Peering Through the Reeds - Radio Astronomy versus Commercial Spectrum Use

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An interferometer is an indirect imaging device
An interferometer is an indirect imaging device

Young’s double slit experiment
An interferometer is an indirect imaging device.

Young's double slit experiment:
- Light waves
- Barrier
- Interference pattern

Each antenna-pair => one 2D fringe
An interferometer is an indirect imaging device

Young’s double slit experiment

Each antenna-pair => one 2D fringe

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

Instrument Transfer Function

Observed Image
Aperture Synthesis Imaging

Image with 11 antennas => 55 fringes

Instrument Transfer Function

Observed Image
Aperture Synthesis Imaging

Image with 27 antennas => 351 fringes

Instrument Transfer Function

Observed Image
Aperture Synthesis Imaging

Image with 27 antennas over 2 hours

"Earth Rotation Synthesis"

Instrument Transfer Function

Observed Image
Aperture Synthesis Imaging

Image with 27 antennas over 4 hours

“Earth Rotation Synthesis”

Instrument Transfer Function

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”

Instrument Transfer Function

Observed Image
## Current NRAO interferometers

<table>
<thead>
<tr>
<th></th>
<th>VLA</th>
<th>VLBA</th>
<th>ALMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dishes</td>
<td>27 dishes (25m each)</td>
<td>10 dishes (25m each)</td>
<td>60 dishes (12m + 7m)</td>
</tr>
<tr>
<td>Frequency</td>
<td>1 GHz - 50 GHz</td>
<td>1 GHz - 50 GHz</td>
<td>84 GHz - 950 GHz</td>
</tr>
<tr>
<td>Configurations</td>
<td>4 configurations</td>
<td>200km - 8000 km</td>
<td>150m - 16km</td>
</tr>
<tr>
<td>Locations</td>
<td>Plains of San Augustin, NM</td>
<td>Spread across the USA.</td>
<td>Chajnantoor Plateau Atacama Desert, Chile</td>
</tr>
<tr>
<td>Year</td>
<td>1975 +</td>
<td>1993 +</td>
<td>2011 +</td>
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Radio Frequency Interference (RFI)
Radio Frequency Interference (RFI)

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

- GPS-sat
- LEO-sat
- Aviation/Military Comm
- Cell 5G
- 4G-5G mobile Network Infrastructure

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
How does an interferometer see RFI?

Measured Visibility: \( \langle E_i E_j^* \rangle \)

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How does an interferometer see RFI?

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

= Mutual coherence of two incident E-fields.

$\Rightarrow$ Both antennas need to see the signal.

Correlated RFI

(Visibilities have RFI)

Visibilities without RFI
How does an interferometer see RFI?

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

= Mutual coherence of two incident E-fields.

=>$\text{Both antennas need to see the signal}$

Correlated RFI (Visibilities have RFI)

Un-Correlated RFI (No RFI, but noise is higher)
How does an interferometer see RFI?

**Signal De-Correlation**

For the source being looked at,

Phase difference $\phi$ between signals at each antenna $= 0$

\[
\langle E_i E_j^* \rangle_{\delta t, \delta \nu}
\]
How does an interferometer see RFI?

**Signal De-Correlation**

For the source being looked at,

Phase difference $\phi$ between signals at each antenna = 0

For a source in another direction

Phase difference $\phi > 0$

$\Rightarrow$ If $\delta t, \delta \nu$ are high enough

Signals away from the center will attenuate $\propto \text{Sinc}(\phi)$
How does an interferometer see RFI?

Signal De-Correlation

For the source being looked at,

\[ \phi \] between signals at each antenna = 0

For a source in another direction

\[ \phi > 0 \]

=> If \( \delta t, \delta \nu \) are high enough

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

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
Some signals are continuous and some are intermittent.

Some are narrow-band and some are broad-band
How does RFI affect our science?
How does RFI affect our science?

Continuum Imaging

Intensity \( (\nu_{\text{ref}}) \)

Spectrum

- Active Energetics
- Passive Ageing
- Old emission source

Abell 2256 Galaxy Cluster
How does RFI affect our science?

Continuum Imaging

- 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
How does RFI affect our science?

Spectral Line Imaging

Chemistry:
- Emission and Absorption lines

Distance / Age:
- 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?

- Astrophysical events have similar characteristics as RFI: False positives
- A problem for triggered follow-ups on other instruments

Time-Domain Astronomy

Pulsars

Merger events

Time (pulse phase)
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)

| Pulse: Duration: nano-s | Short : Duration and duty cycle : Few micro-s to milli-s | Few sec or more | Color: Local RFI (~ few antennas) | Shading: White : Seen for a small fraction of observing time.

1 GHz | 5 GHz | 10 GHz | 20 GHz | 50 GHz | 100 GHz |

**Pulse:**
- DME
- UWB (wearable, cars)
- Bluetooth - wearables - car ent.
- Wifi - wearables - car ent
- Cow rf id
- Civilian aircraft
- Military : WSMR, GPS jamming, radar tracking, F-35 crosslinks (L/C band)
- SAR ground/airborne (X, Ku)
- SAR L-band
- Aircraft with 5G
- Satellites: L, S, C, X, Ku bands
- Space-Net (Ku band)
- Space-Net (Ka band)
- OneWeb, SpaceX
- Boeing

**Duration:**
- UWB
- Bluetooth - wearables
- Wifi - wearables
- Wireless usb - wearables
- WiGig / WHD - wearables
- Bluetooth - car ent.
- Wifi - car ent
- Military (F-35 comms)
- Ku band
- WiGig / WHD - car ent
- Traffic radar (24)
- Military (F-35 comms)
- Cow rf id
- WiWig / WHD
- Cow rf id
- WiWig / WHD

**Satellites:**
- L, S, C, X, Ku bands
- Space-Net (Ku band)
- OneWeb, SpaceX
- Space-Net (Ka band)
- Boeing
- Cell (60-76)
- Cell (76-80)
- Car radar (76-80)

**Satellites:**
- L, S, C, X, Ku bands
- Space-Net (Ku band)
- OneWeb, SpaceX
- Space-Net (Ka band)
- Boeing
- Cell (60-76)
- Cell (76-80)
- Car radar (76-80)
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

- FFT
- Online Averaging
- Data Archive
- Flagging
- Calibration
- Imaging

Correlation

Data Analysis
Data acquisition and analysis – Real Time System

Analog to Digital

N data streams

Correlation

FFT
FFT
FFT
FFT

Online Averaging

Data Archive
Obs flags

Flagging
Calibration
Imaging

Data Analysis
Data acquisition and analysis – Real Time System

Correlation

Online Averaging

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Data Analysis

Analogue to Digital

N data streams

FFT channelization

N x nchan
data streams

Samples: 10 nano-s
Channels: 10 kHz
Analog to Digital
N data streams

Correlation
N(N-1)/2 x nchan data streams
Samples: 1 micro-sec
Channels: 10 kHz

FFT channelization
N x nchan data streams
Samples: 10 nano-s
Channels: 10 kHz

Data acquisition and analysis – Real Time System
Data acquisition and analysis – Real Time System

Analog to Digital

N data streams

FFT

Correlation

Correlation = Multiply + Accumulate

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

Samples: 1 micro-sec
Channels: 10 kHz

FFT channelization

N x nchan data streams

Samples: 10 nano-s
Channels: 10 kHz

Data Averaging

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

Samples: 1 sec
Channels: 1 MHz

Online Averaging

Data Archive

Obs flags

Flagging

Calibration

Imaging

Data Analysis
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

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

Flagging
Calibration
Imaging
Data Analysis

Correlation
Online Averaging
Data Archive
Obs flags
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
**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
(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

  =>$\Rightarrow$ 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

Many sources of radio frequency interference

Future instruments

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...