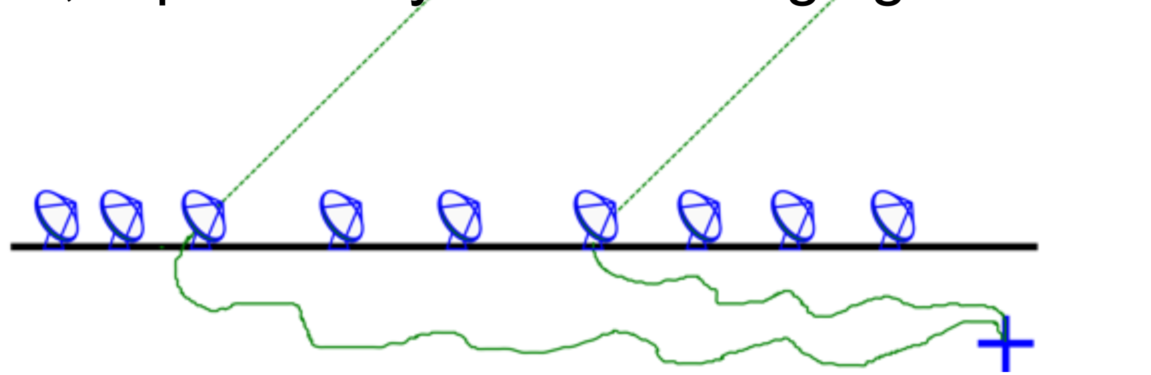


Similarities to Optical Telescopes



Fourier Transforms

- An optical imaging system implicitly performs two Fourier transforms:
  - Aperture EMF distribution = FT of the sky
  - Focal plane = inverse FT of aperture EMF
- A radio interferometer array measures FT of the sky
  - Then, we do the second FT in software
  - Hence, "aperture synthesis" imaging



Earth Rotation Aperture Synthesis

- Every pair of antennas (baseline) is correlated, measures one complex visibility = one point on the uv-plane
- As Earth rotates, a baseline sweeps out an arc in the uv-plane
  - See uv-coverage plot (next slide)
- Even a one-dimensional East-West array (WSRT = 14 antennas) is sufficient

Image Plane and UV-Plane

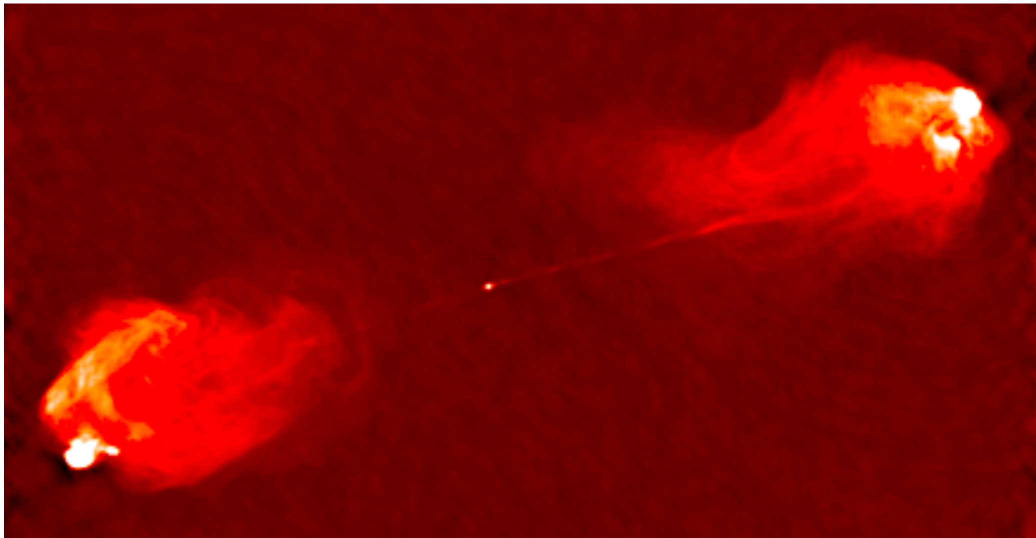
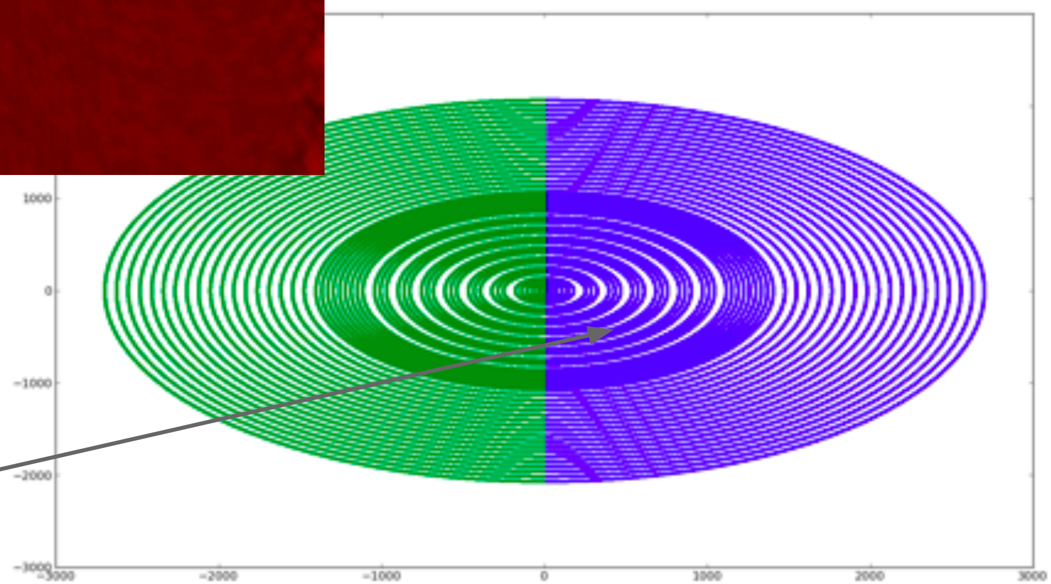


Image plane

uv-plane
(12 hours)

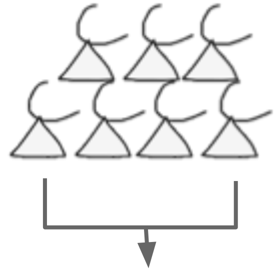


FT

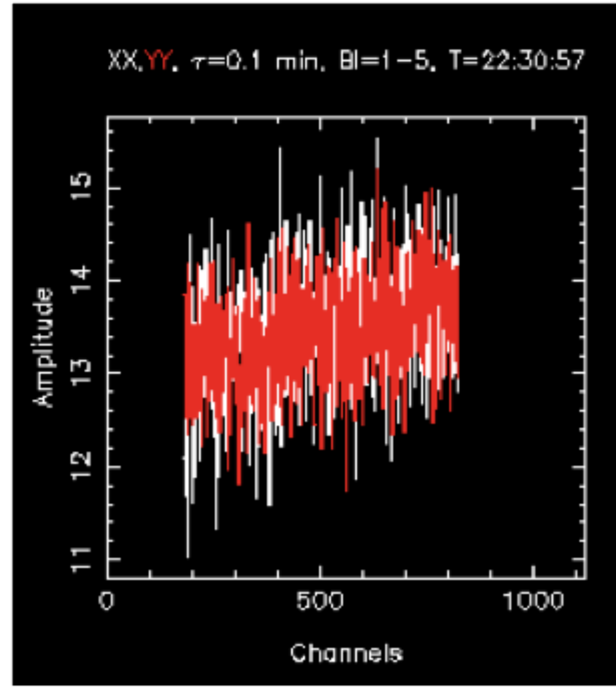
One baseline samples
one visibility at a time

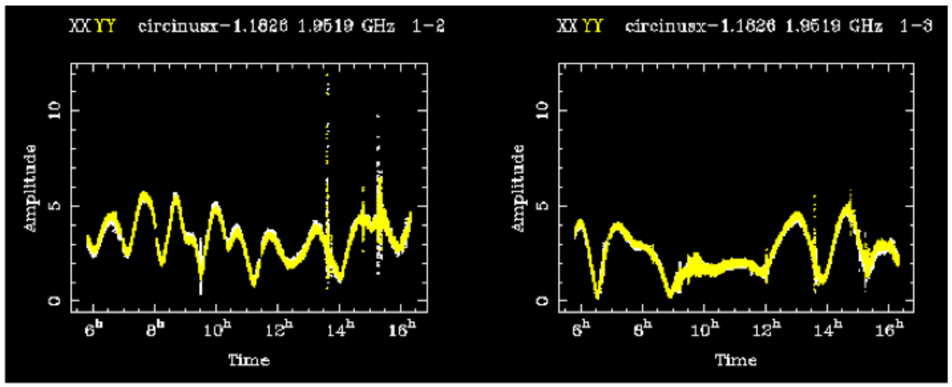
- In a sense, the two are entirely equivalent

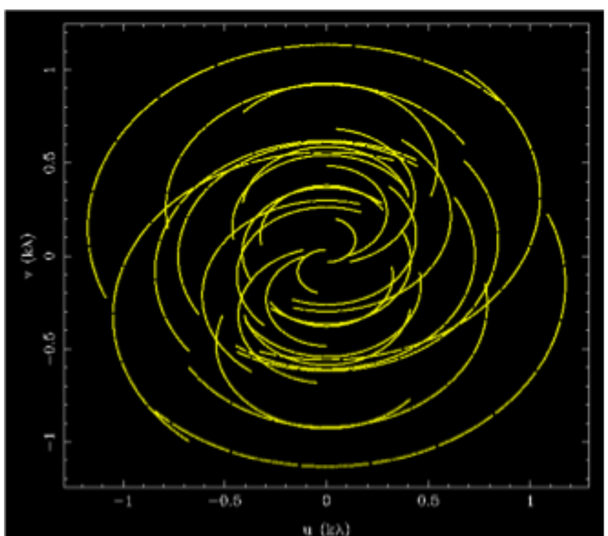
Visibilities



$V_{ij}(u,v) = \langle X_i X_j^* \rangle$

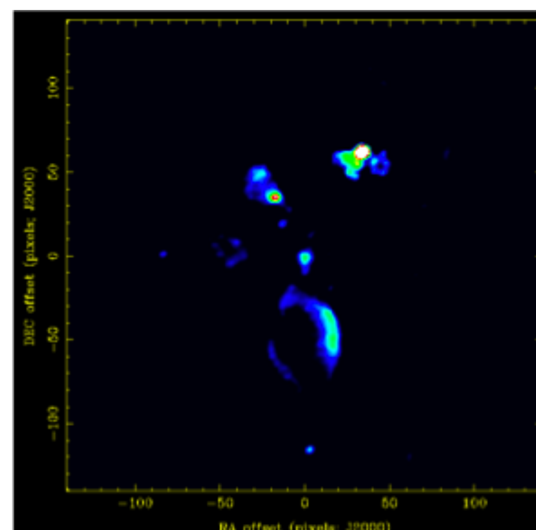




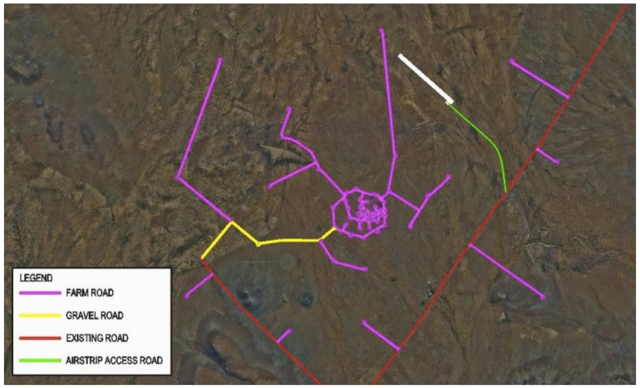


FT

$V(u,v) \Longleftrightarrow I(l,m)$



Array Layouts



Where's the Catch?

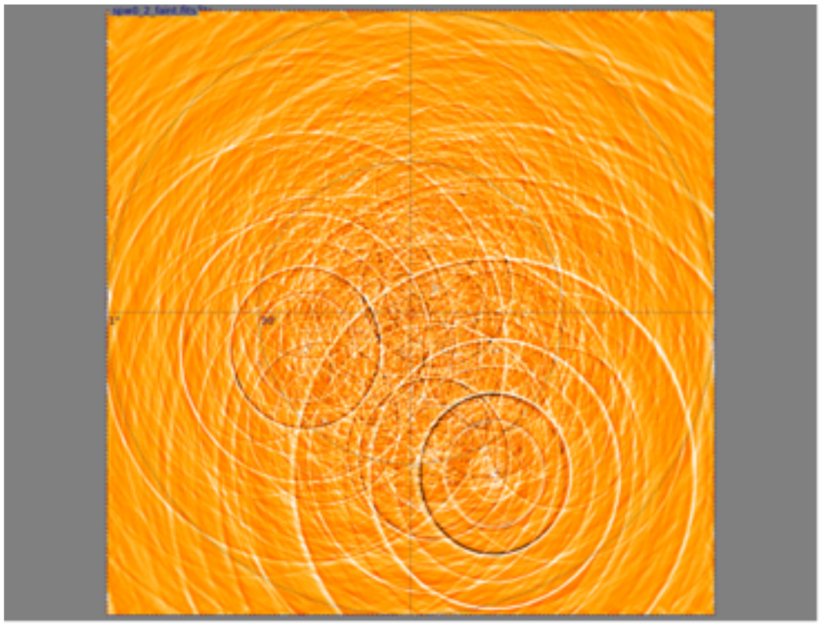
- We don't measure the full uv-plane, thus we can never recover the image fully (missing information).
- Every visibility measurement is distorted (complex receiver gains, etc.), needs to be calibrated.
- (Doesn't work the same way in optical interferometry at all..)
  - Can't really form up complex visibilities, etc

Catch 1 : Missing Information

12-hour WSRT PSF

- Response to a point source: Point Spread Function (PSF)
- PSF = FT(uv-coverage)
- Observed "dirty image" is *convolved* with the PSF
- Structure in the PSF = uncertainty in the flux distribution (corresponding to missing data in the uv-plane)

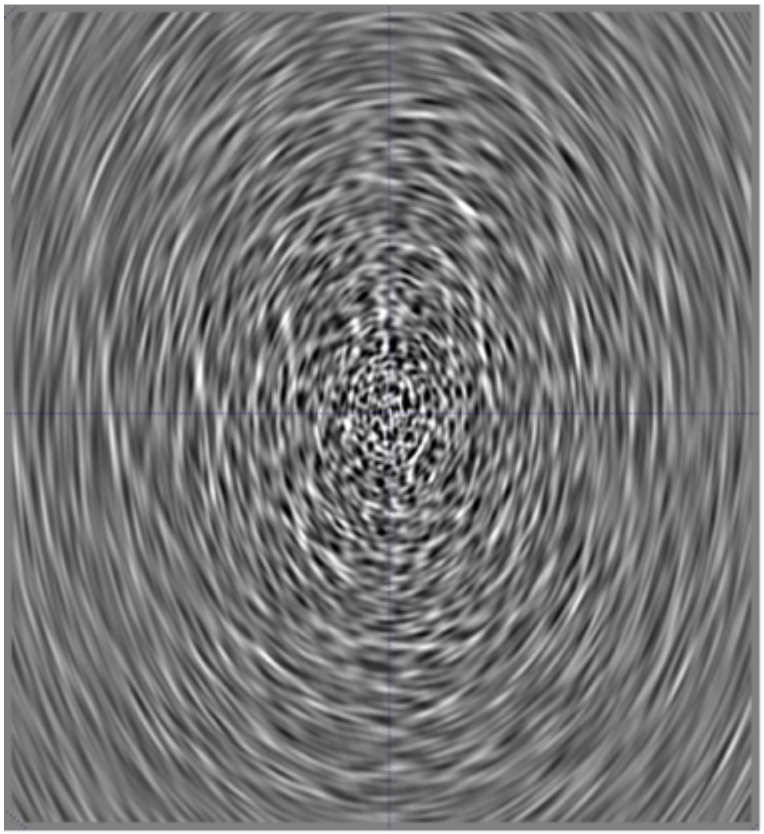
Deconvolution: From Dirty to Clean Images



real-life dirty WSRT image

- Dirty image dominated by PSF sidelobes from the stronger sources
- *Deconvolution* required to get to the faint stuff underneath
- A whole continuum of skies fits the dirty image (pick any value for the missing uv components)
- Deconvolution picks one = interpolates the missing info from extra assumptions (e.g. "sources are point-like")

Catch 2: Distorted Measurements



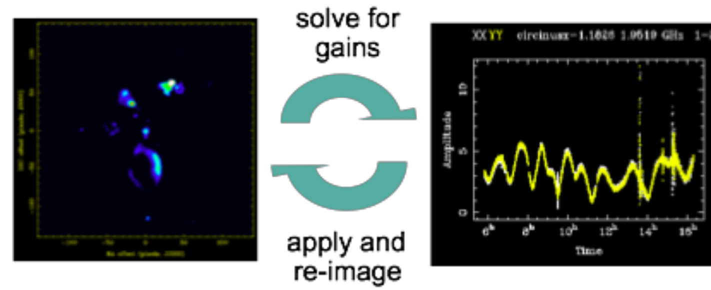
- Same picture as before, but with phase errors
  - Ionosphere, troposphere, electronics
- In the uv-plane, phase encodes information about location
- Phase errors tend to spread the flux around
- Calibration of complex gains required before we can see anything at all

Self-cal

"Radio astronomy has achieved incredible results (> 10^6 dynamic range) despite using incestuous calibration methods held together with spit, duct tape, baling wire and oral tradition." - O. Smirnov

Welcome to the world of self-cal....

Typical Self-Cal Cycle



Pre-cal:

- Pre-calibrate antenna-based gains (*g*) using external calibrators
- Correct with g^{-1}, make dirty image, deconvolve
- Generate rough initial sky model

Self-cal loop:

- Solve for *g* using current sky model
- Correct with g^{-1}, make dirty image, deconvolve
    - Optional: subtract model and work with residuals
- Update the sky model
- Rinse and repeat

Self-cal Limitations

- One complex gain per antenna per entire field of view
- Direction dependent effects are a problem
- Polarization is a problem

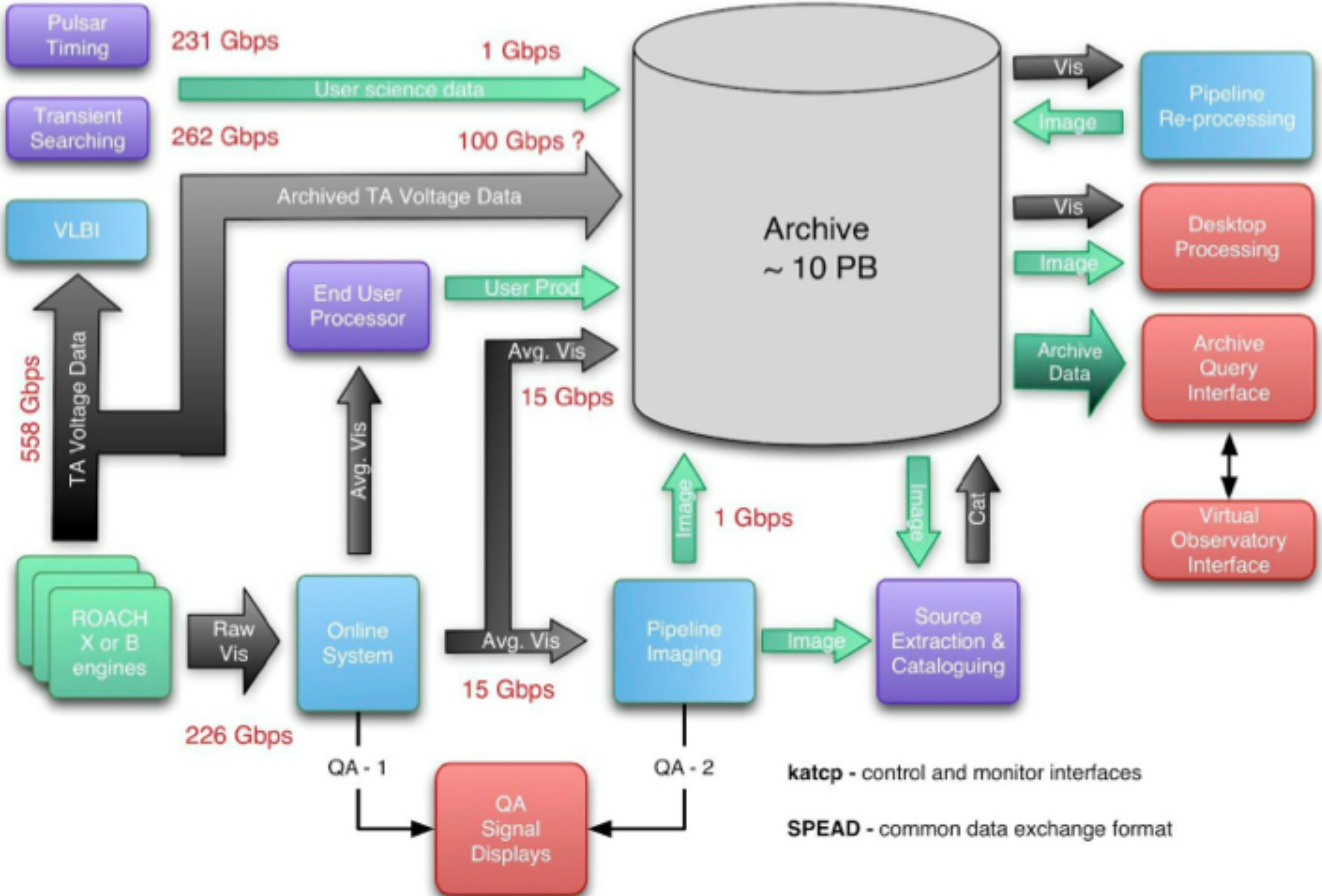
Measurement Equation...

Measurement Equation

- Provides a neat, powerful and consistent mathematical framework to replace some of the spit and duct tape
- Jones matrix formulation where each Jones matrix ***J*** represents a linear propagation effect and $\boldsymbol{J_1 .. J_n}$ represents the full propagation path

$$\mathbf{V_{pq} = J_{pn} .. J_{p2} J_{p1} B J^{*}_{q1} J^{*}_{q2} .. J^{*}_{qn}}$$

MeerKAT Data Processing



katcp - control and monitor interfaces

SPEAD - common data exchange format

SKA Dishes: Data Rates

- SKA Phase 1 dishes (2020): ~10-20 times MeerKAT data rates -> 100 PB storage for first couple of years
- SKA Phase 2 dishes (2025): ~100-1000 times MeerKAT -> few Exabytes storage for first couple of years

Pressing Challenges

- Data rates on new telescopes very high -> human in the loop won't work
- New instruments need correction of more subtle effects to reach full science performance (e.g. direction dependent gains, wide field of view, wide bandwidths, etc)
- Approximate techniques still needed despite Measurement Equation formalism
- Statistical techniques show promise, but too many flops at present

Conclusions

- Radio interferometry can be tricky... "if you think you understand it, you don't"
- However, much progress with existing arrays
- MeerKAT and SKA will each bring new challenges especially in data processing
- New algorithms and implementations are needed
- We have an excellent set of skills developing in these areas around the project
- Exciting times!


Questions?
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