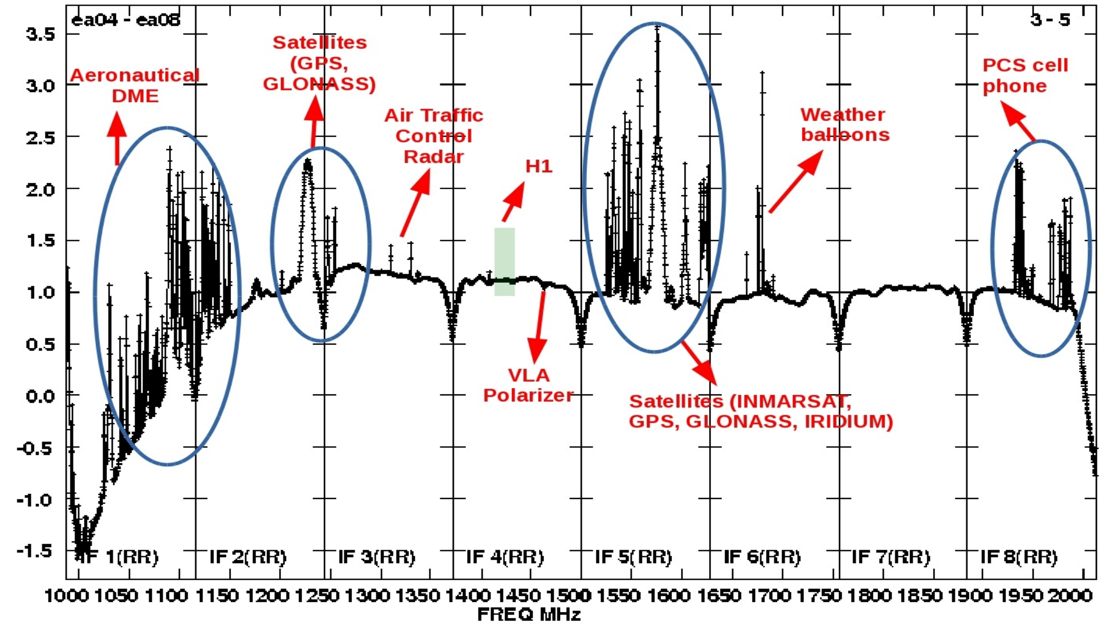
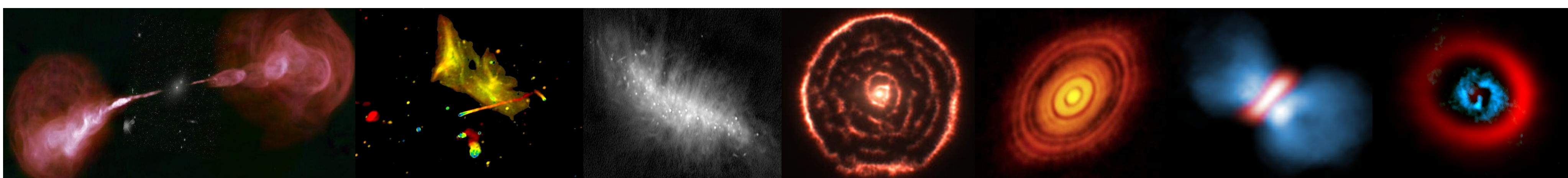
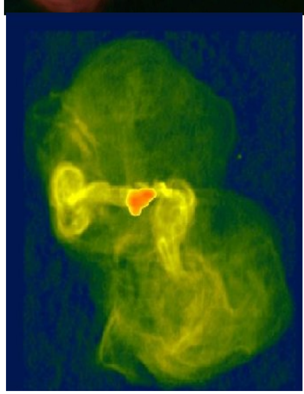
Peering Through the Reeds - Radio Astronomy versus Commercial Spectrum Use







Urvashi Rau

National Radio Astronomy Observatory

7 November 2019

Physics Department Colloquium, New Mexico Tech

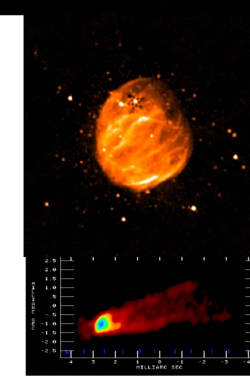
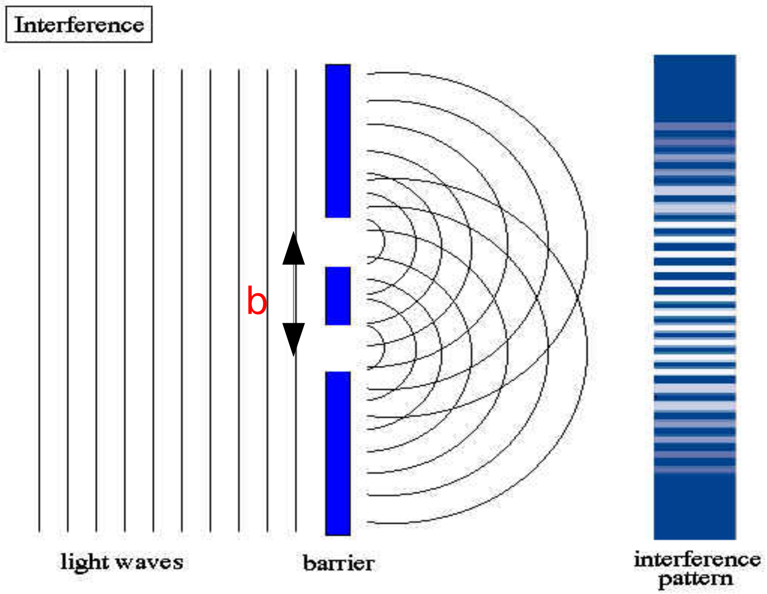


Image Credits : NRAO

An interferometer is an indirect imaging device

An interferometer is an indirect imaging device

Young's double slit experiment



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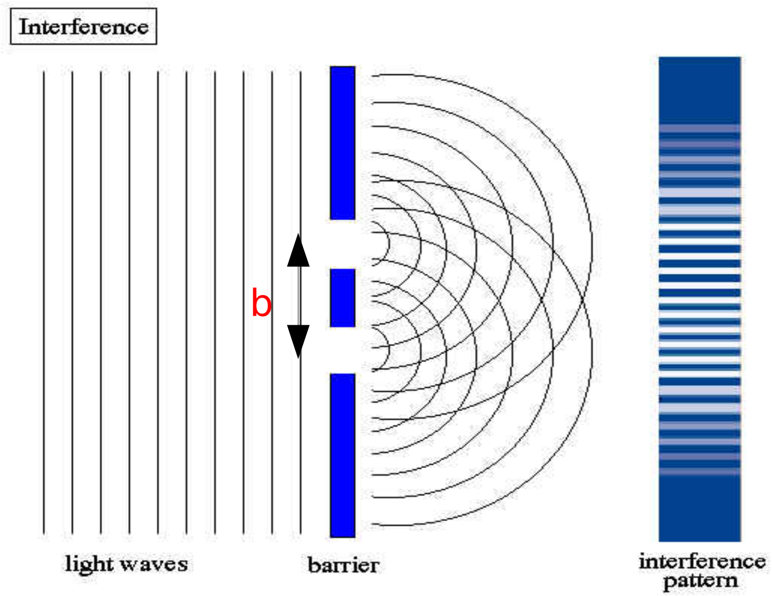
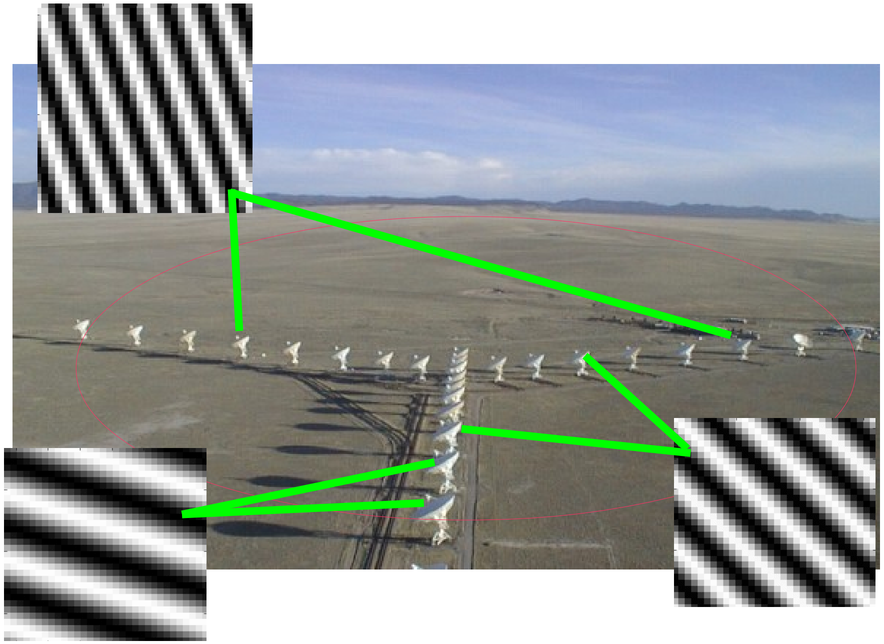


Each antenna-pair => one 2D fringe



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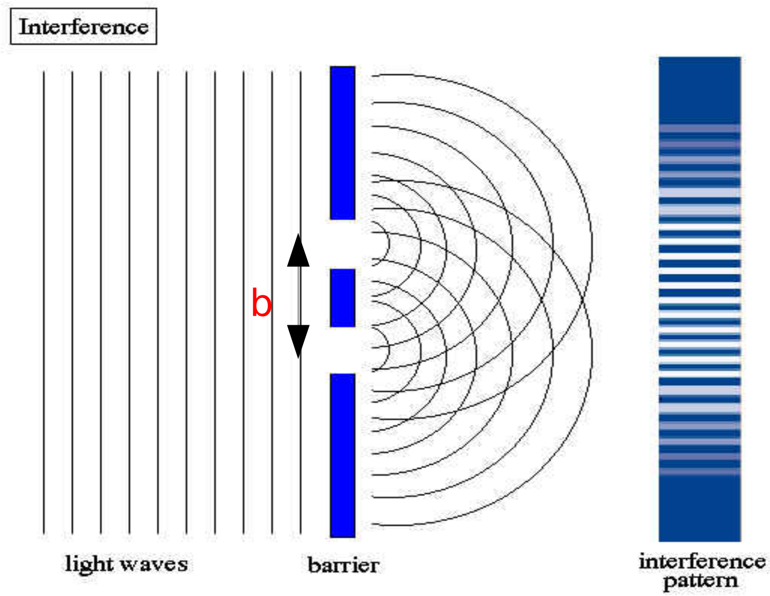

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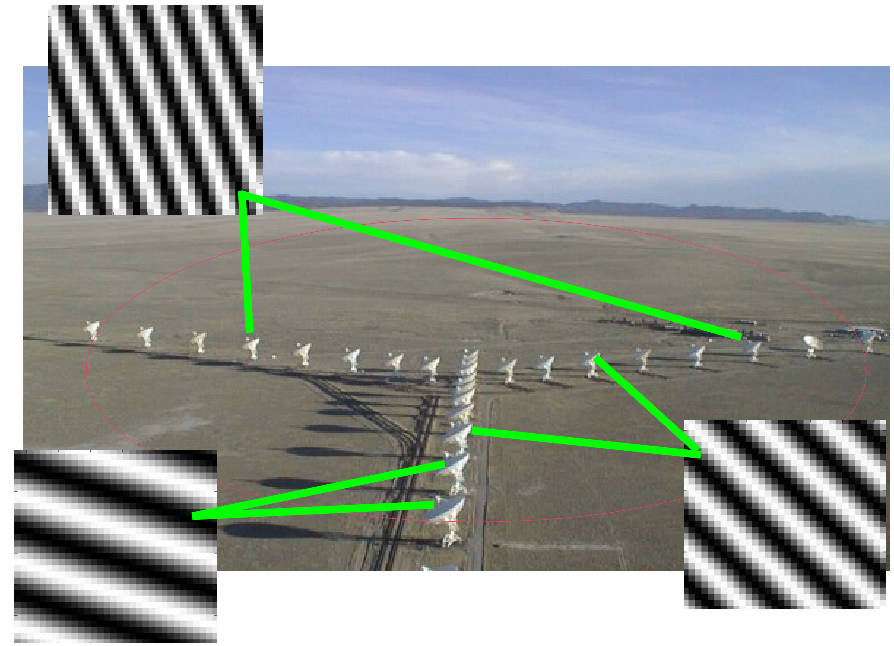
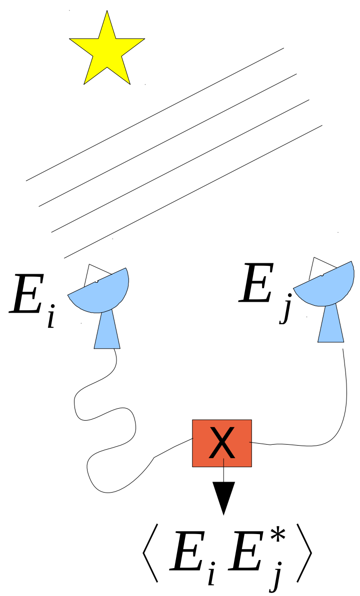




Measuring fringe parameters

Amplitude, Phase : $\langle E_i E_j^* \rangle$ is a complex number

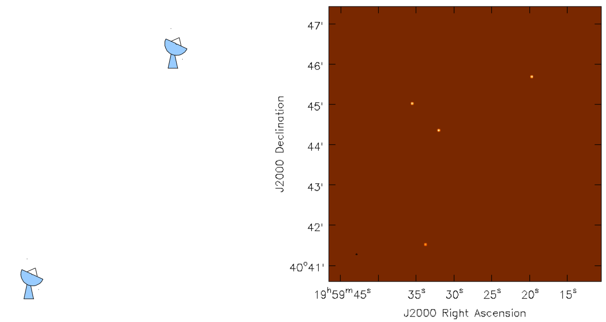
Orientation, Wavelength : Vector between each pair of antennas

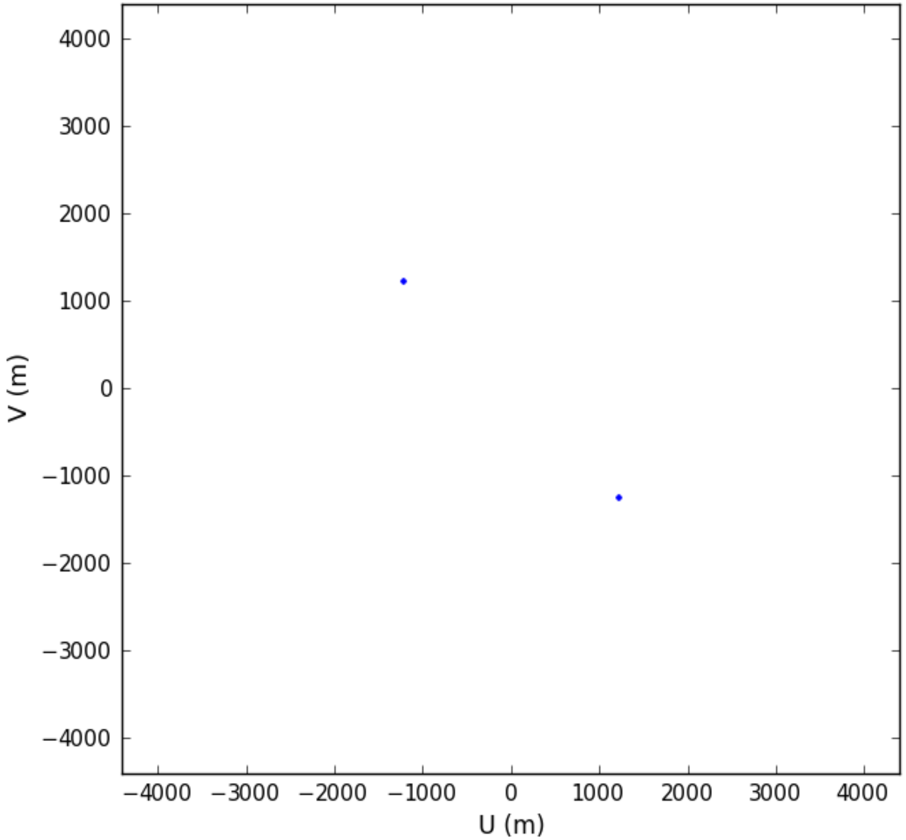
Goal : Measure as many distinct fringes as possible

Add them together => 2D Fourier transform

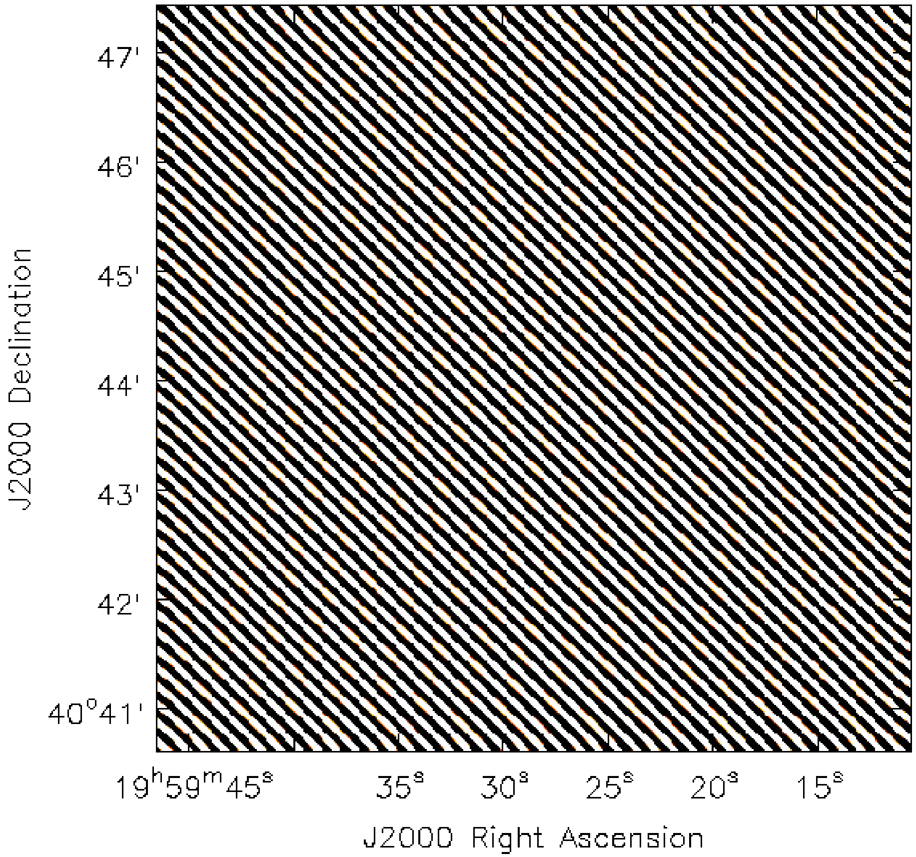
Aperture Synthesis Imaging

Image with 2 antennas => 1 fringe





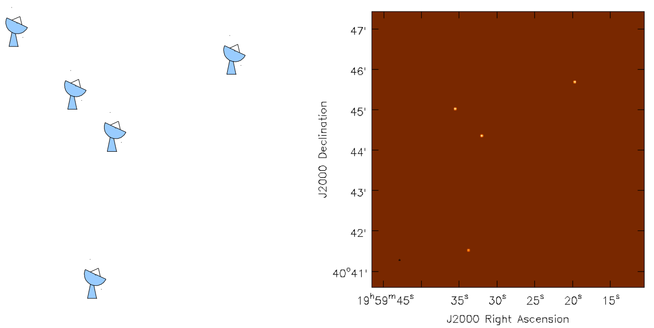
Instrument Transfer Function

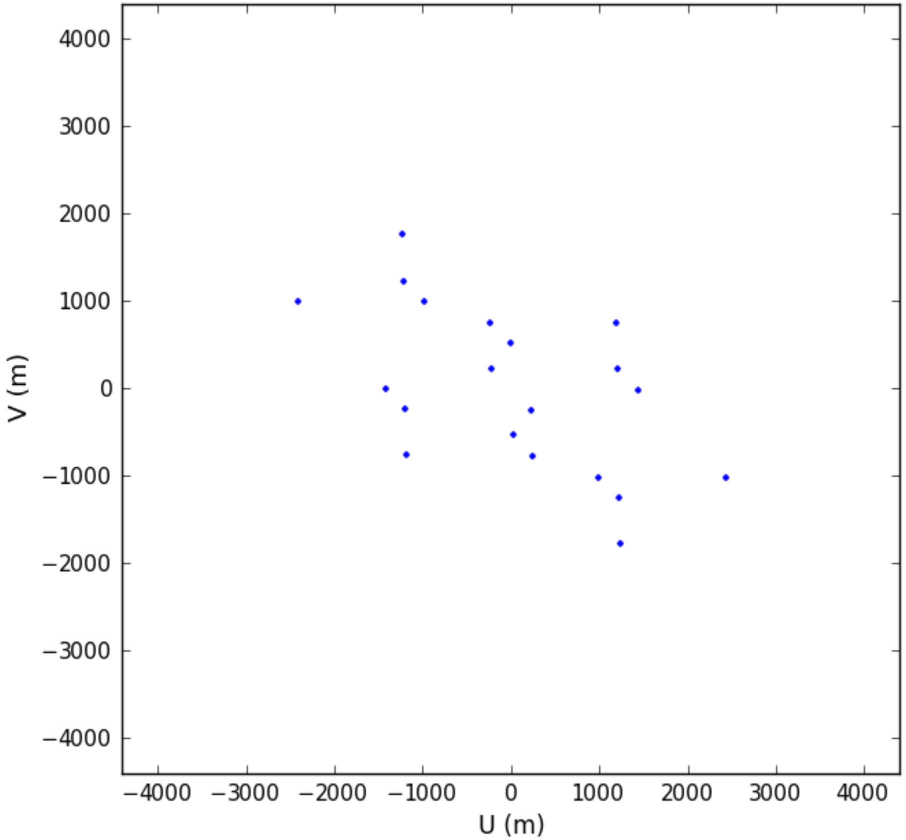


Observed Image

Aperture Synthesis Imaging

Image with 5 antennas => 10 fringes





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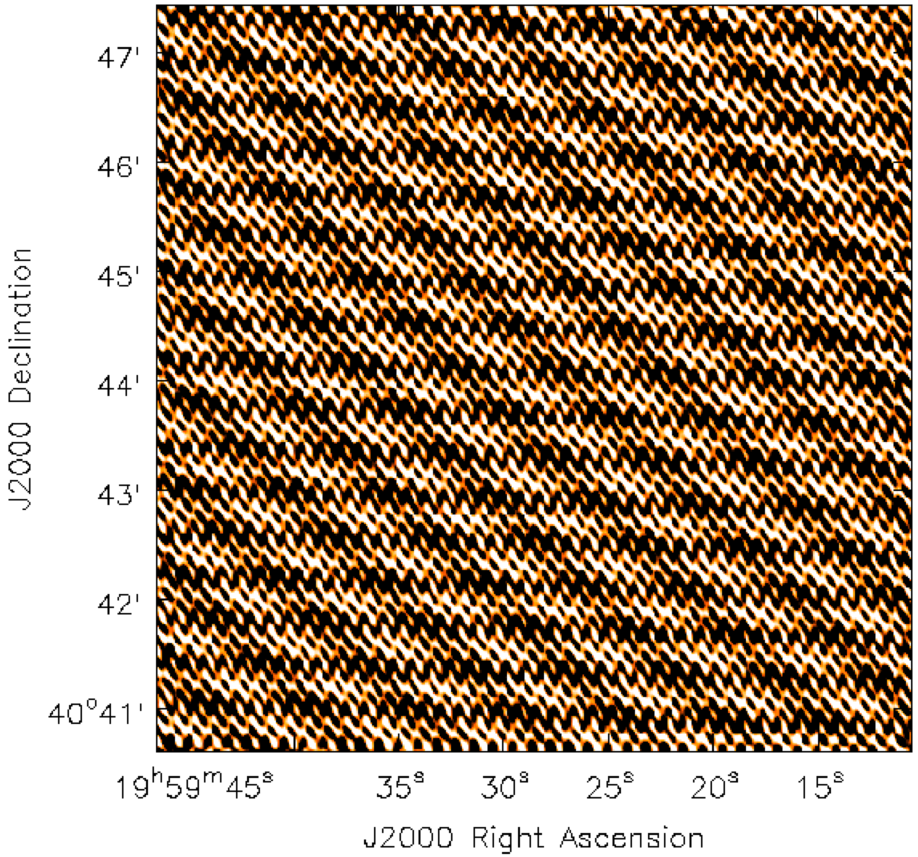
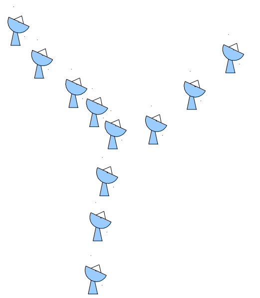
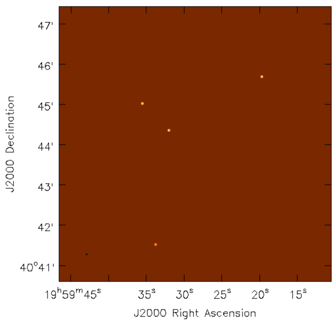


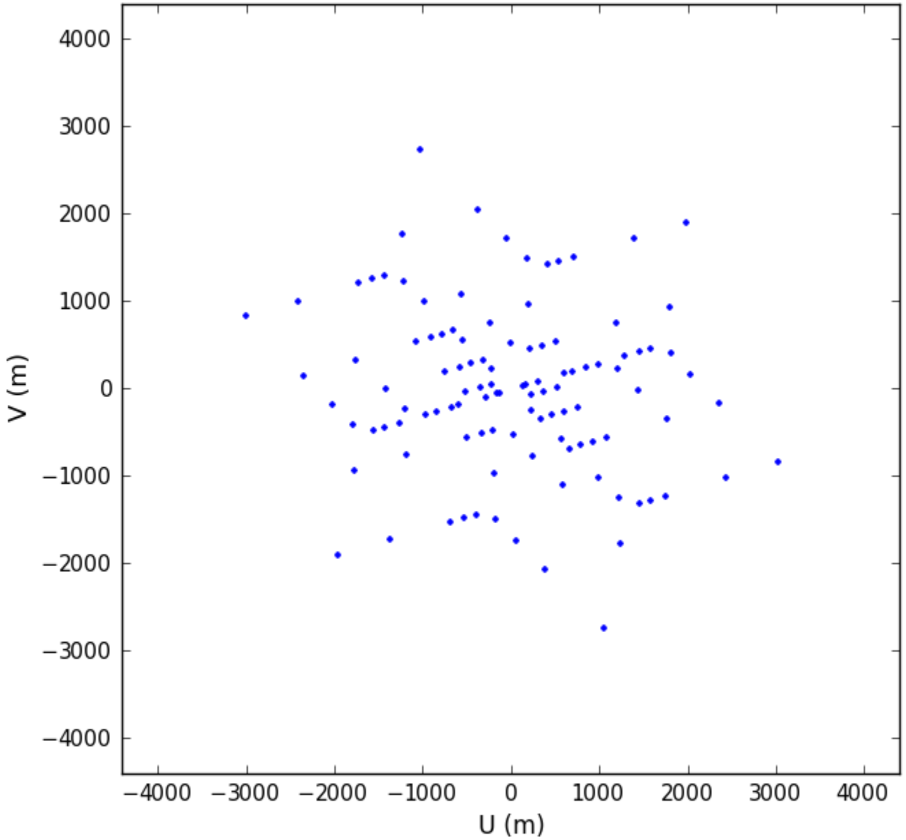
Observed Image

Aperture Synthesis Imaging

Image with 11 antennas => 55 fringes







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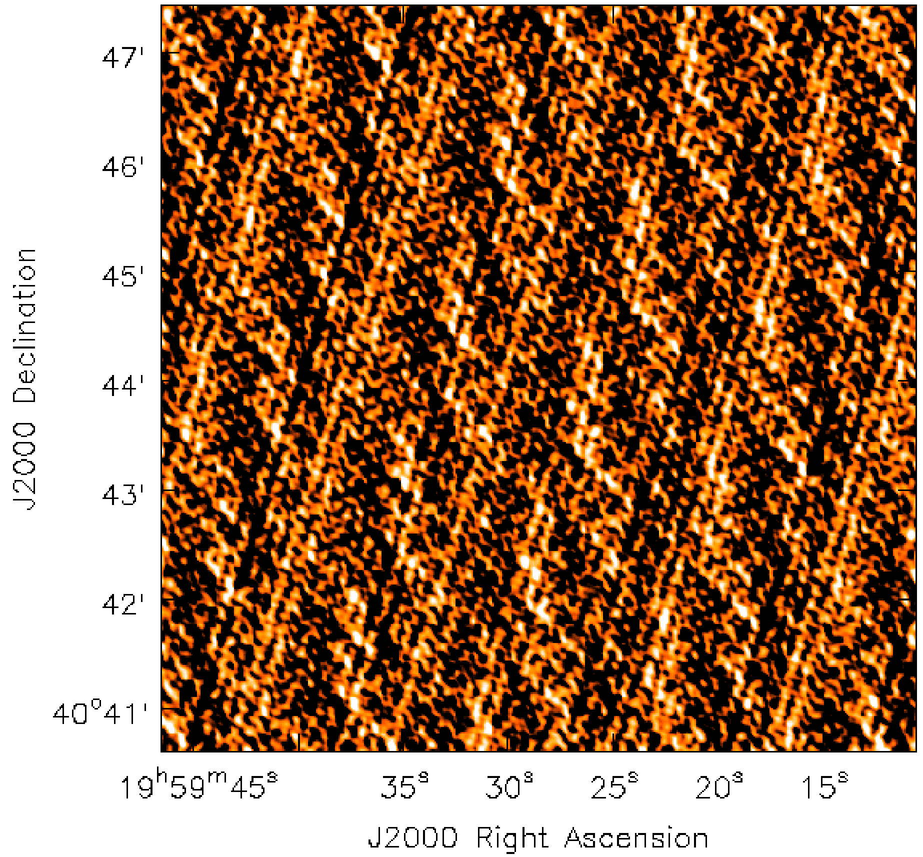
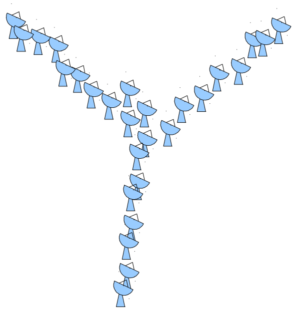
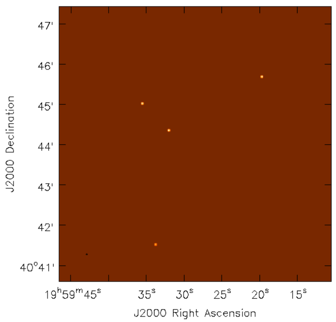


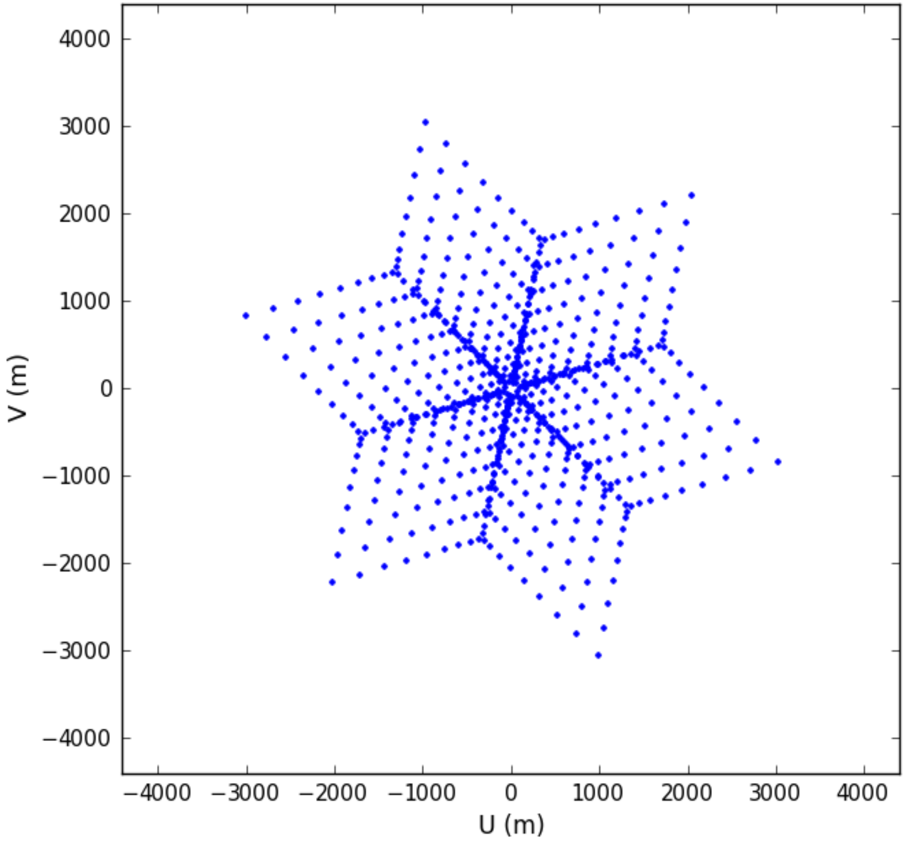
Observed Image

Aperture Synthesis Imaging

Image with 27 antennas => 351 fringes







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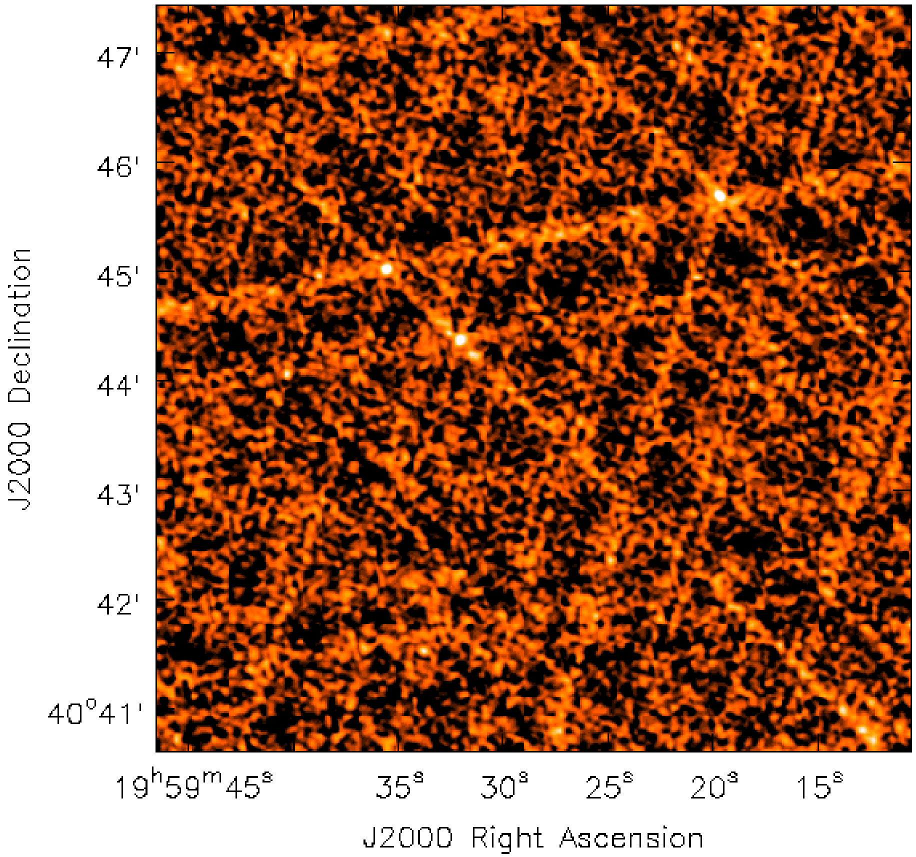
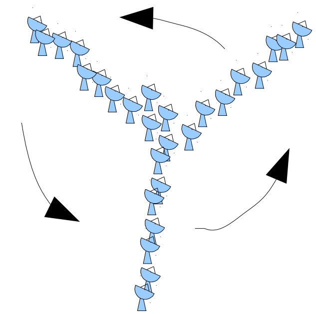


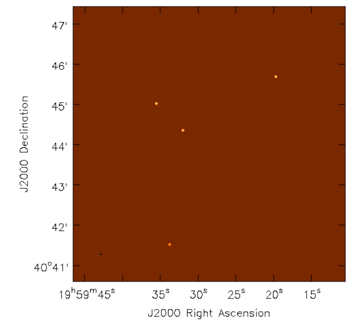
Observed Image

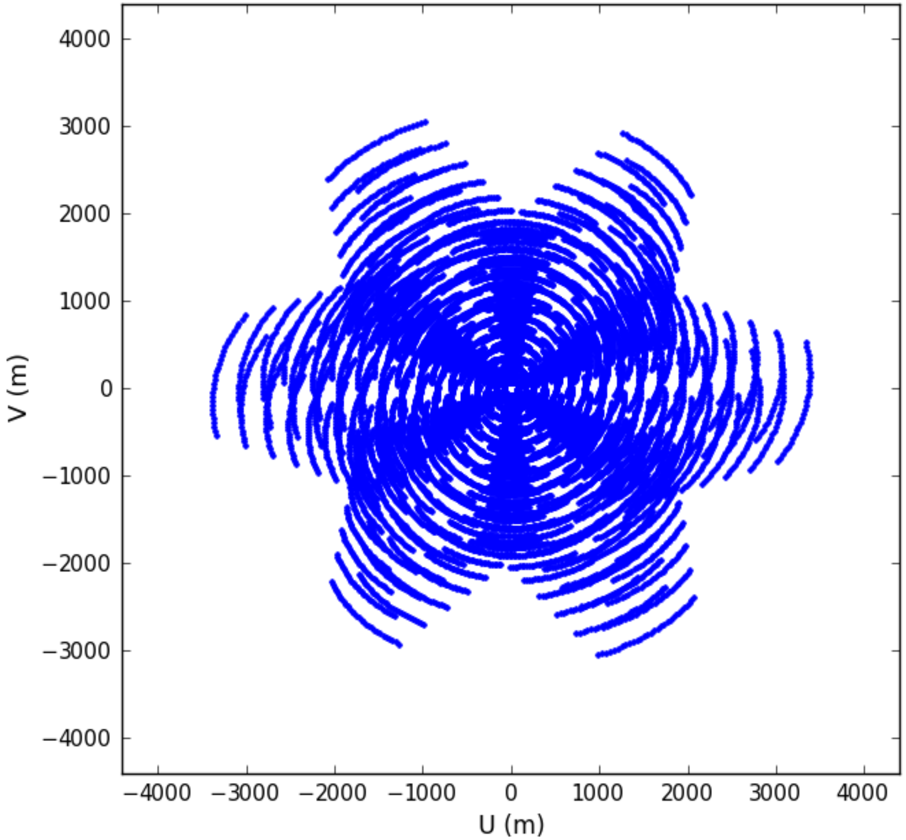
Aperture Synthesis Imaging

Image with 27 antennas over 2 hours

“ Earth Rotation Synthesis “







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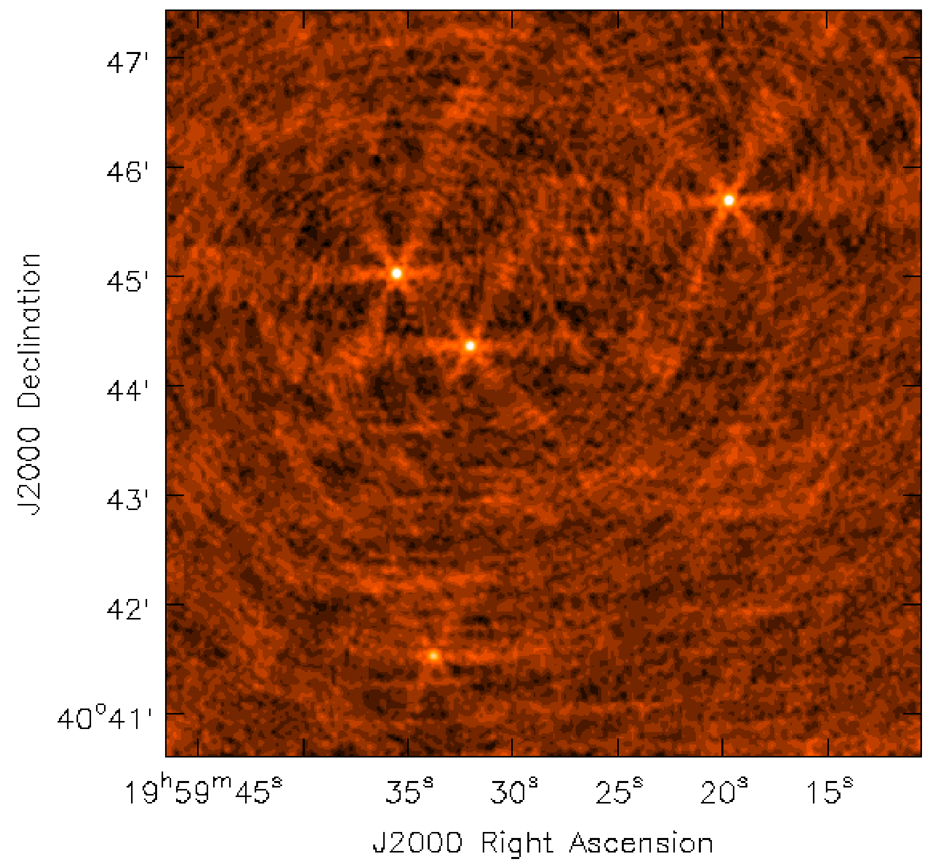
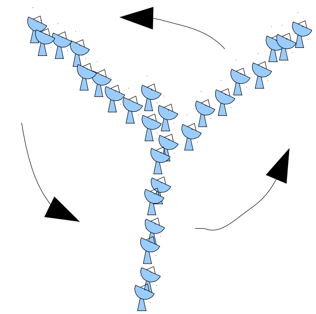


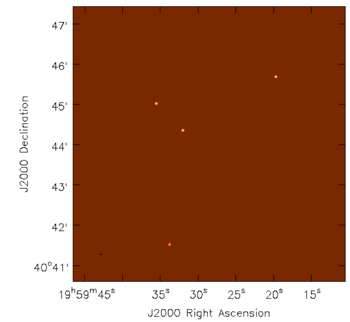
Observed Image

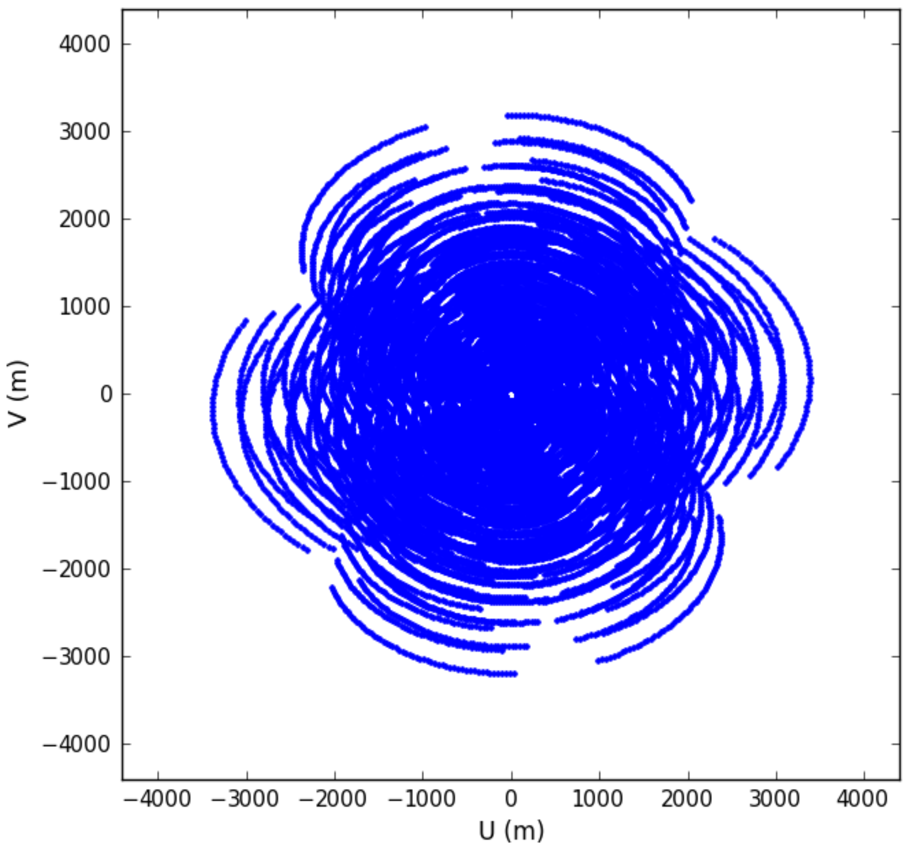
Aperture Synthesis Imaging

Image with 27 antennas over 4 hours

" Earth Rotation Synthesis "







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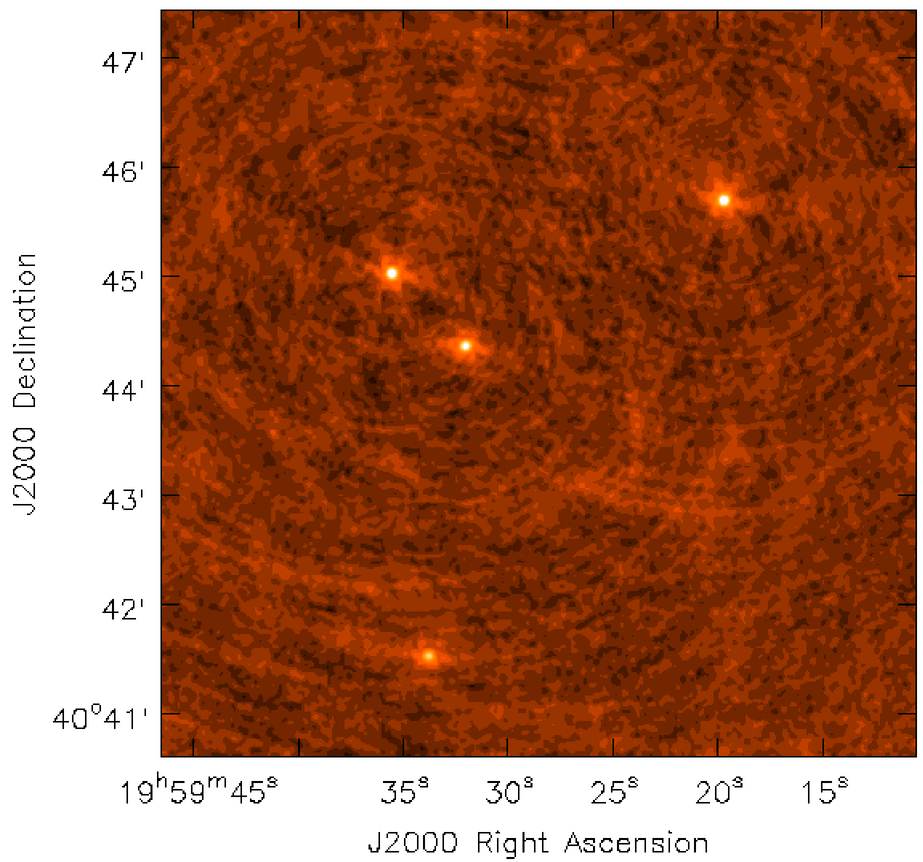
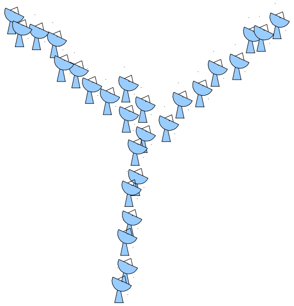


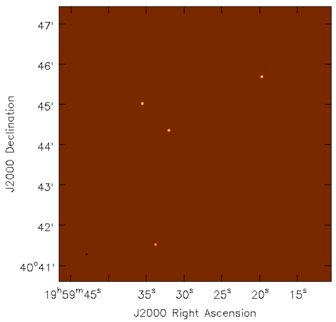
Observed Image

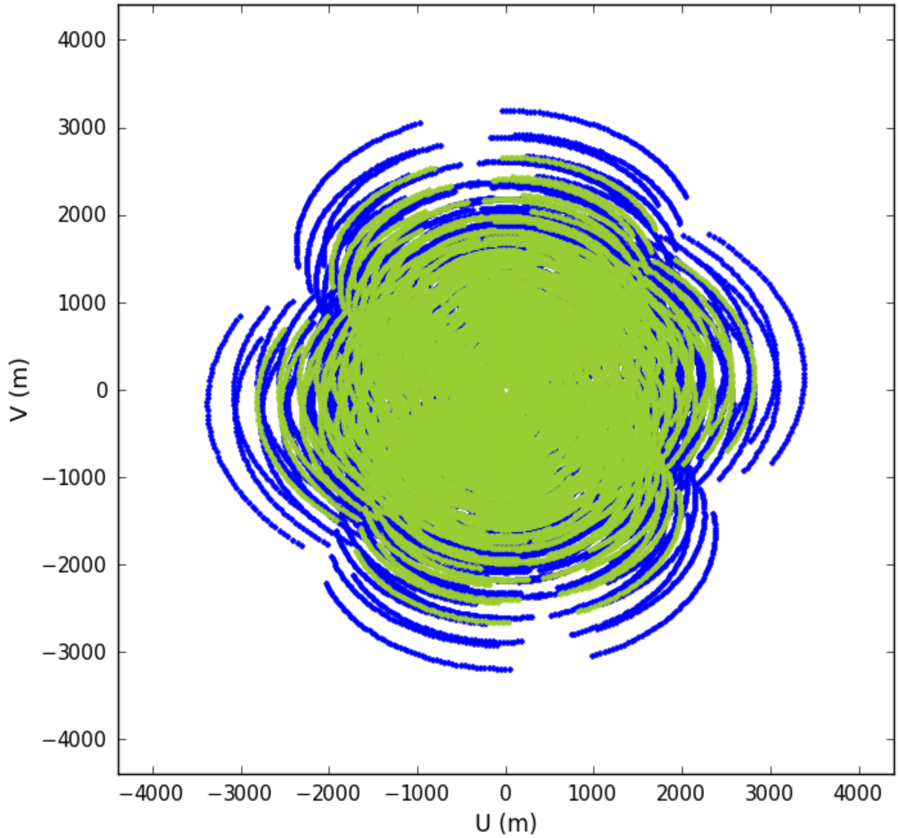
Aperture Synthesis Imaging

Image with 27 antennas over 4 hours
at 2 observing frequencies

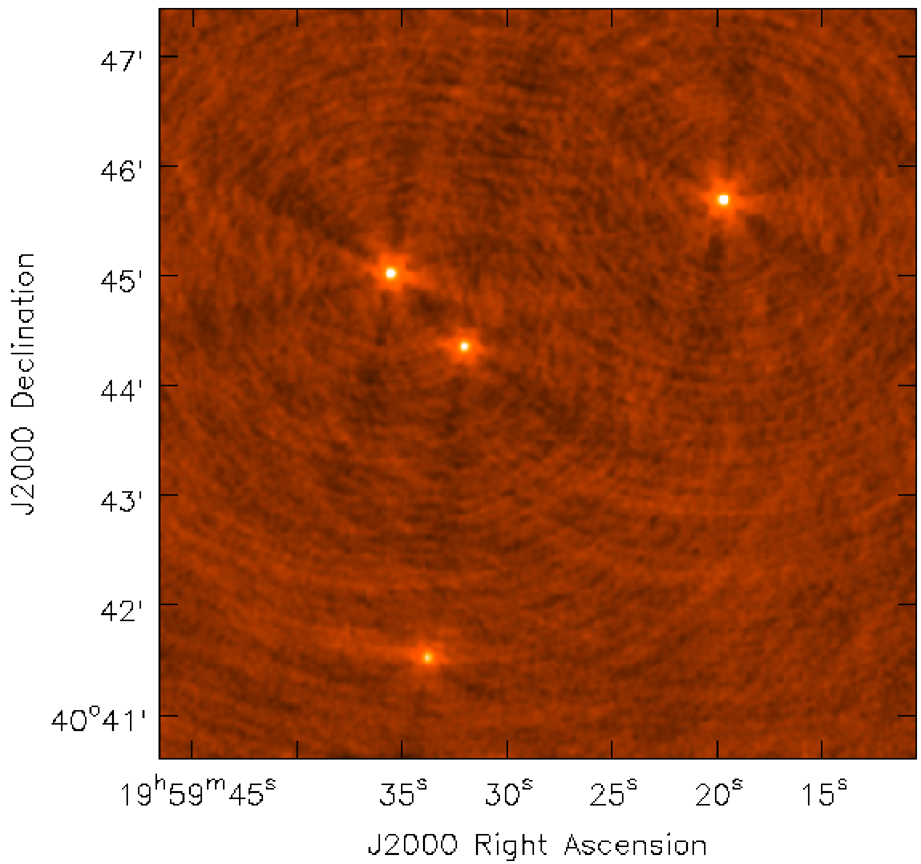
" Multi-frequency Synthesis "







Instrument Transfer Function

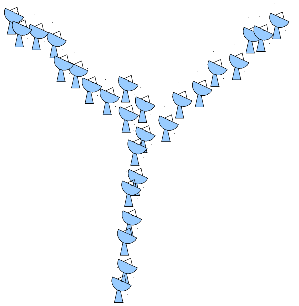


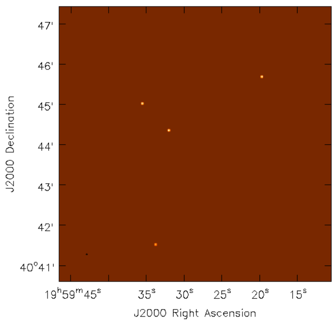
Observed Image

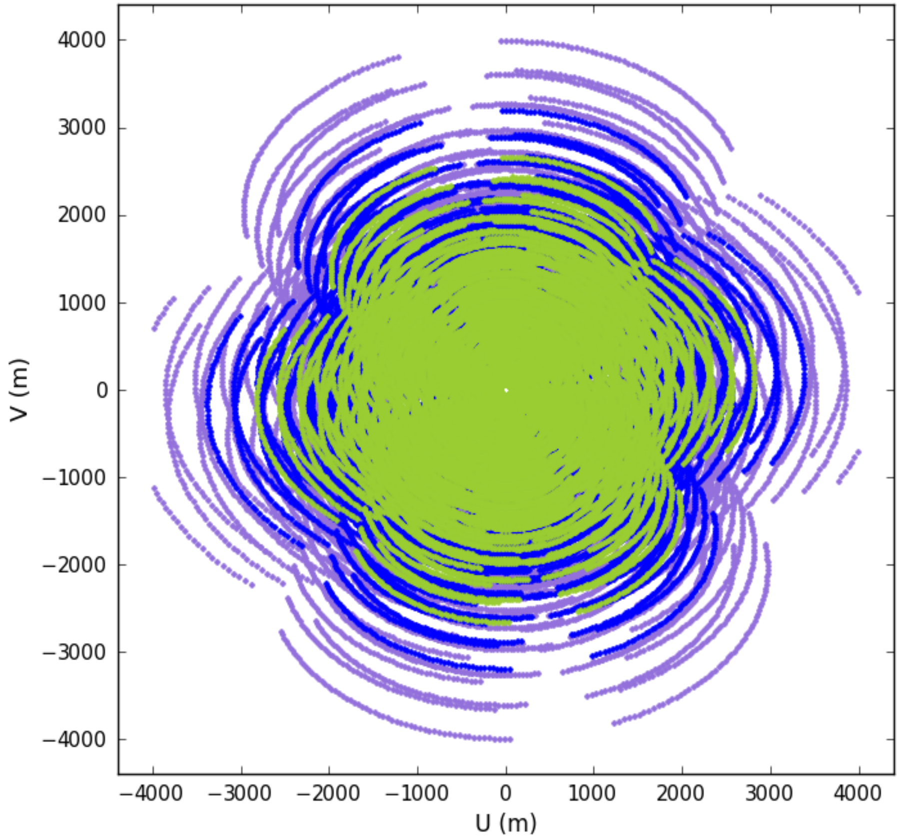
Aperture Synthesis Imaging

Image with 27 antennas over 4 hours
at 3 observing frequencies

" Multi-frequency Synthesis "







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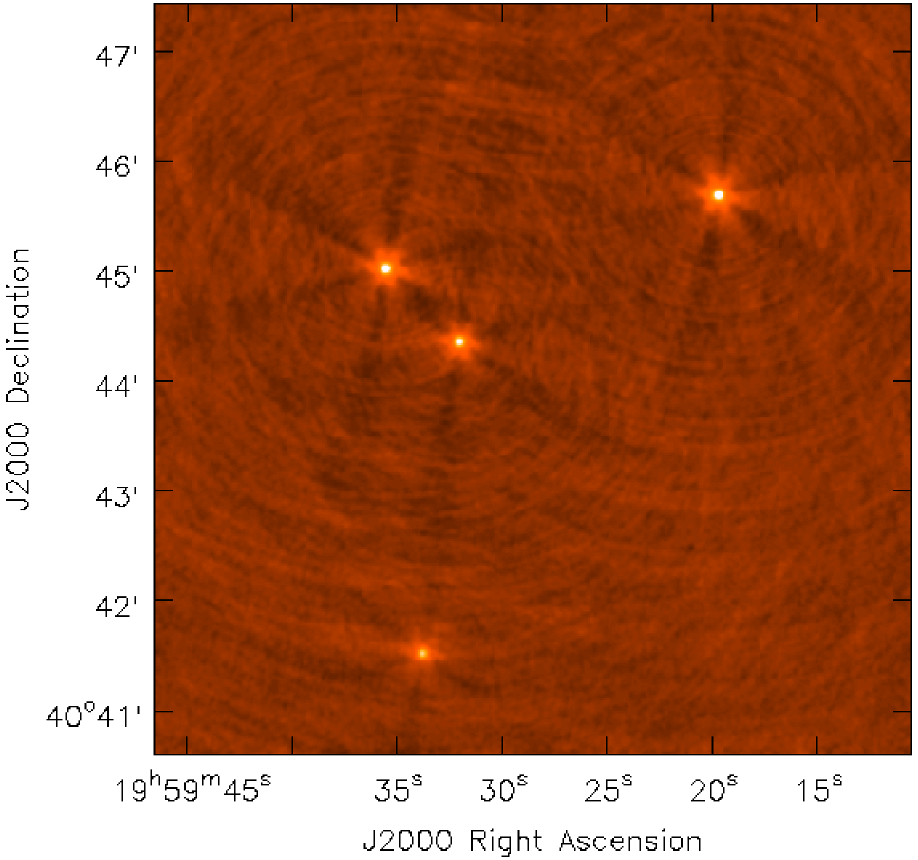
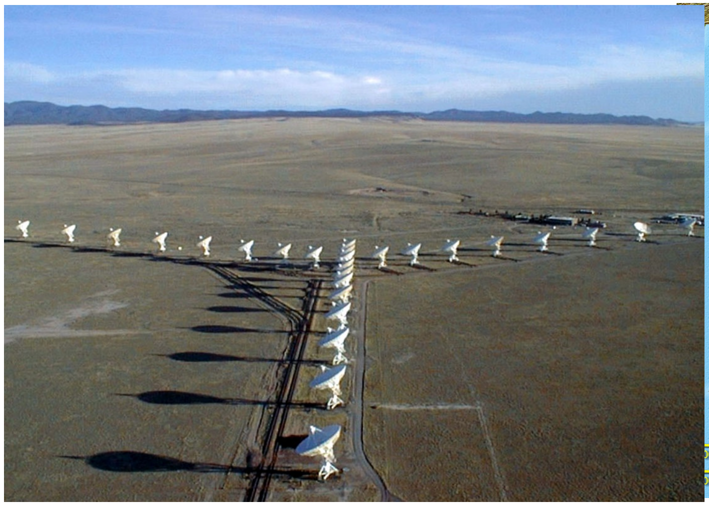


Observed Image

Current NRAO interferometers



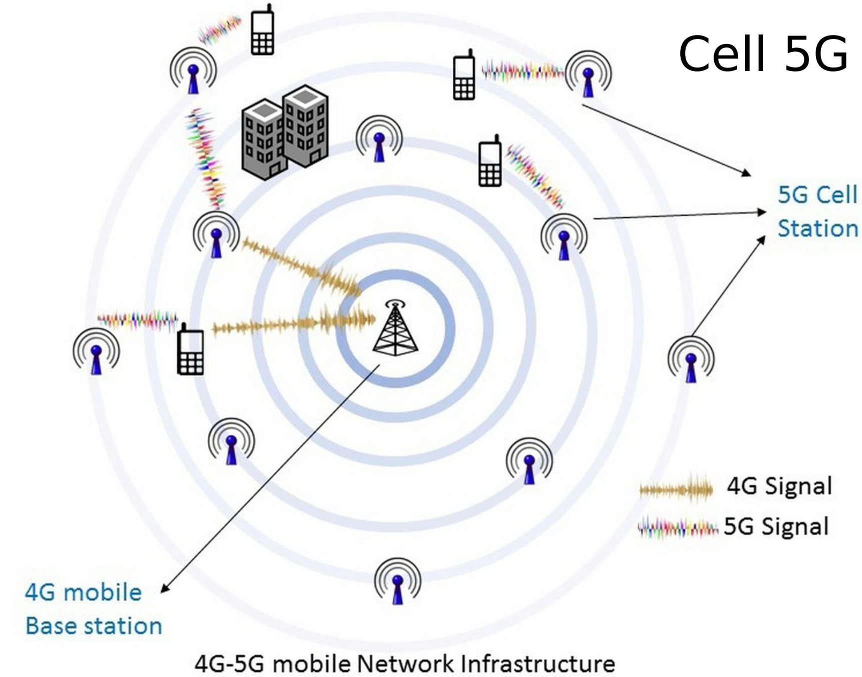
VLA	**VLBA**	**ALMA** (ESO, NAOJ partners)
27 dishes (25m each)	10 dishes (25m each)	60 dishes (12m + 7m)
1 GHz - 50 GHz	1 GHz - 50 GHz	84 GHz - 950 GHz
4 configurations 1km, 3km, 10km ,30 km	200km – 8000 km	150m – 16km
Plains of San Augustin, NM	Spread across the USA.	Chajnantoor Plateau Atacama Desert, Chile
1975 +	1993 +	2011 +

Radio Frequency Interference (RFI)

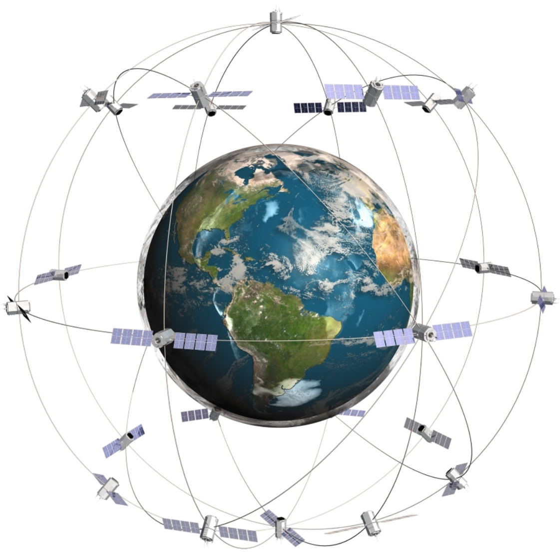
Radio Frequency Interference (RFI)

Commercial signals transmitted in the same frequency range as interesting astrophysical emissions.

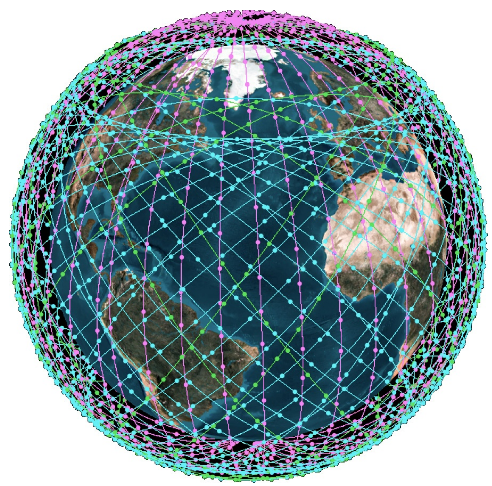
Cell 5G



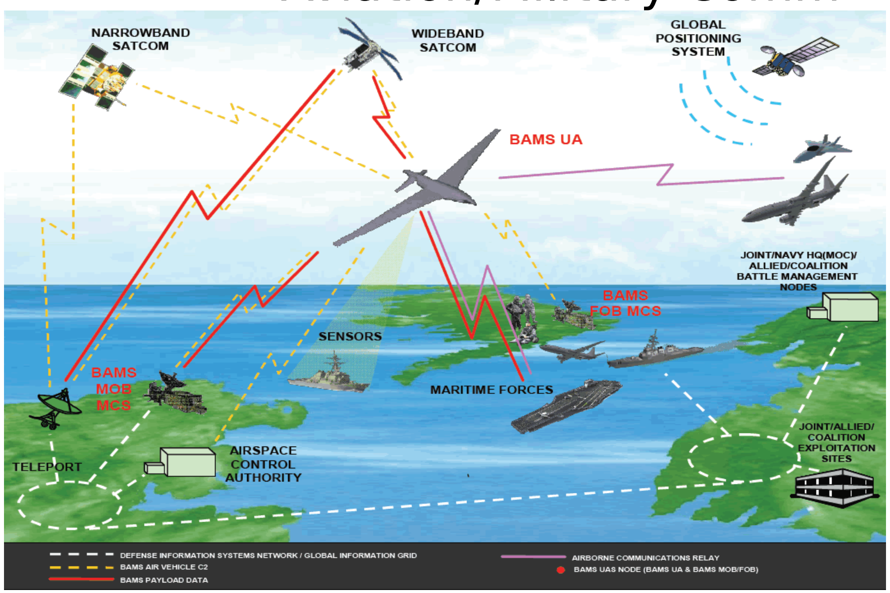
GPS-sat



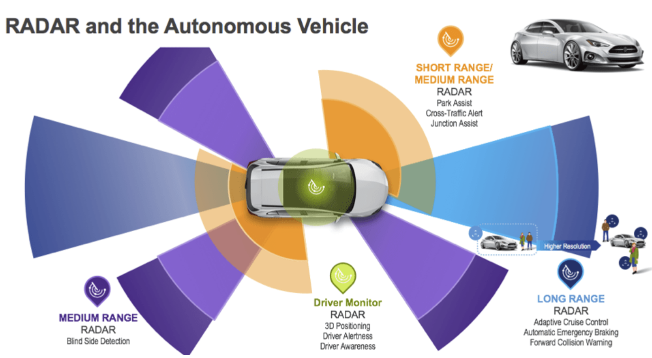
LEO-sat



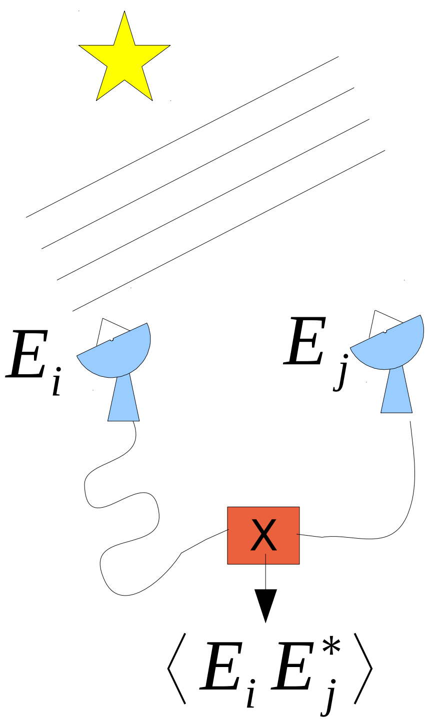
Aviation/Military Comm



Car Radar



How does an interferometer see RFI ?



Measured Visibility : $\langle E_i E_j^* \rangle$

= Mutual coherence of two incident E-fields.

=> Both antennas need to see the signal

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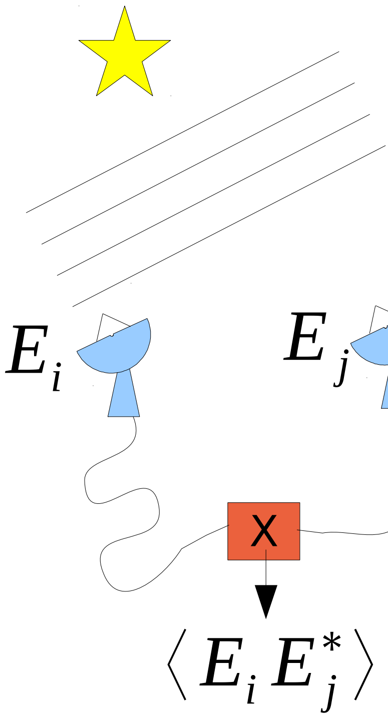

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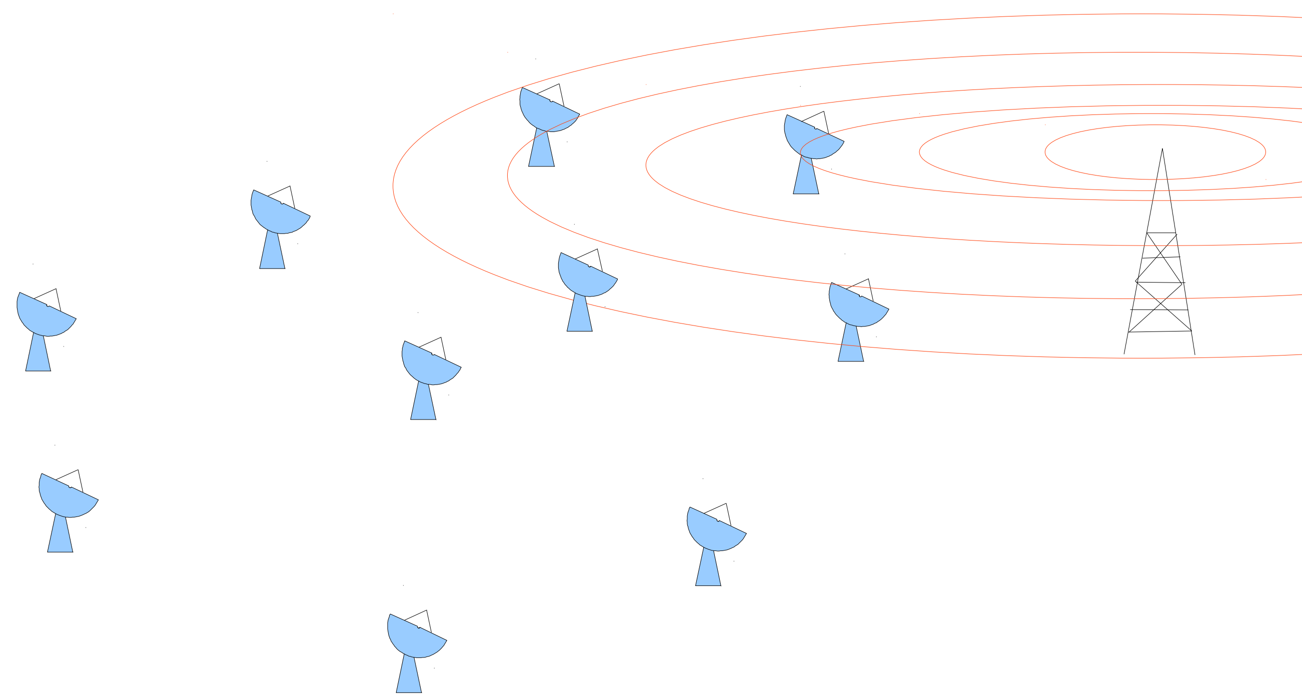

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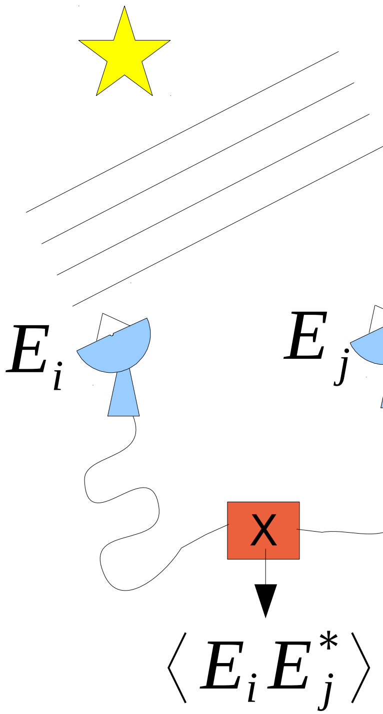

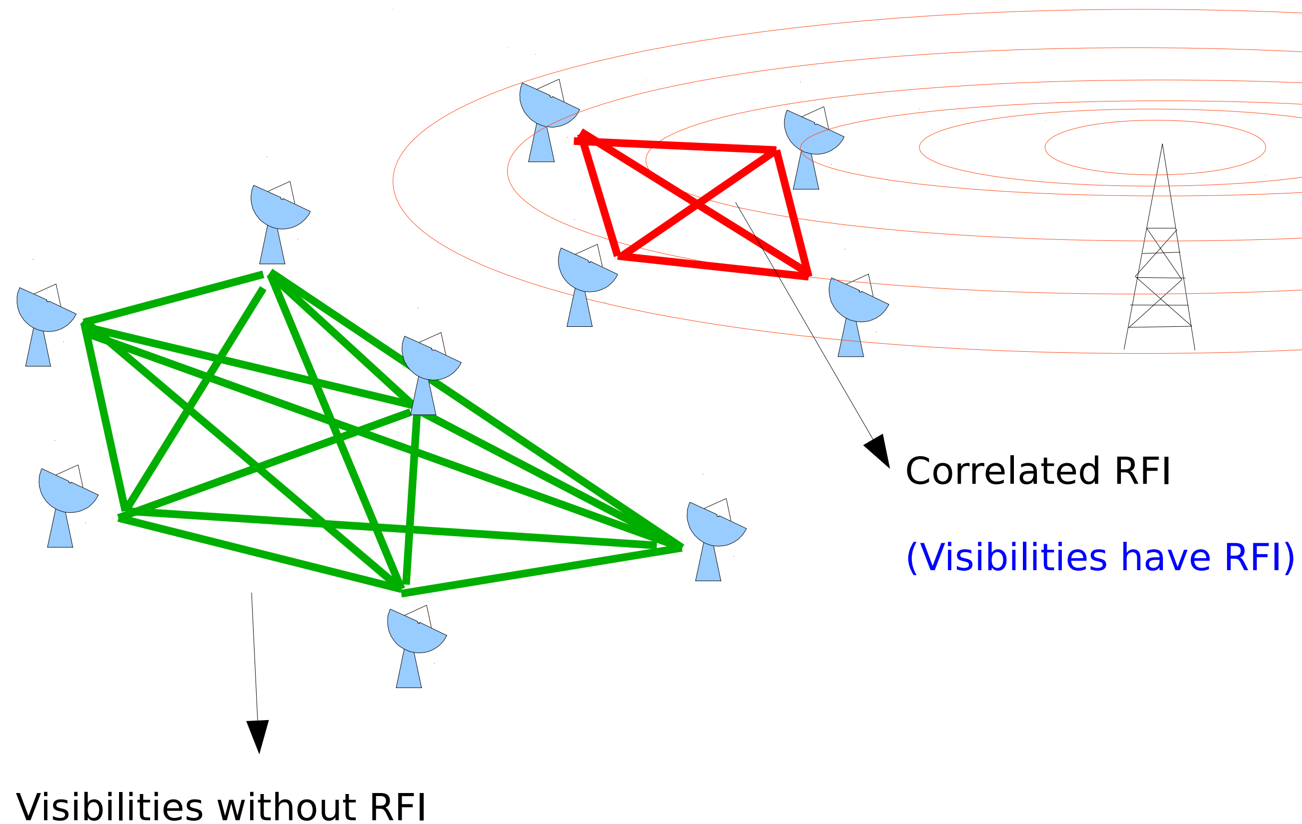

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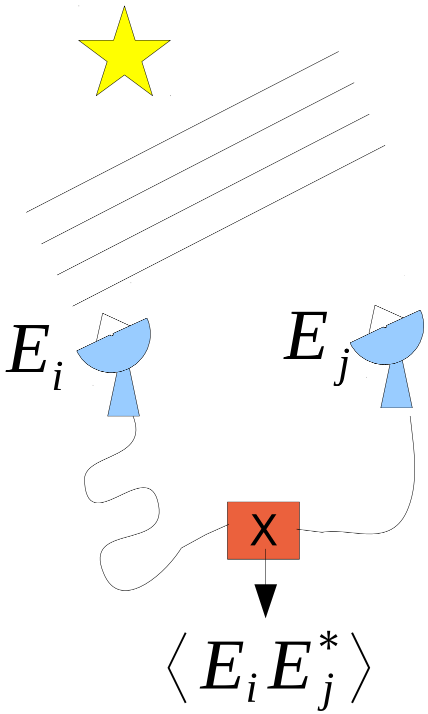

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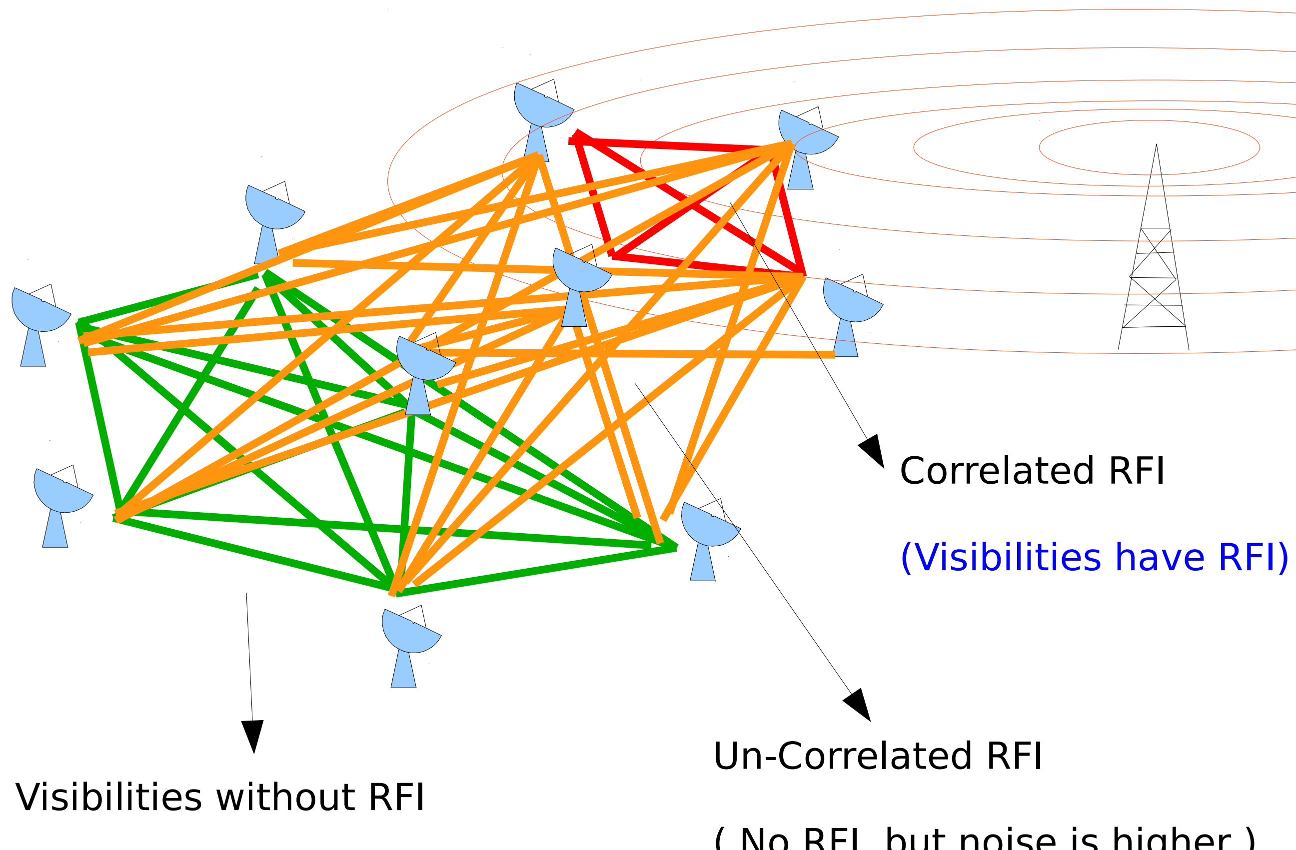

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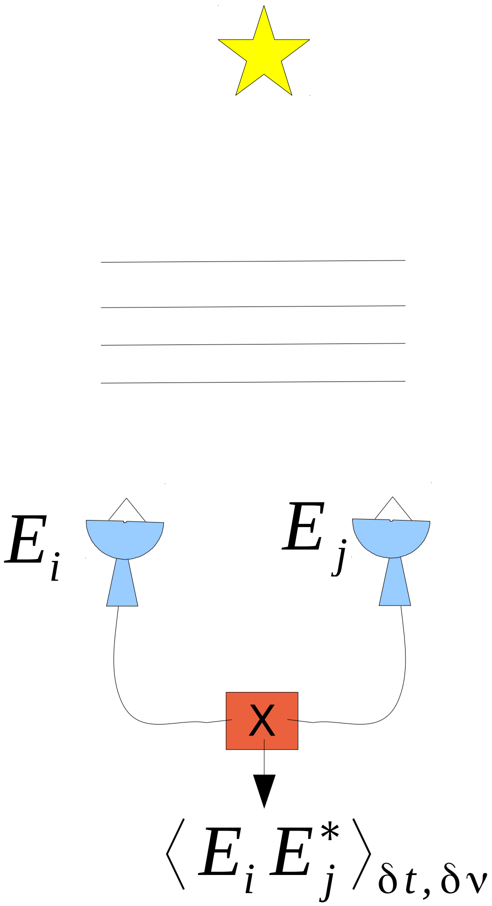
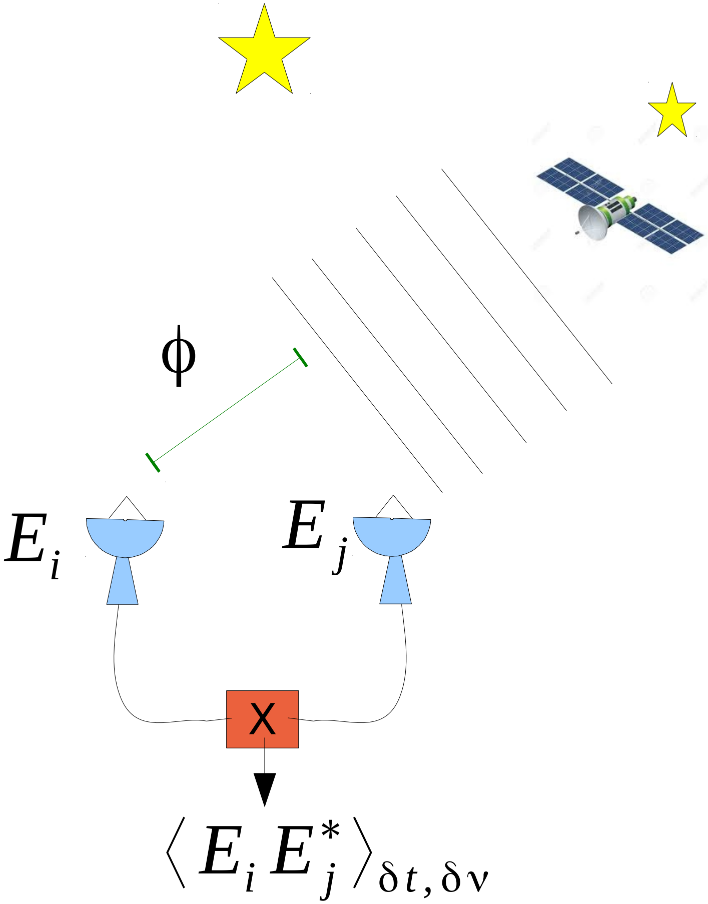


Signal De-Correlation

For the source being looked at,

Phase difference ϕ between signals at each antenna = 0

How does an interferometer see RFI ?



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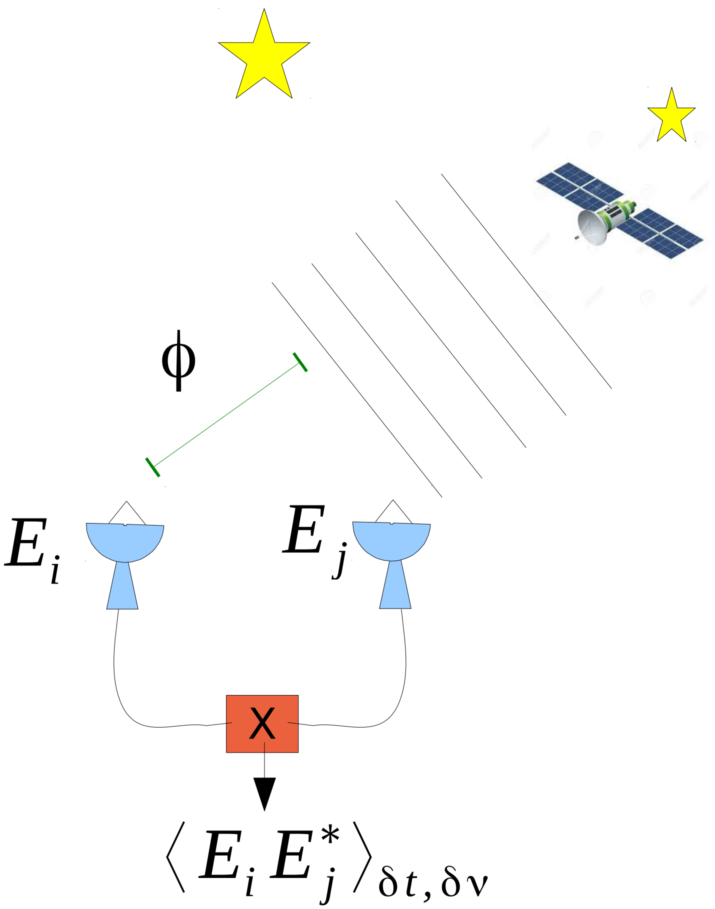
For a source in another direction

Phase difference $\phi > 0$

=> If $\delta t, \delta \nu$ are high enough

Signals away from the center will attenuate $\propto$ $Sinc(\phi)$

How does an interferometer see RFI ?



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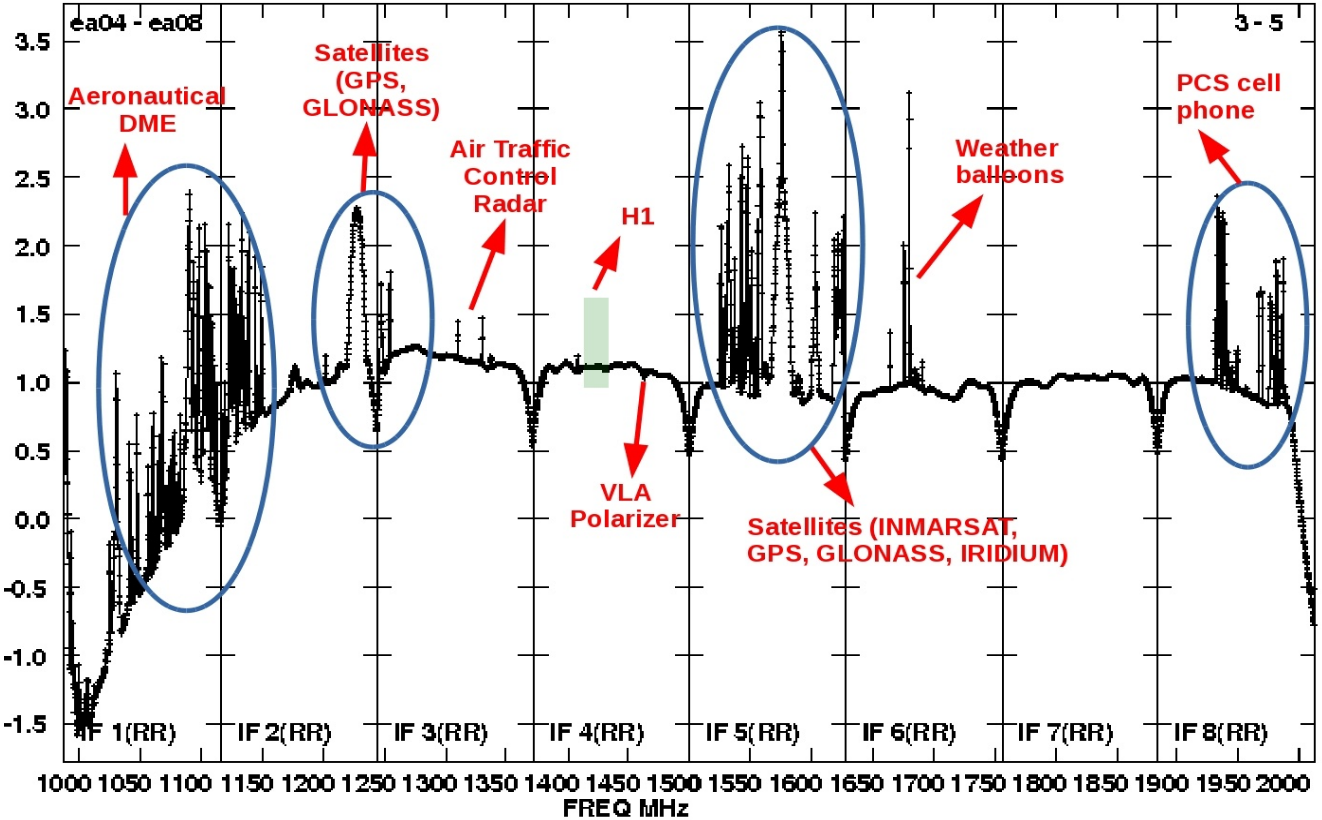
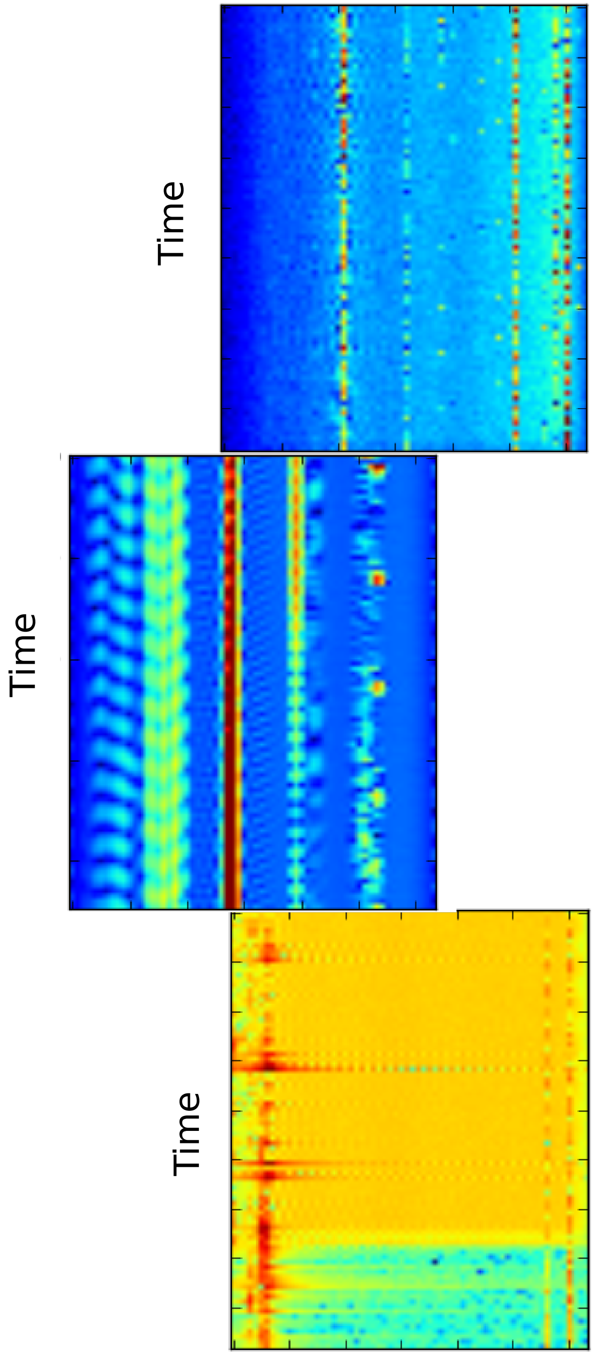
Some RFI signals can be suppressed, but they will still be seen in the data.

De-correlation makes it harder to model and subtract...

Example of current RFI at L-Band (1-2 GHz)





Some signals are continuous and some are intermittent.

Some are narrow-band and some are broad-band

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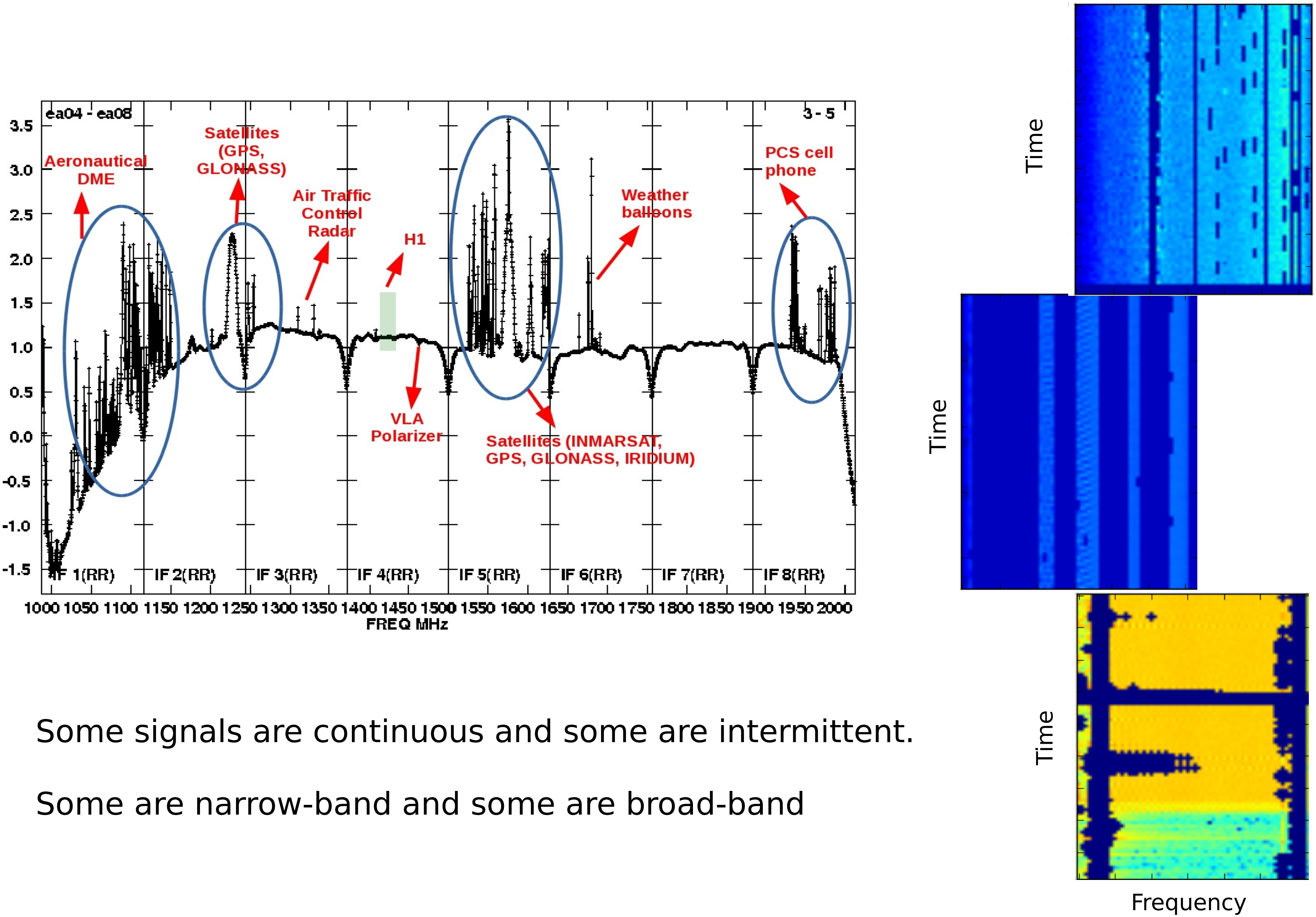

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How does RFI affect our science ?

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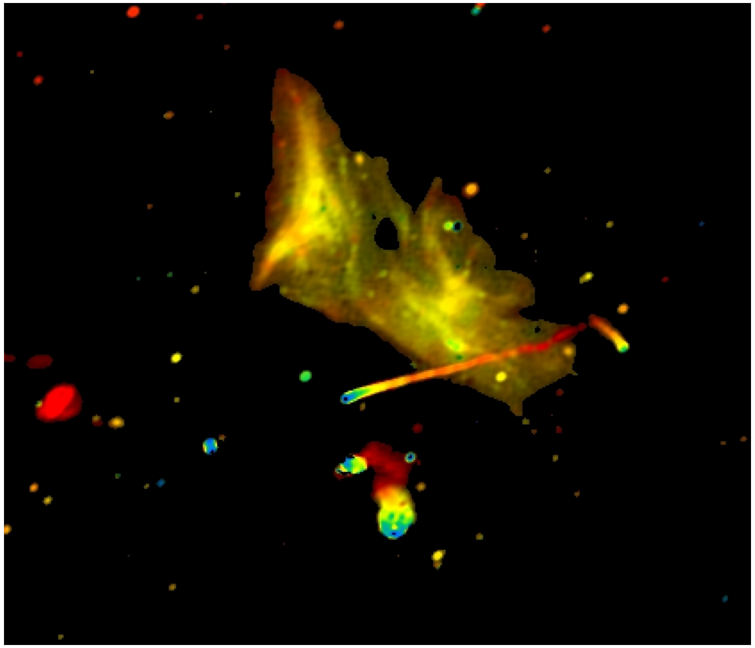
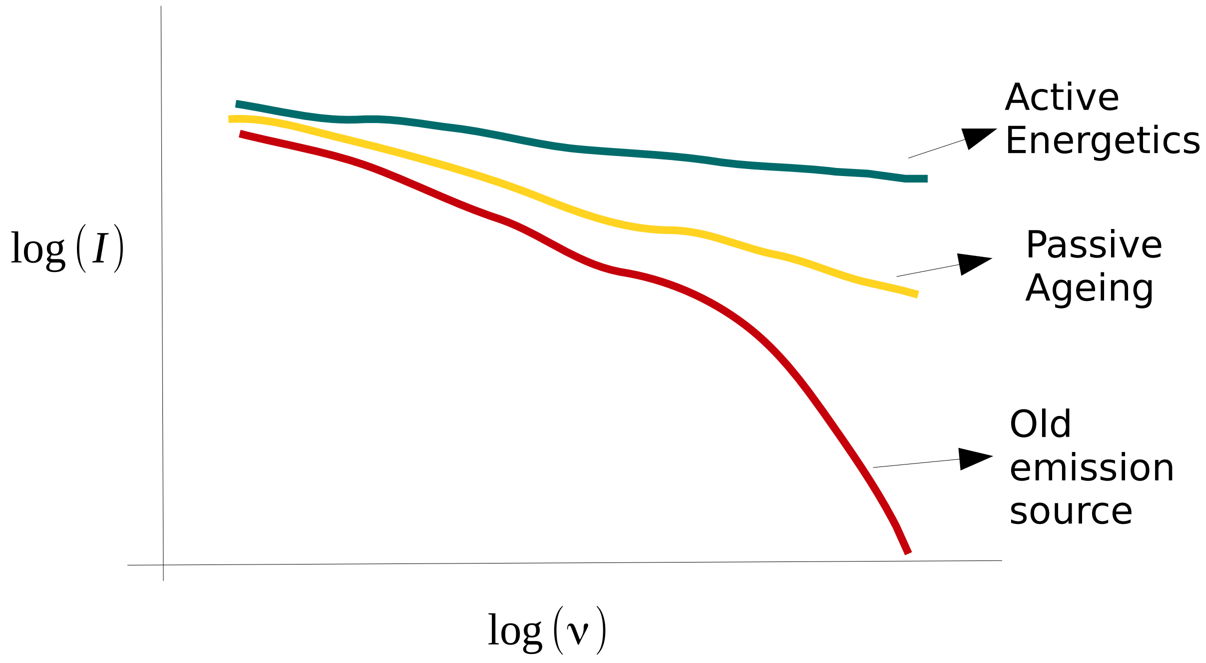
Continuum Imaging

Intensity $\left(\nu_{ref}\right)$



Abell 2256 Galaxy Cluster

Spectrum



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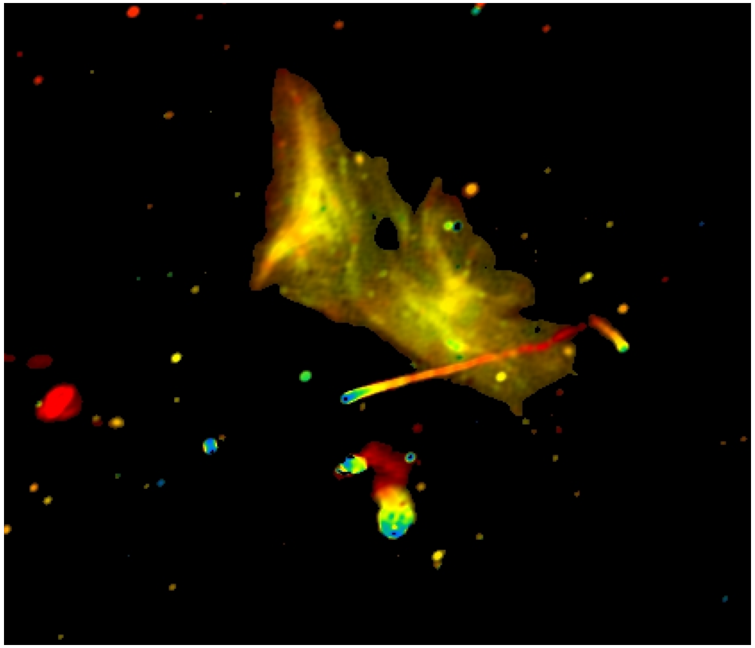

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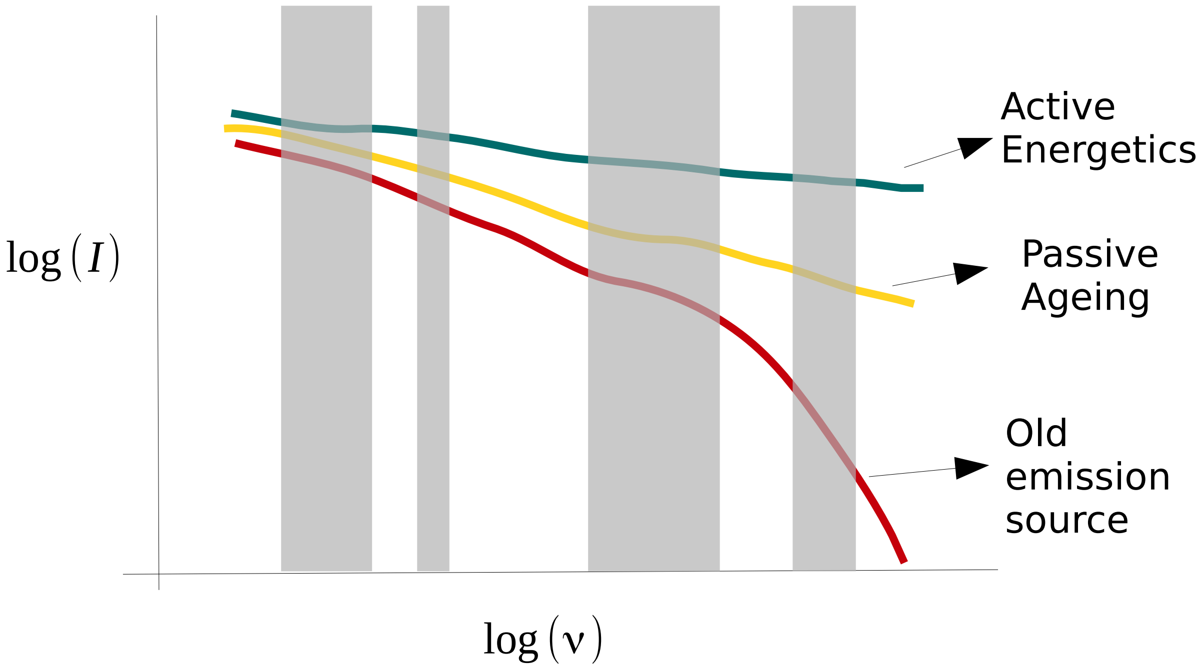


- Astrophysical quantities can be derived from gaps between RFI bands

- But, need extra observing time to increase imaging sensitivity (lower noise)

How does RFI affect our science ?

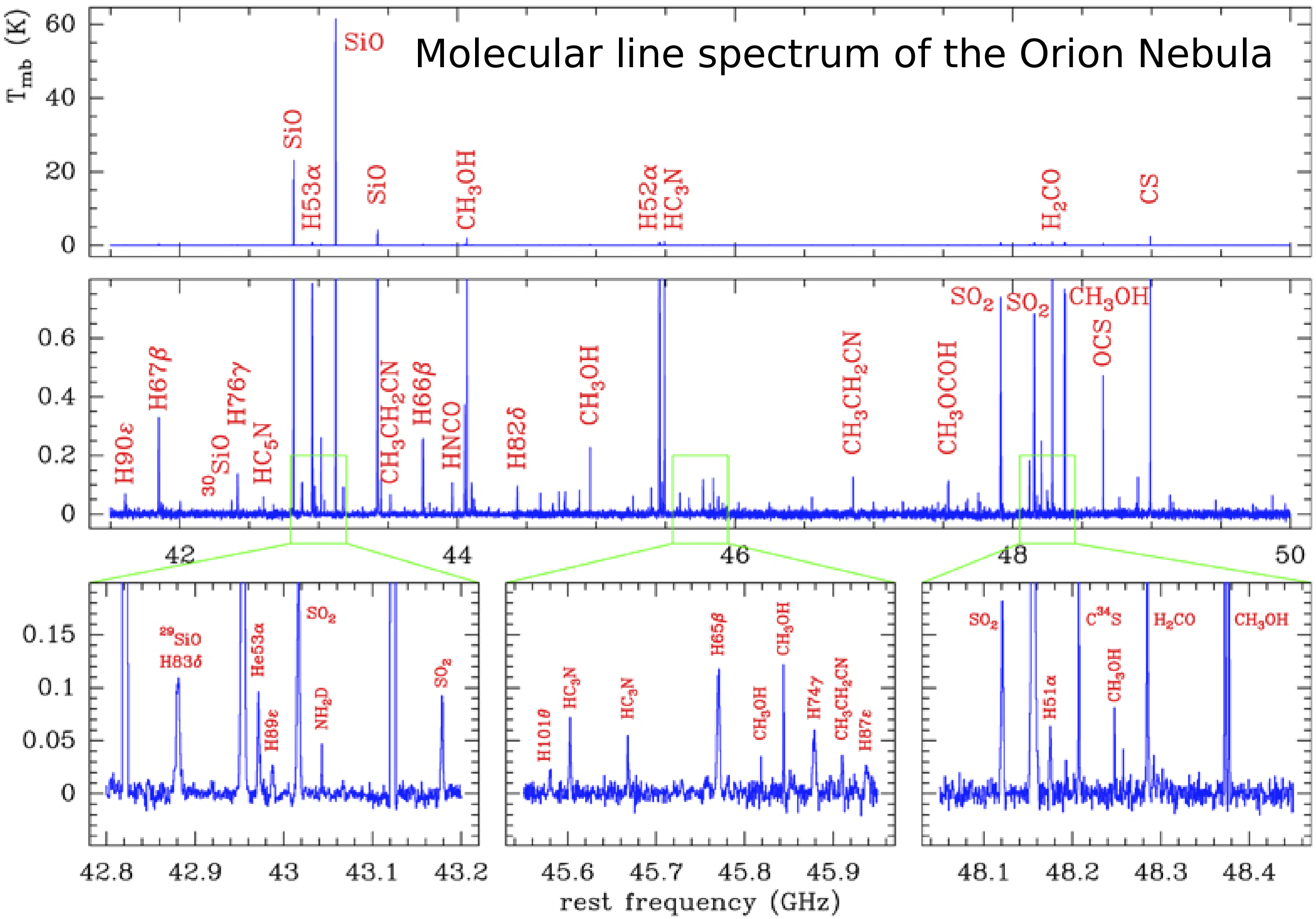
Spectral Line Imaging

Chemistry :

– Emission and Absorption lines

Distance / Age :

– Doppler Shifts



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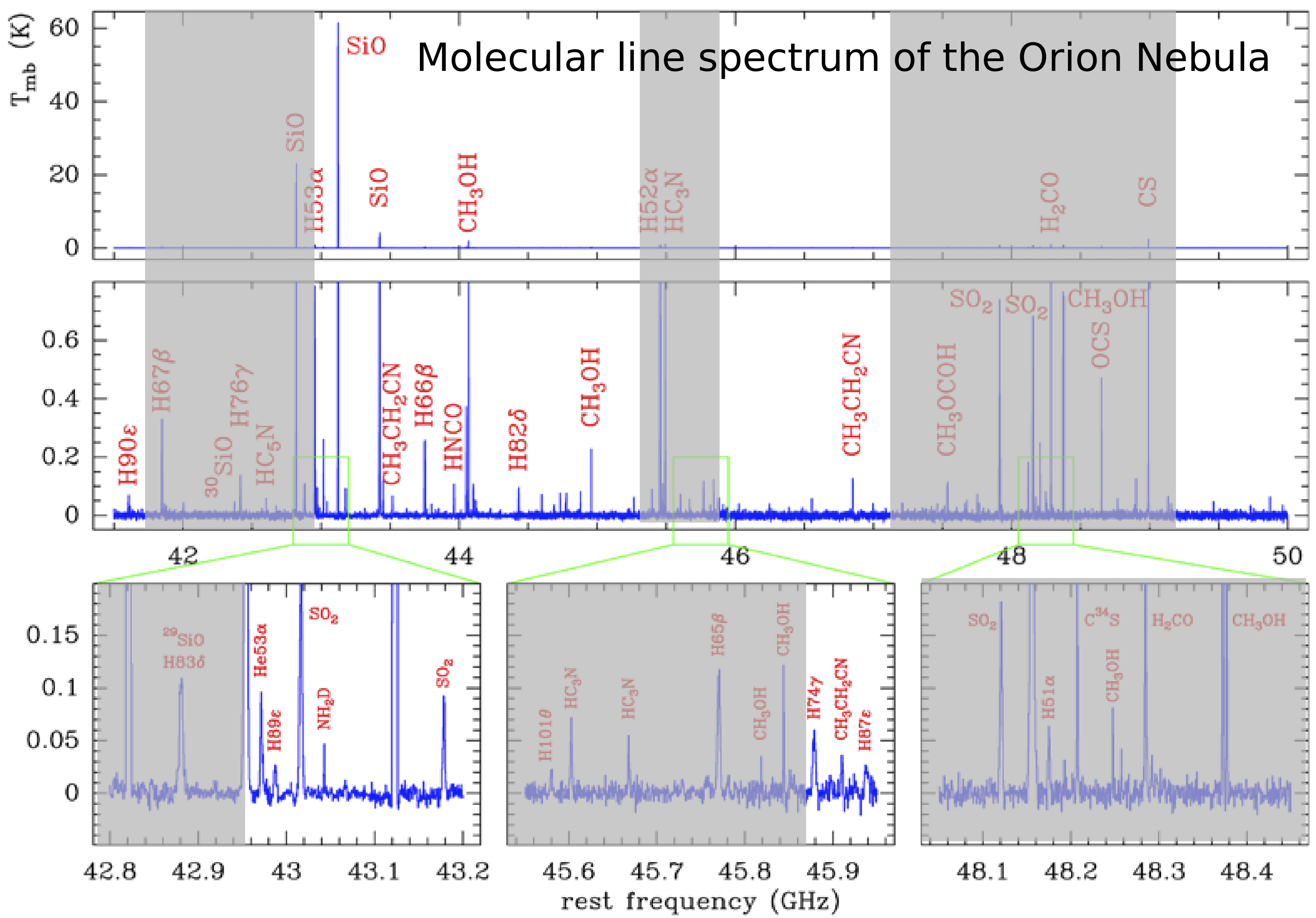
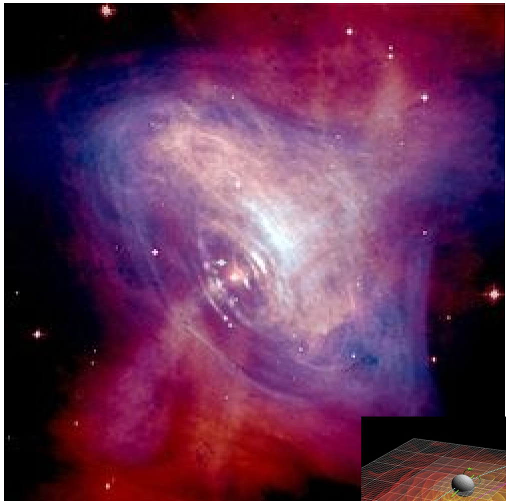
– Doppler Shifts



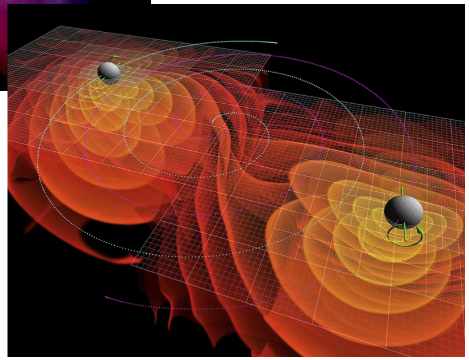
- Spectral lines that fall outside of tiny protected radio astronomy bands are lost if any RFI is present.

How does RFI affect our science ?

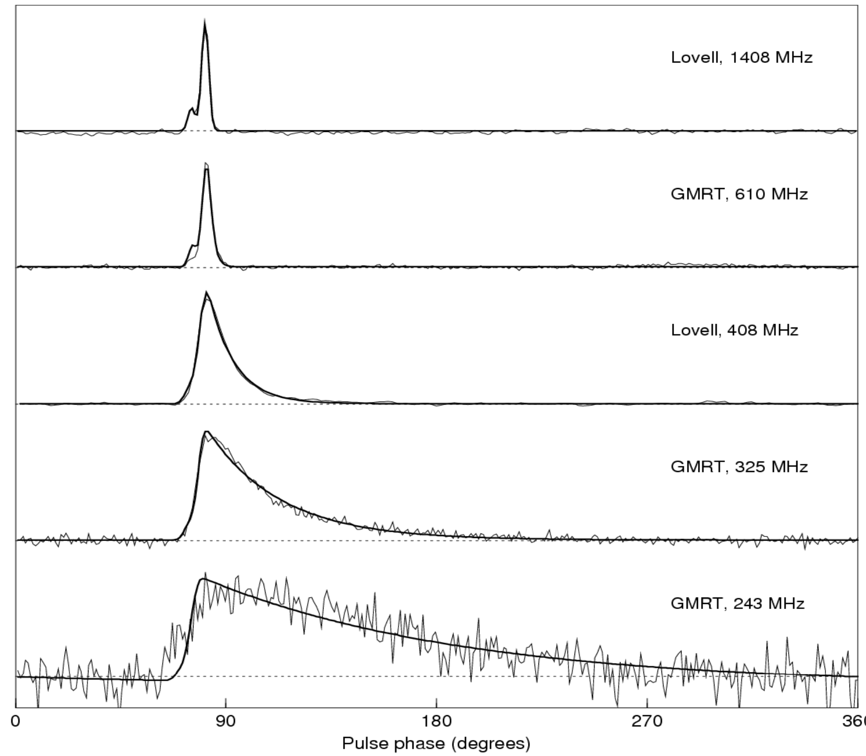
Time-Domain Astronomy



Pulsars



Merger events



ν

Time (pulse phase)

- Astrophysical events have similar characteristics as RFI : False positives

- A problem for triggered follow-ups on other instruments

Present to Future…..

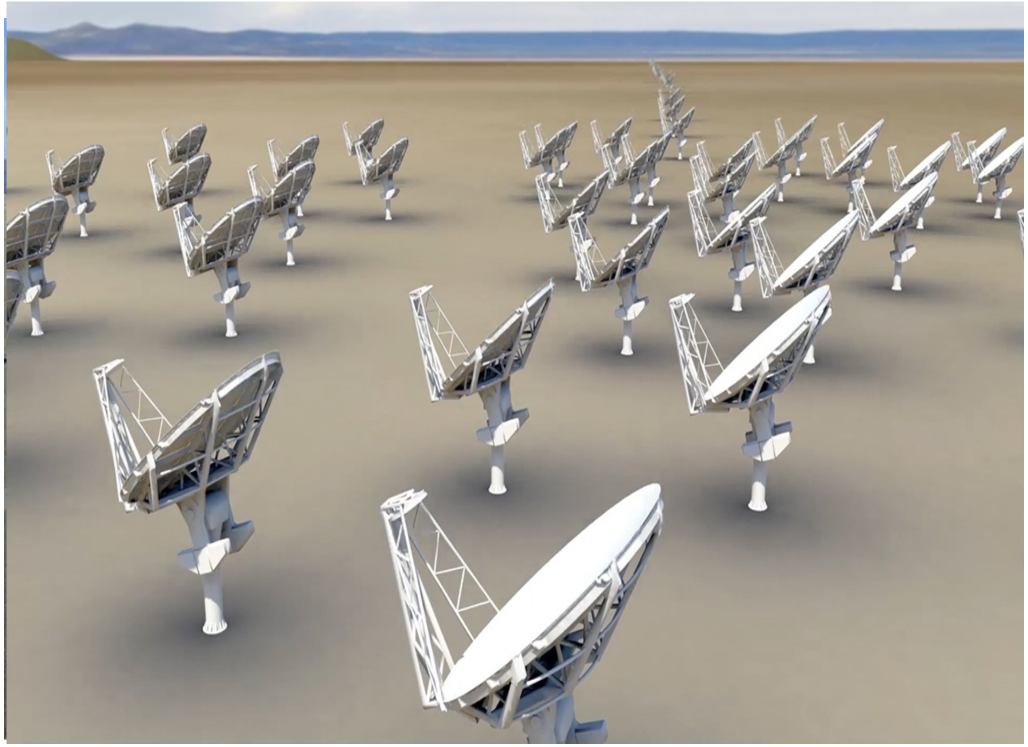
Present :

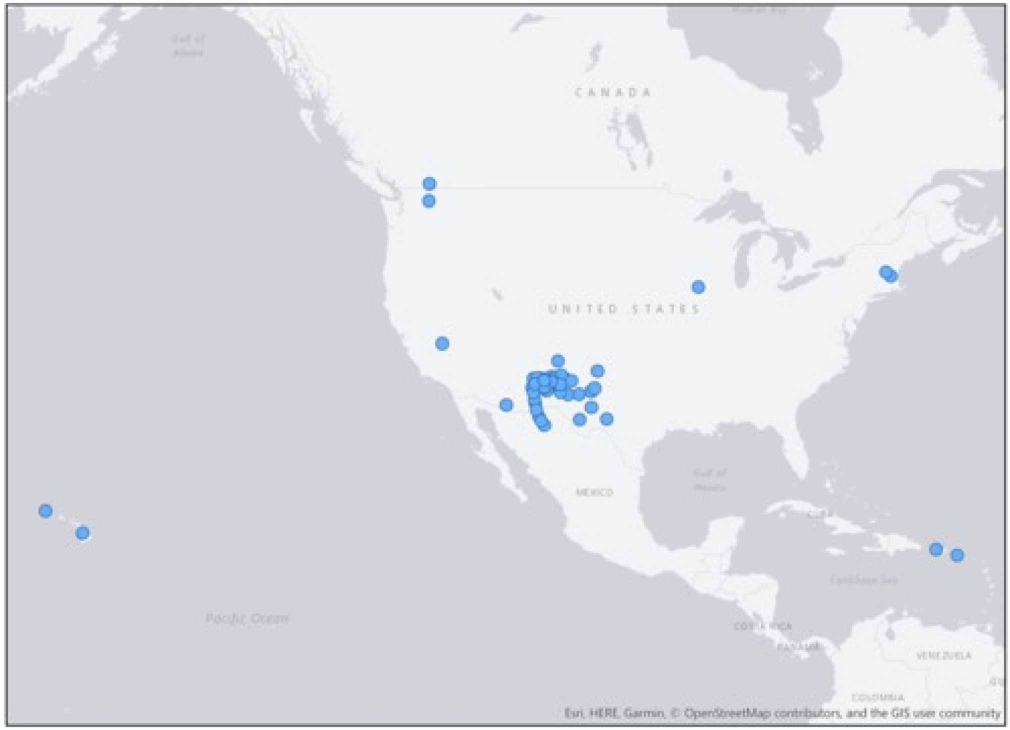
- RFI causes problems
- We have been able to work around some of them

Future :

- The RFI environment is getting much worse
- We want to observe in wider frequency ranges
- We have to innovate, especially for future (expensive) instruments

Future : Next Generation VLA (2030+ if funded)





NGVLA

263 dishes (18m and 6m)

1.2 – 116 GHz, in 6 bands (except 50-70 GHz)

Fixed configuration : ~50m to 8000km baselines

Location : In/around New Mexico + VLBA sites

Purpose :

- 10x improvement in imaging sensitivity and resolution (compared to VLA)

- Bridge the gap between current VLA and ALMA frequencies

- New Science

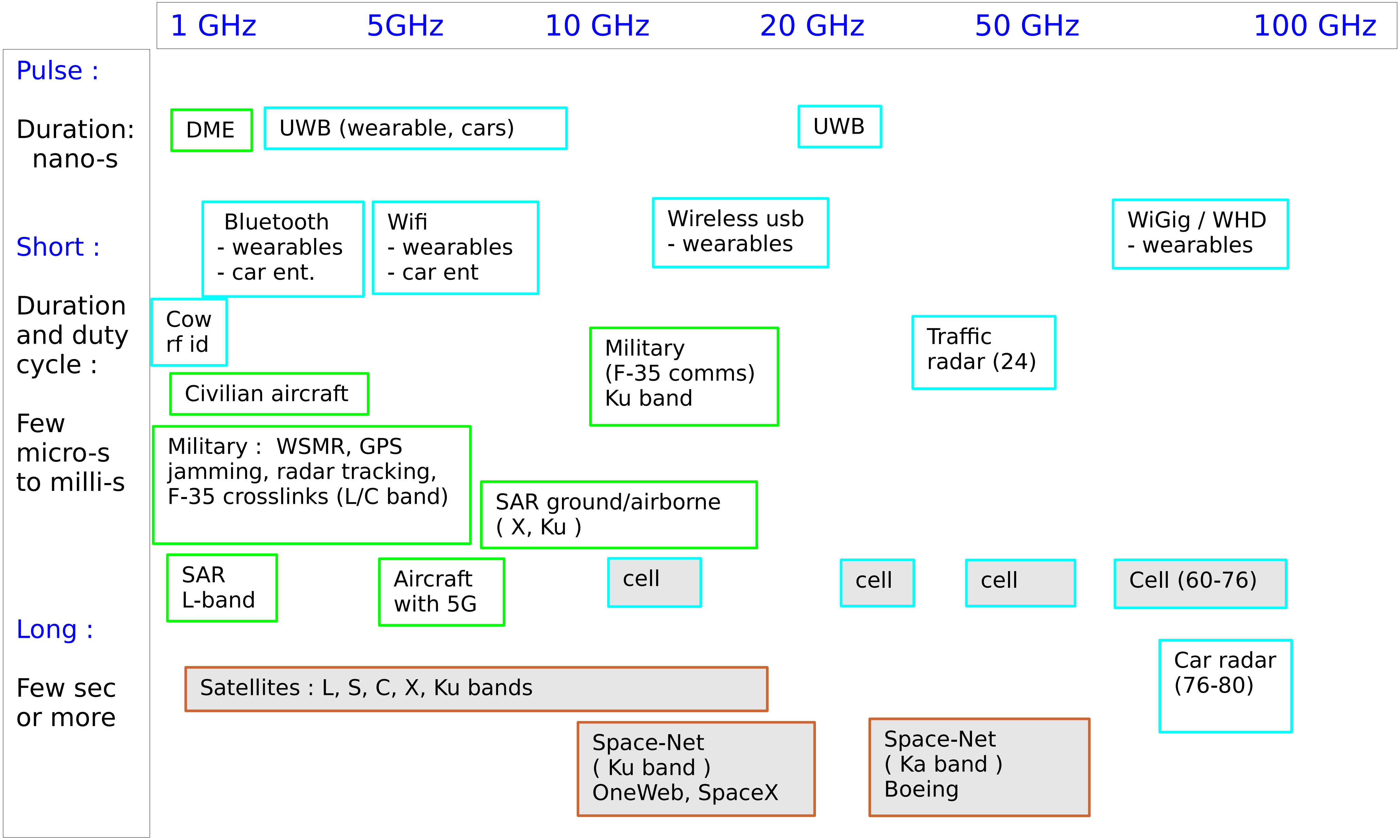
Future : Next Generation VLA (2030+ if funded)

Main Core : 100 x 18m dishes (< 2km baselines)
Plains Spiral : 114 x 18m dishes (< 70 km baselines)
Compact core : 19 x 6m dishes (< 0.1 km baselines)
Long Baselines : 30 x 18m dishes (100 – 8000 km baselines)

Main/Compact Cores (119) : Plains of San Augustin (remote)

Other antennas (144) : Near humans. All antennas : Will see satellites

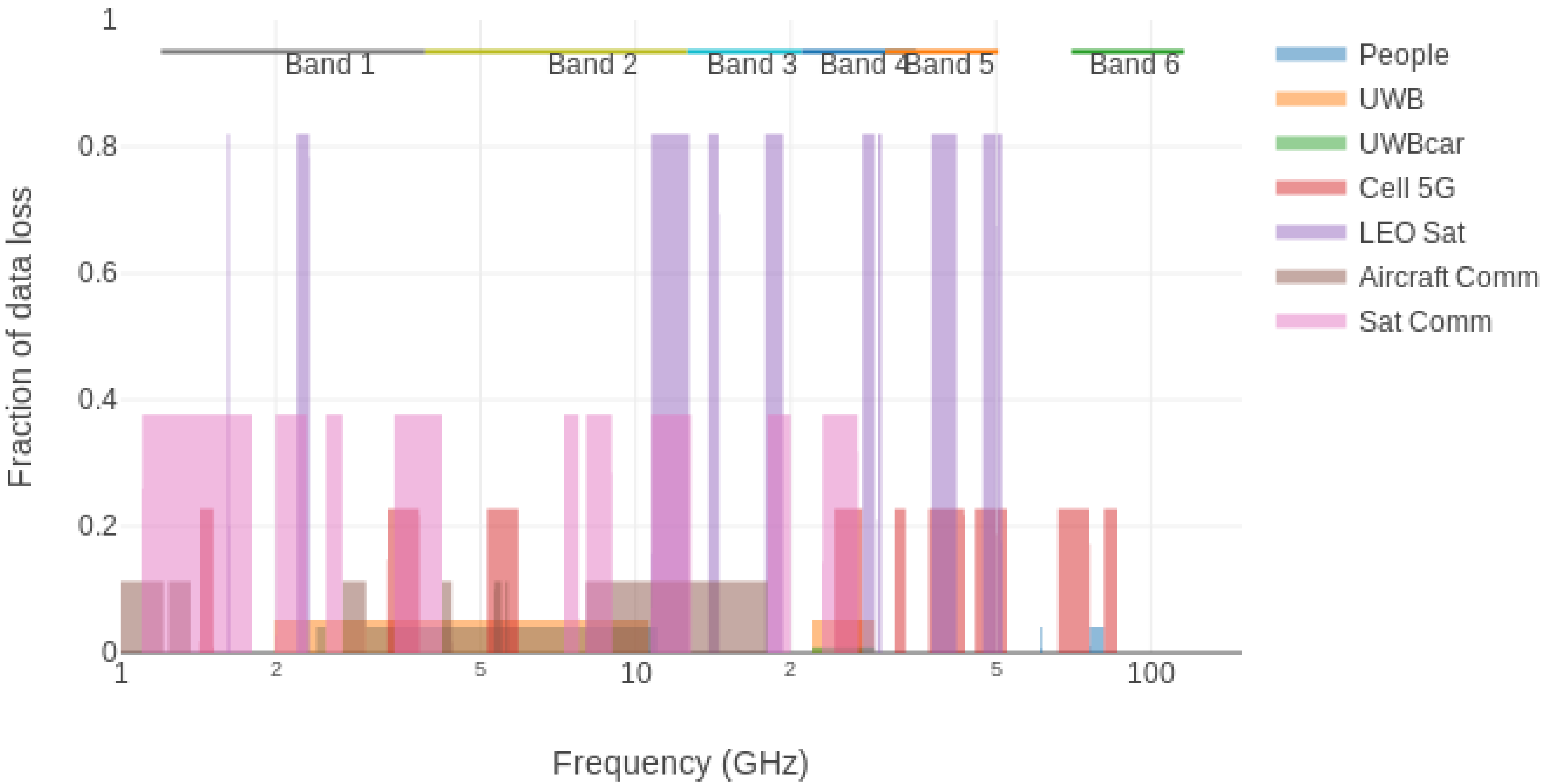
Future RFI Landscape (1-100 GHz)



Color : Local RFI (~ few antennas) RFI on large fraction of array(airborne) RFI on entire array (satellite)

Shading : White : Seen for a small fraction of observing time. Grey : Seen for most/all observations

Estimated fraction of data loss – status quo



Assumptions : Multiple RFI types with different footprints in frequency, time, and antennas.
Entire allocated band is filled at once (i.e. no usable gaps), no spillover/saturation

Calculations : Fraction of affected baselines, effects of RFI decorrelation and uncorrelated RFI

RFI mitigation : Only post-processing flagging

How can regulation help ?

(1) LEO satellites : A quiet zone (footprint) above the telescope

– Main Goal : To avoid saturating entire receiver bands.

=> Data loss is confined to LEO bands only.

(2) 5G Cell Towers :

– No new 5G towers near the ngVLA array core.

- Data loss will be similar to that from LEO satellites (at diff freqs) if cell 5G is active near the core.

– Band-selection for cell 5G towers near ngVLA-spiral antennas.

(3) Other (hard to regulate, but what most of our solutions depend on) :

– The presence of RFI gaps in time and frequency

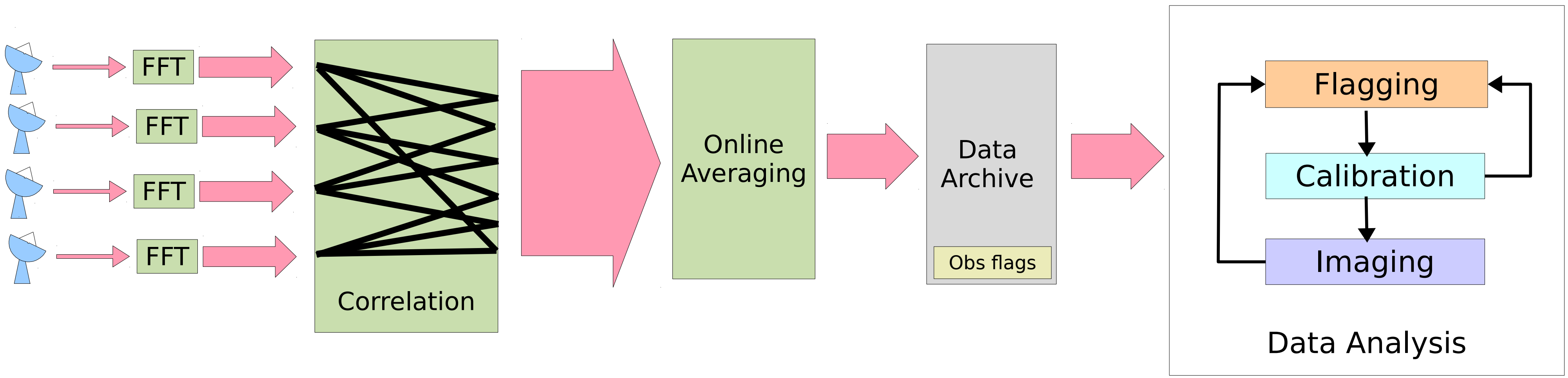
(4) Protected Radio Astronomy bands :

– Don't lose them

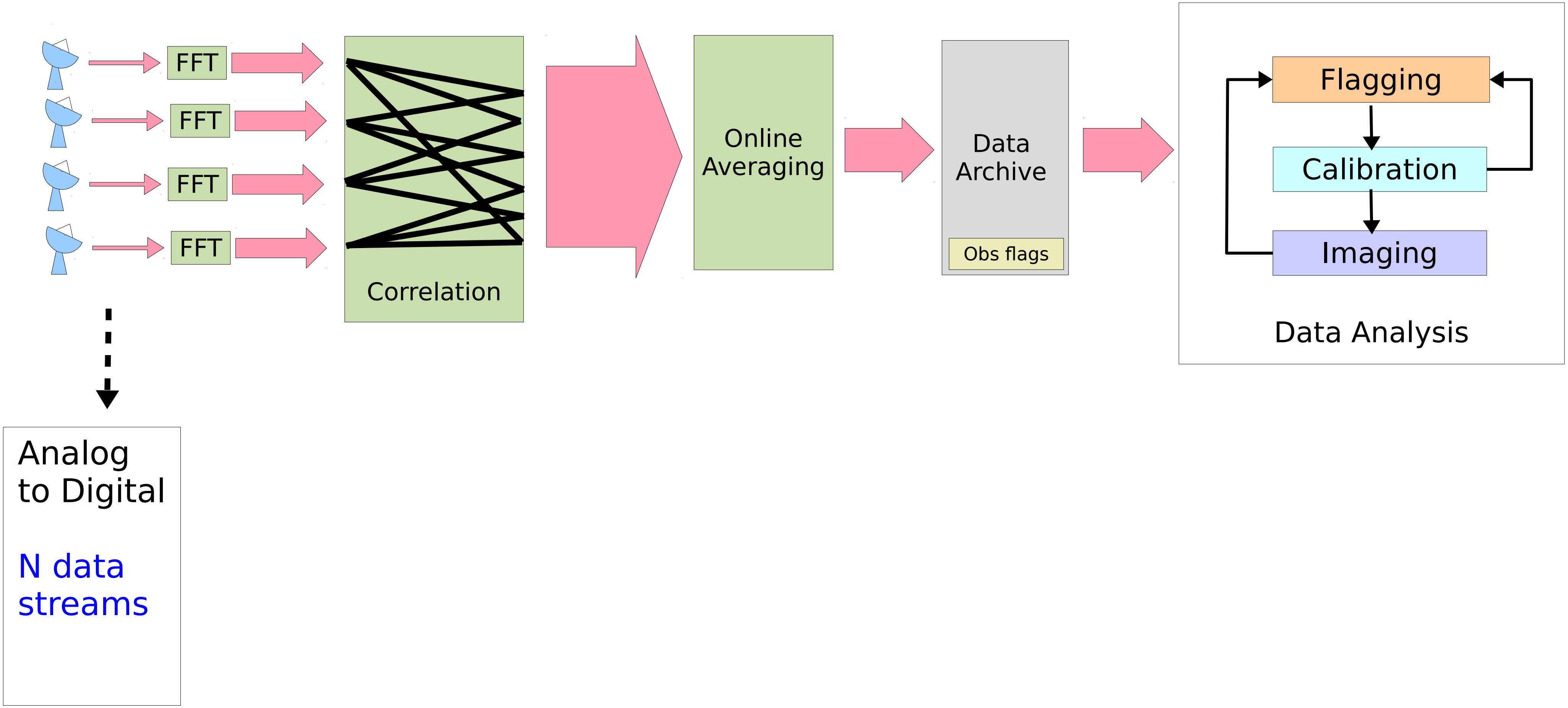
What can we do ?

- Integrated end-to-end RFI mitigation
- Match algorithm to RFI characteristics

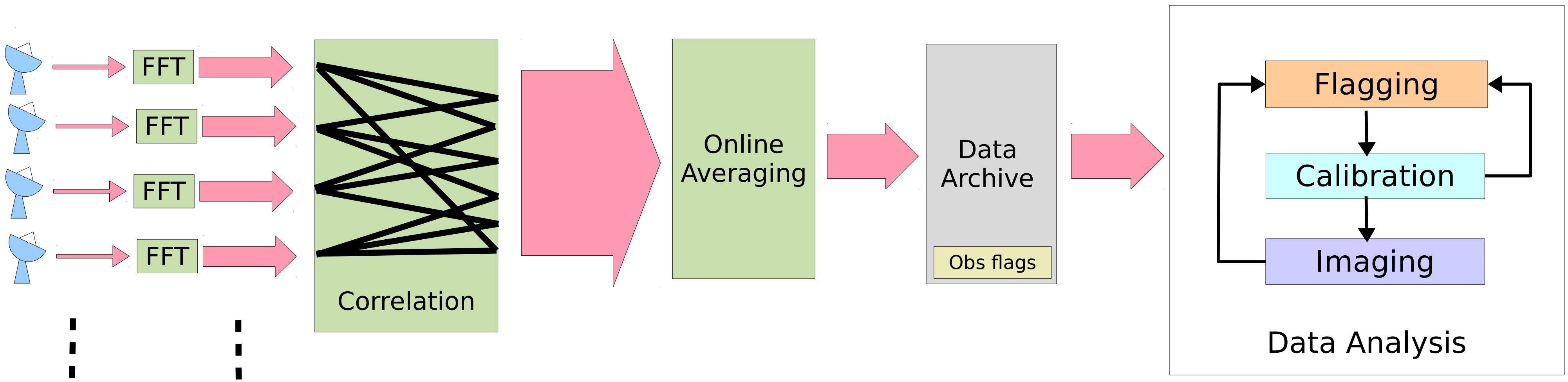
Data acquisition and analysis



Data acquisition and analysis – Real Time System



Data acquisition and analysis – Real Time System



Analog to Digital

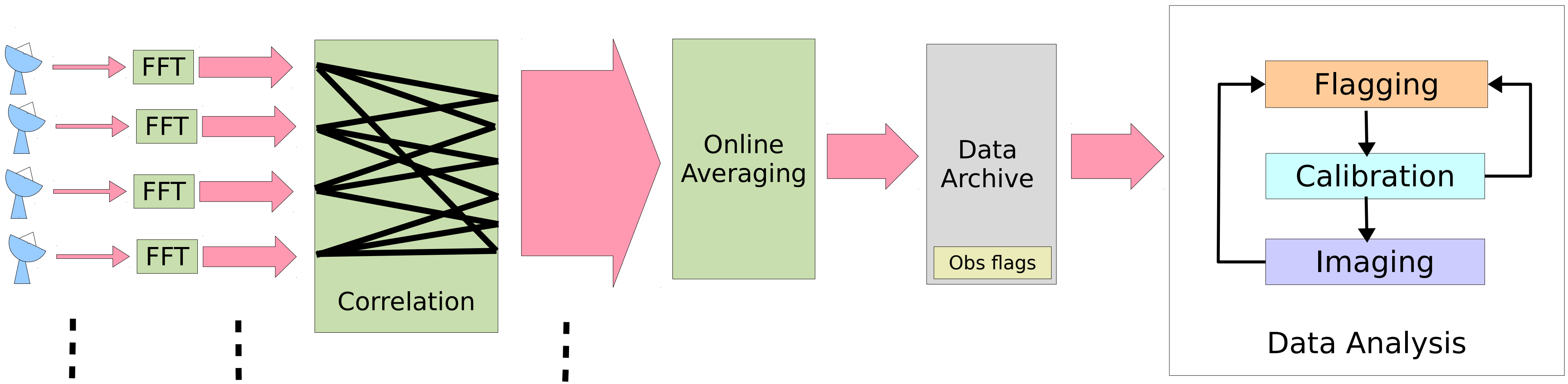
N data streams

FFT channelization

N x nchan data streams

Samples : 10 nano-s
Channels : 10 kHz

Data acquisition and analysis – Real Time System



Analog
to Digital

N data
streams

FFT channelization

N x nchan
data streams

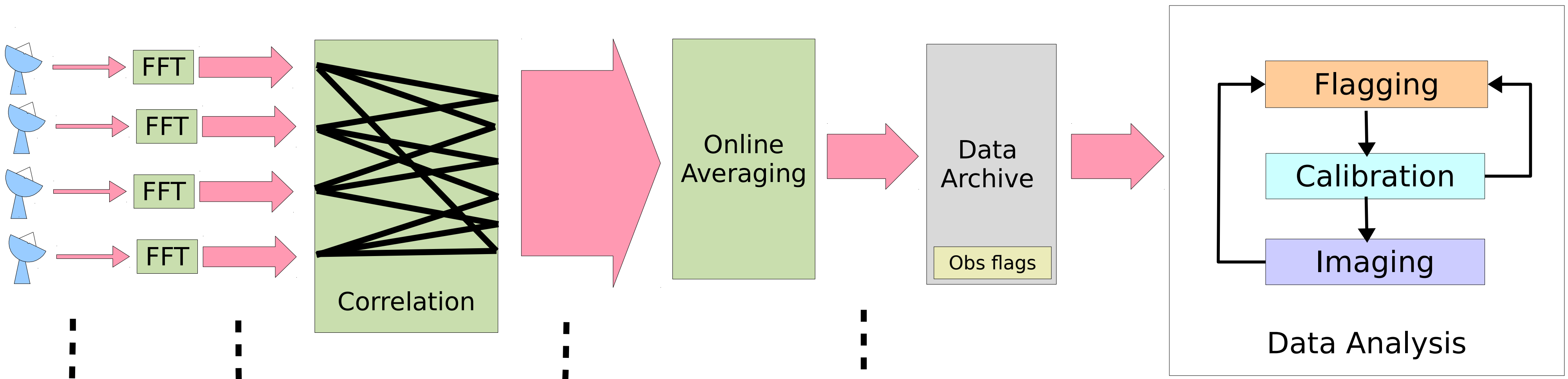
Samples : 10 nano-s
Channels : 10 kHz

Correlation =
Multiply + Accumulate

N(N-1)/2 x nchan
data streams

Samples: 1 micro-sec
Channels : 10 kHz

Data acquisition and analysis – Real Time System



Analog to Digital

N data streams

FFT channelization

N x nchan data streams

Samples : 10 nano-s
Channels : 10 kHz

Correlation = Multiply + Accumulate

N(N-1)/2 x nchan data streams

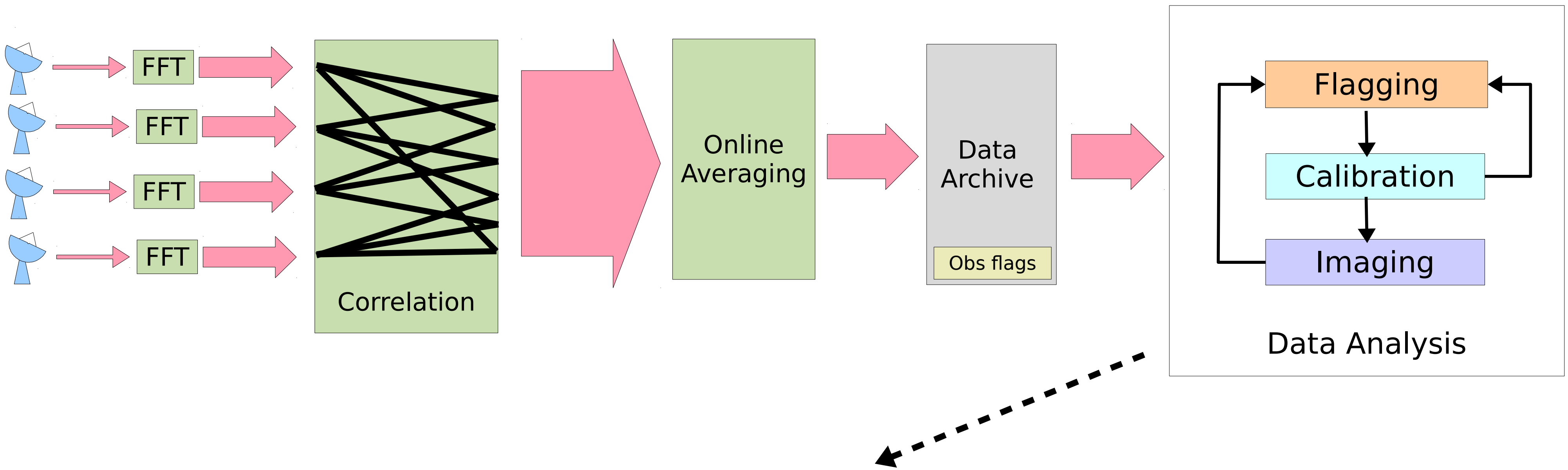
Samples: 1 micro-sec
Channels : 10 kHz

Data Averaging

N(N-1)/2 x nchan/100 Data streams

Samples : 1 sec
Channels : 1 MHz

Data acquisition and analysis – Post Processing



Flagging

Identify and mask corrupted data (Radio Frequency Interference, Instrument errors, etc)

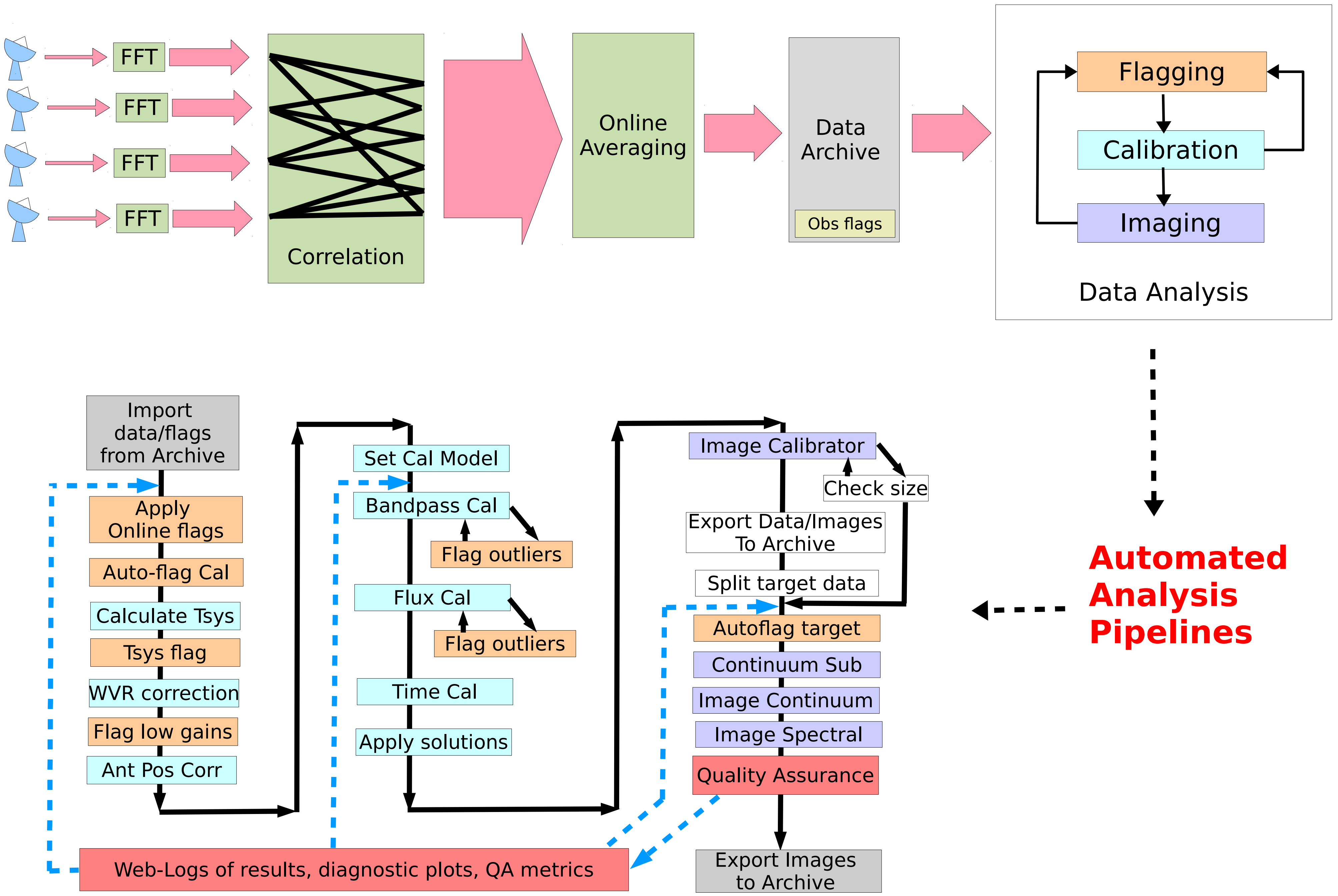
Calibration

Derive and apply corrections to undo the effects of complex valued antenna gains

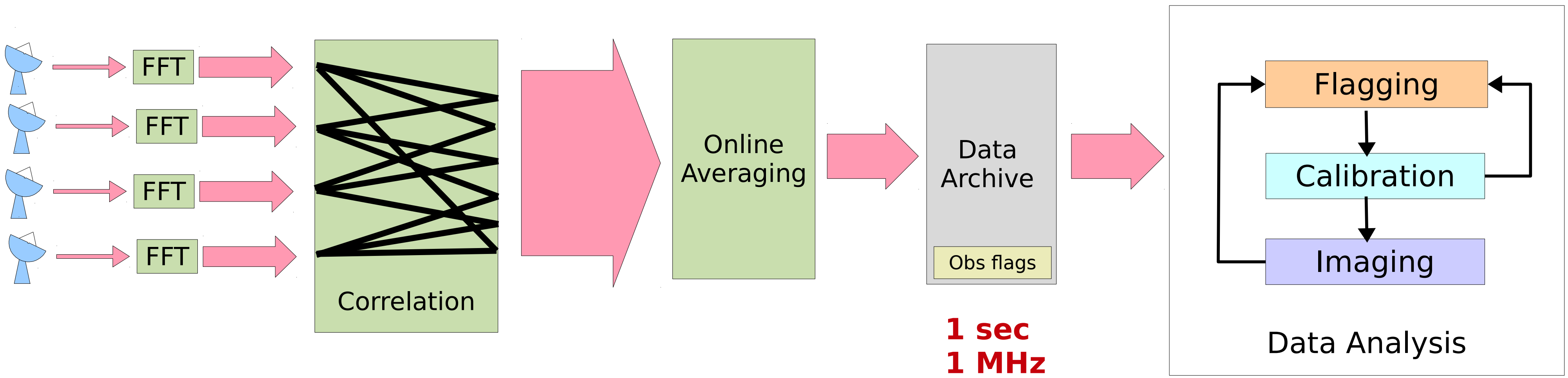
Imaging

Reconstruct images by iterative model fitting while correcting for other instrumental effects

Data acquisition and analysis – Post Processing



Data acquisition and analysis



Problems :

- At 1sec, 1 MHz resolutions, intermittent RFI appears continuous

  => We are throwing away good data

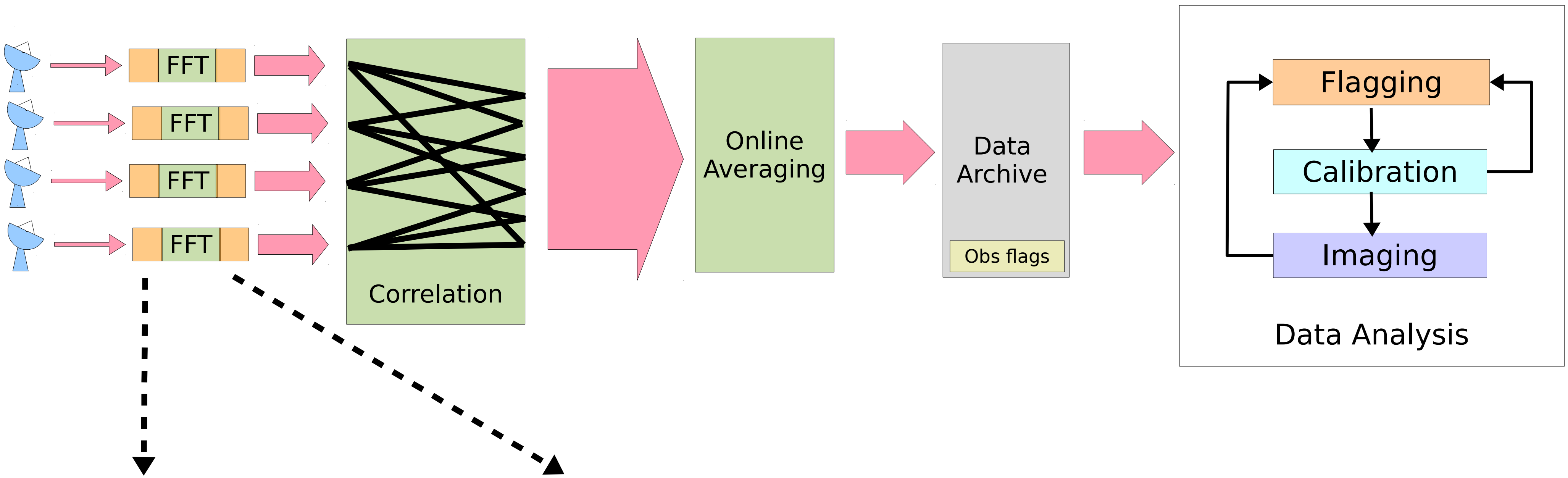
- Satellite RFI is partially decorrelated at 1sec, 1 MHz resolutions

  => Cannot model the signals well enough to subtract them

Ideas : RFI mitigation within the real-time system.

[experimentation, prototyping, research, student projects...]

Real-time RFI mitigation before correlation



Outlier detection on time-series.

Detect and mask nano-second pulses seen by individual antennas

RFI : Sparks,
UWB transmissions

Action : Drop Samples
Gather metadata

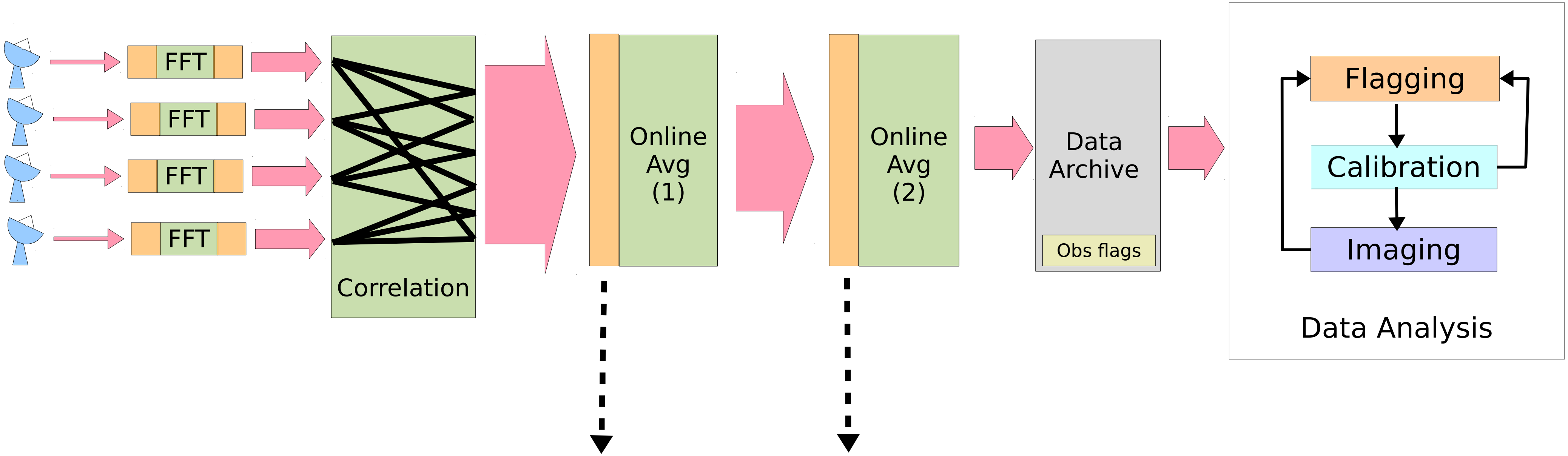
Outlier detection on real-time spectrum

Detect and mask/label corrupted channels per antenna

RFI : Any strong narrow-band signal

Action : Mask samples
Label samples
Gather metadata

Real-time RFI mitigation after correlation



Automatic flagging on visibilities
(1 micro-sec, 10 KHz)

Detect and mask correlated RFI in the baseline x time x frequency (3D) cube

RFI : Intermittent communication signals

- Duty cycles of 10s of micro-sec
- Channel width of 100 KHz.

Action : Drop samples during averaging
Record correct weights

Interference modeling and subtraction
(1 milli-sec, 10 kHz : no decorrelation)

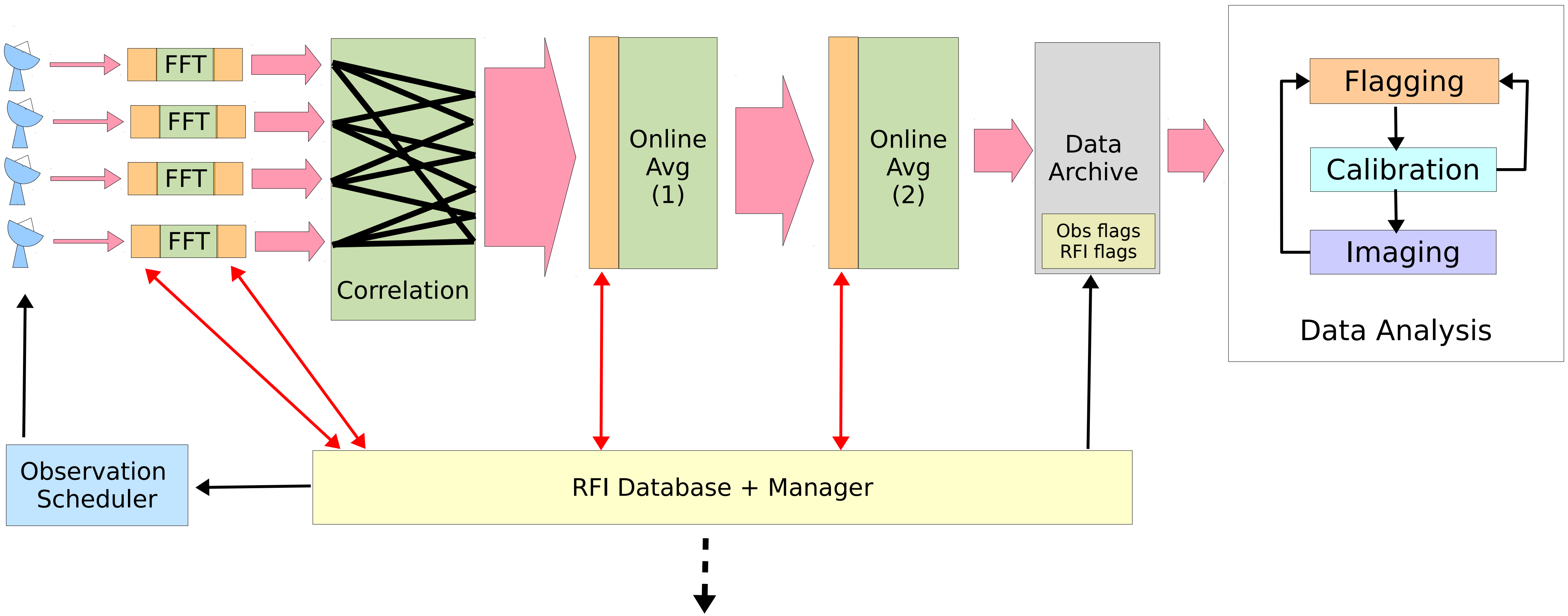
Matrix subspace projection.
Real-time all-sky Imaging.
Source location.

RFI : Continuous data transfer signals

- Cell 5G, Airborne 5G
- Satellite Radio / Internet

Action : Subtract out the RFI signal
Modify weights

RFI Database and Manager



Database : Store RFI characteristics and meta-data

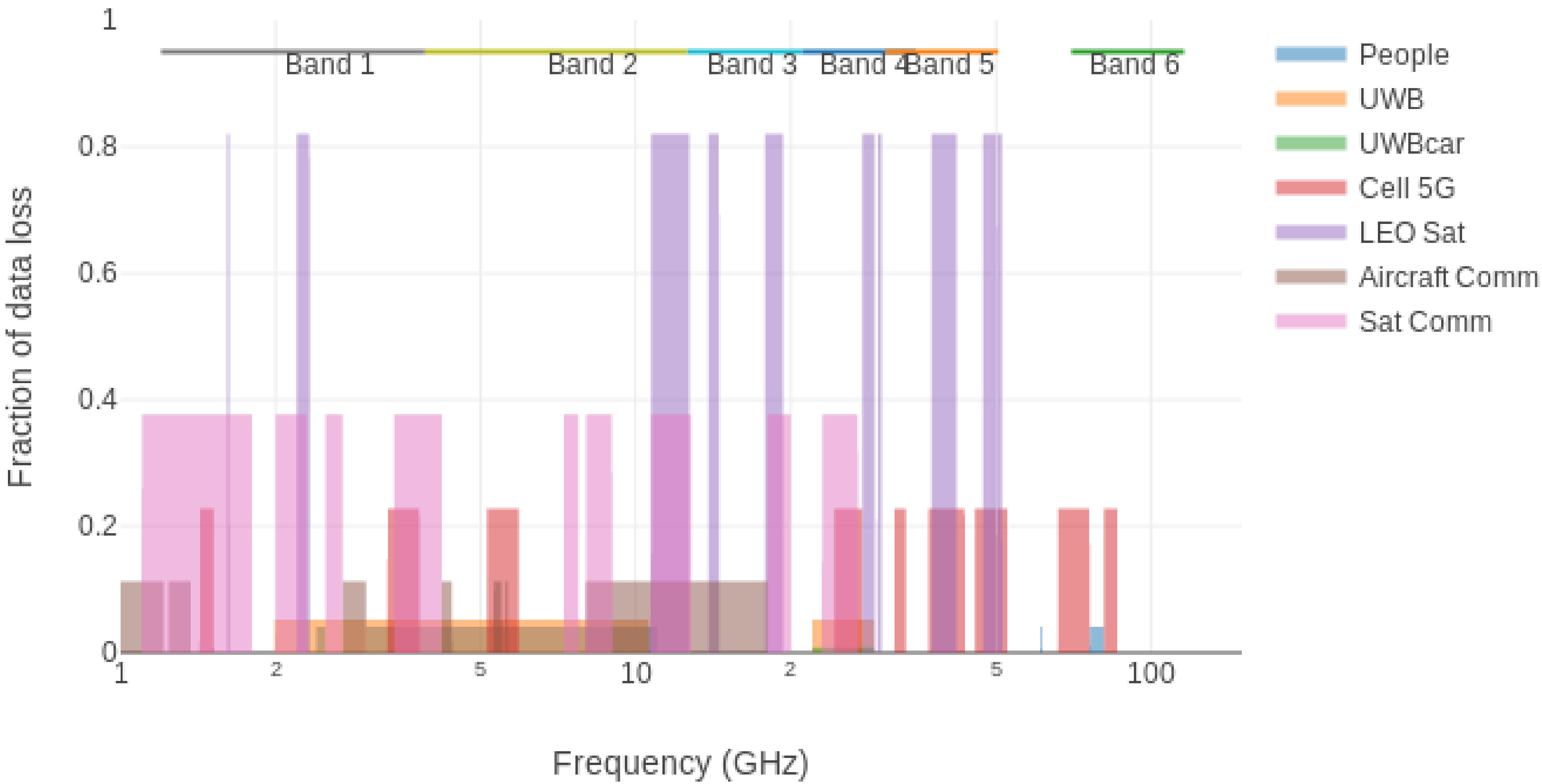
- Known satellite orbits and frequencies, locations / schedules of terrestrial emitters,
- Meta-data about RFI detected by the real-time system

Manager : Analyse RFI metadata and decide optimal actions for the current observation.

- Record RFI information in the archive
- Match the current RFI to suitable mitigation algorithms and tunings
- Smart scheduling around predictable emitters

How effective are these solutions ?

Estimated data loss – Only post-processing

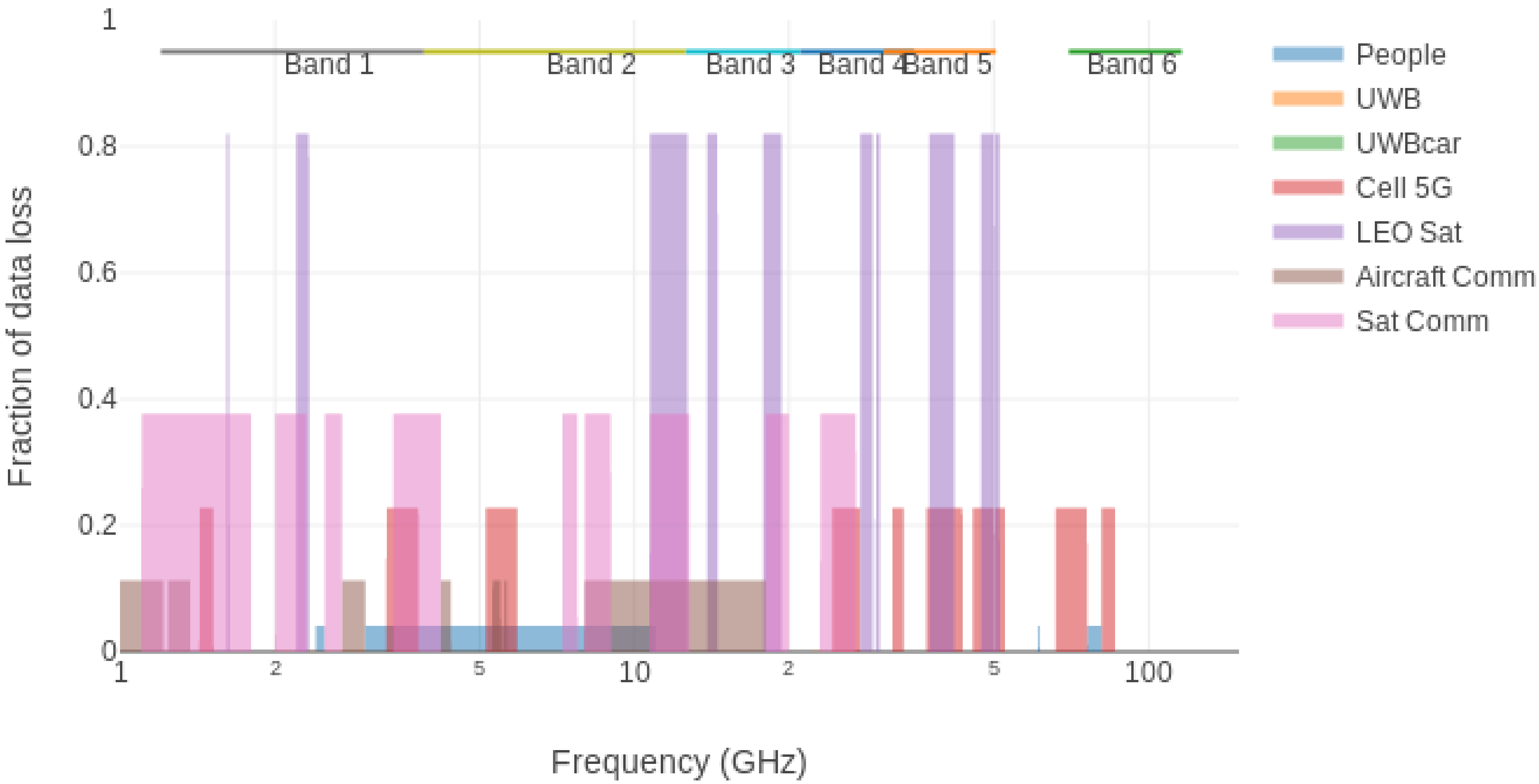


All RFI-affected data are discarded at 1sec, 1MHz resolution

Science is possible, but at lower efficiency (extra observing time)

Nearly complete data loss in LEO-satellite bands

Estimated data loss – RFI mitigation at the antenna

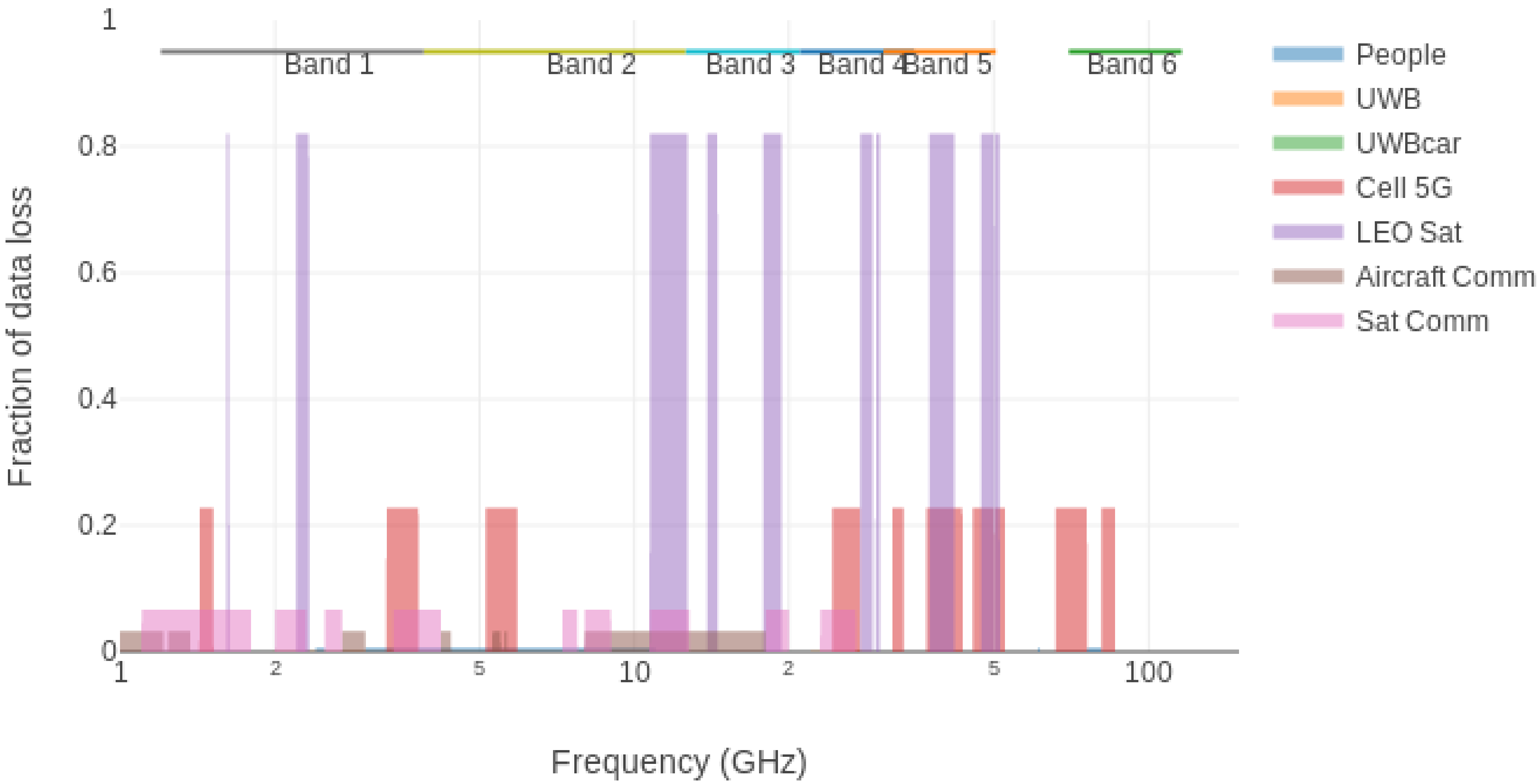


Impulsive, local broadband RFI is removed.

Low impact overall, but useful because of the UWB nature of sparky RFI.

All longer duration RFI persists

Estimated data loss – In-correlator RFI flagging

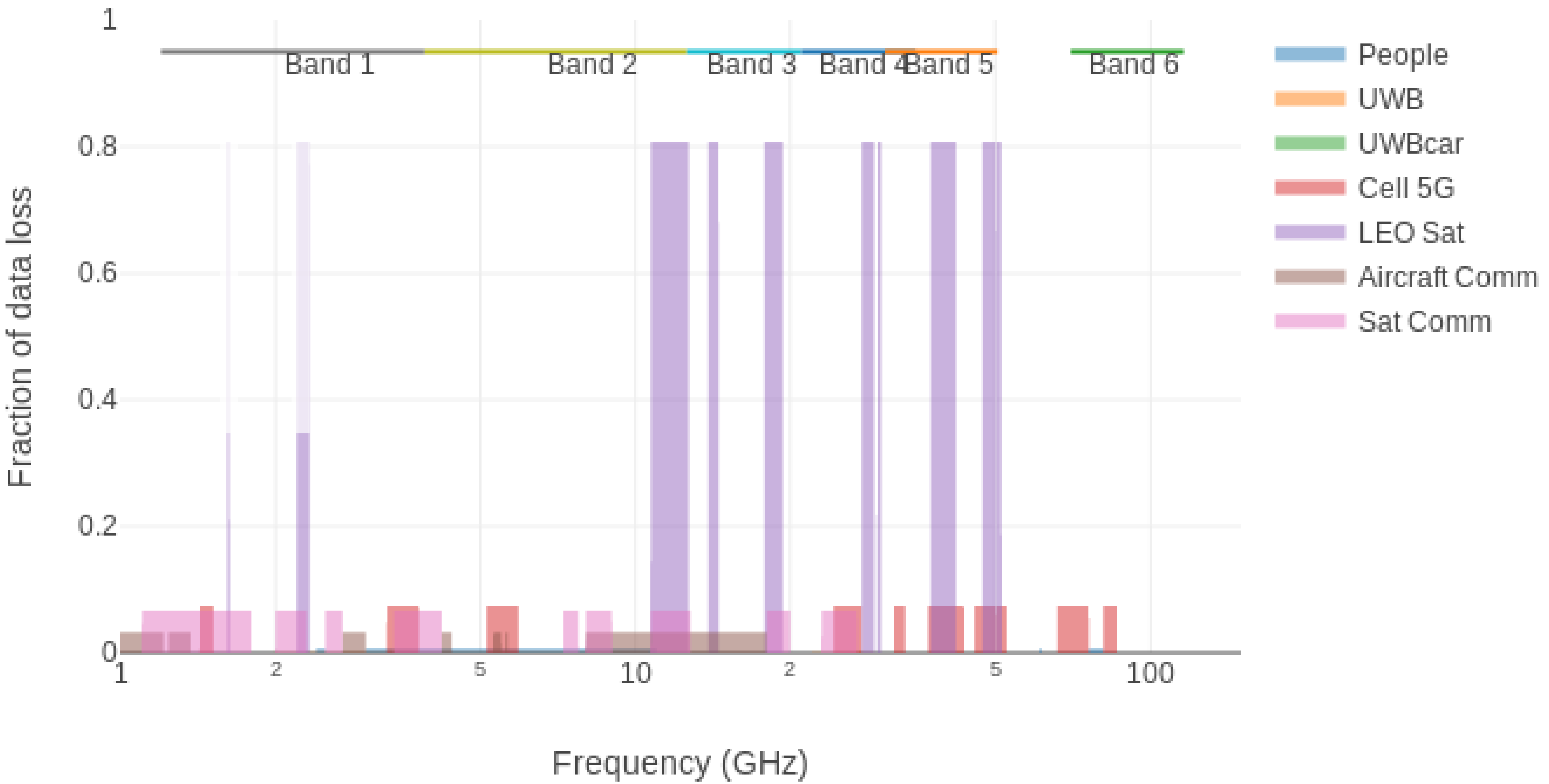


Takes advantage of duty-cycle gaps at the micro-sec to milli-sec timescale

Question : Do we really have usable gaps ?

Continuous RFI persists : Cell 5G and Satellite Data

Estimated data loss – RFI modeling and subtraction



Models and subtracts continuous RFI signals

Question : Experiments so far have not been very successful

Geostationary/Local RFI is easier. LEO satellite bands may be lost (too many).

Moving from theory to the real world…..

Moving from theory to the real world…..

(1) What is our real RFI environment ?

- Pulsed RFI : Sparse enough at nano-s timescales : Don't know
- Micro-s to milli-s duty cycles : Usable gaps in time/freq : Don't know
- Long RFI : Can we handle many interferers at once : Unlikely
  Are signals long enough to decorrelate effectively : Don't know
  Can we schedule around satellite orbits : Maybe

Experiments to do :

- Record and inspect data at high time/freq resolution to identify if we have usable gaps in time/freq or not.

  E.g. : ABQ aircraft radar (DME) : Continuous at 1sec resolution, but very sparse impulses at a sub-microsec timescale

- Satellite RFI : How many sources do we see at once ? Geostationary or not ?

- How predictable is our RFI ? Can we match orbit information to our data ?

Moving from theory to the real world…..

(2) Do the mitigation approaches work ?

- 1D statistical filters : Reasonably well
- Auto-Flagging correlated data : Reasonably well
- Modeling and subtraction of continuous signals : Experimental (R&D)
- Attenuation due to decorrelation : Maybe
- RFI database and manager : Don't know.

Experiments to do :

- Record high time/freq resolution data
  – Run filtering/flagging algorithms.
  – Apply modeling and subtraction algorithms
- Use a known isolated continuous RFI source to test the impact of decorrelation
- Generate an RFI database
  – Use it to tune auto-flag algorithms downstream
  – Evaluate efficacy of RFI classification and prediction

Moving from theory to the real world…..

(3) Evaluate cost versus benefit ….

If nothing is done : 25%-40% data loss (90+% at LEO)

- Some continuum science is possible with longer observation times.
- Spectral line science is lost in all satellite bands.
- Time-domain science gets harder

If solutions are implemented :

- Real-time RFI excision algorithms must operate at very high data rates

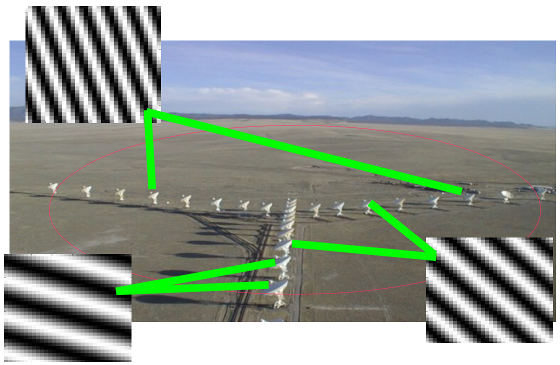
=> Is the expense worth the fraction of data saved ?

Experiments to do :

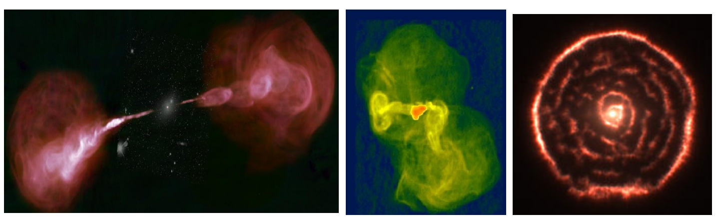
– Build a prototype of a real-time flagging system and test scaleability.

Peering through the (RFI) reeds

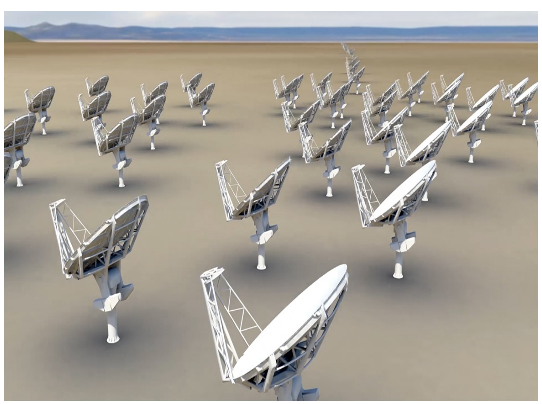
An imaging radio interferometer

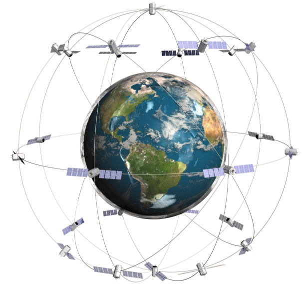


Radio images of objects in space
- Phy, Chem, Dynamics, History

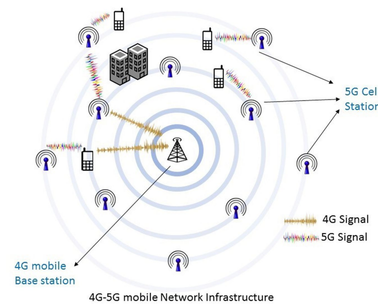


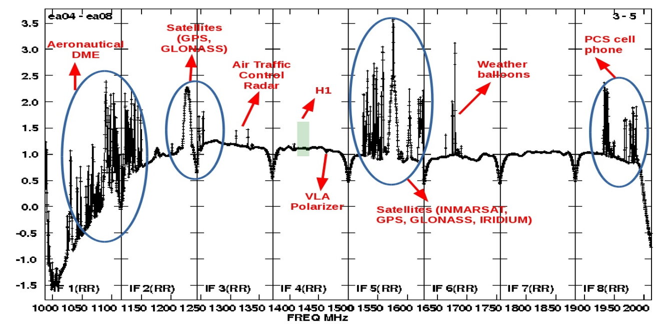
Future instruments



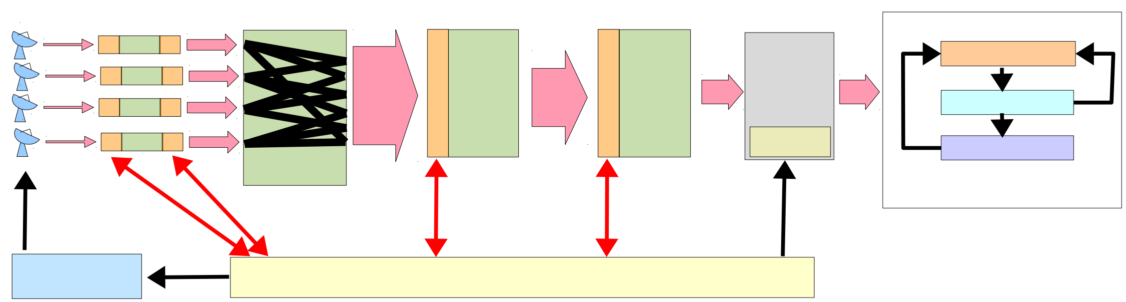


Many sources of radio frequency interference





Need integrated end-to-end RFI mitigation



Ideas for experiments and projects + Many open questions

- Physics, Interferometry, Signals and Systems, Analog/Digital, Computer Science (ML/AI, HPC/HTC), Applied Math...