Interference in Radio Astronomy and RFI Mitigation Techniques

Karl F. Warnick

Department of Electrical and Computer Engineering

Brigham Young University, Provo, UT, USA

Collaborators:

Brian D. Jeffs, Jonathan Landon, Michael Elmer, David Carter, Taylor Webb, Vikas Asthana, Brigham Young University

J. Richard Fisher, Roger Norrod, and Anish Roshi, National Radio Astronomy Observatory, Green Bank, West Virginia, USA

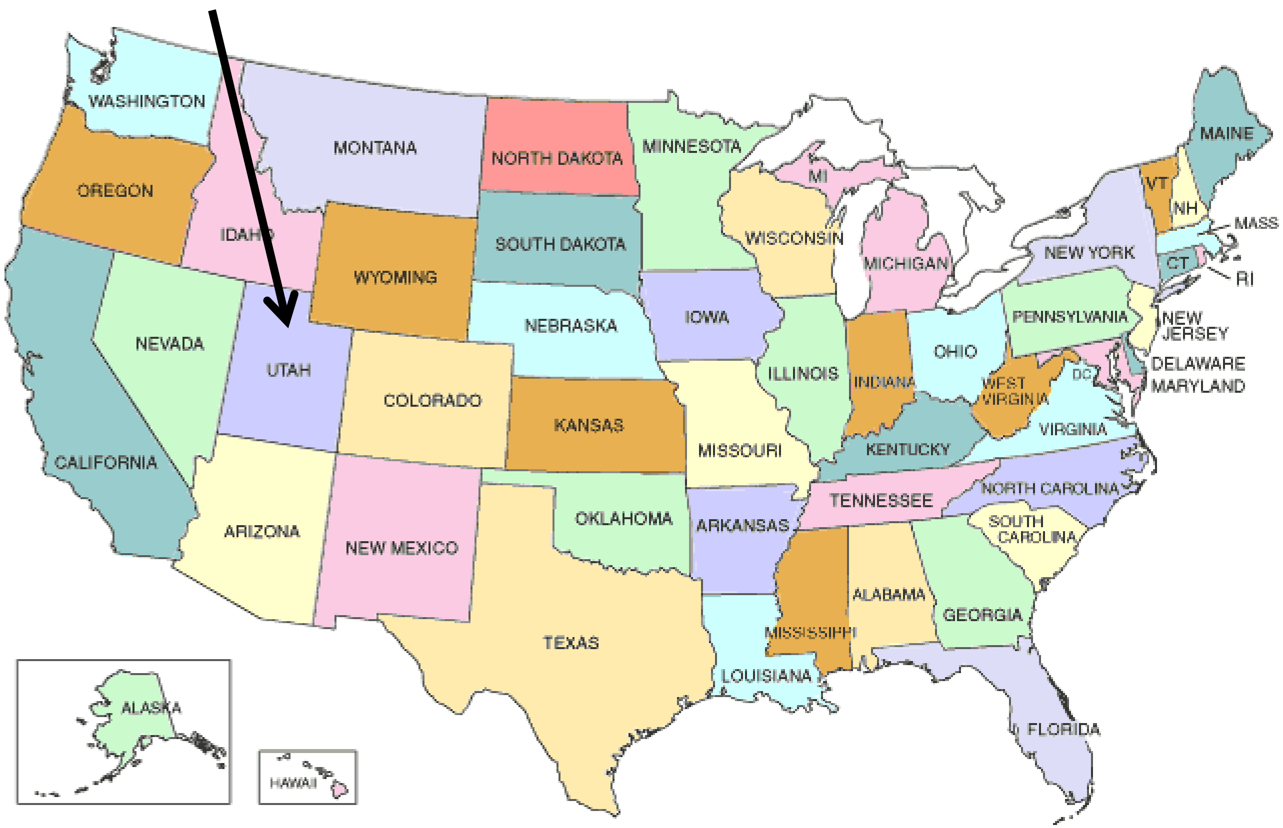
Marianna Ivashina and Rob Maaskant, Chalmers University of Technology, Sweden

April 2014

Brigham Young University

BYU
Radio Astronomy Systems Research Group

Location: Provo, Utah, USA
Students: 34,000
#10 in U.S. in number of graduates who go on to earn PhDs



Radio Astronomy Systems Research at BYU

Faculty Directors: Karl F. Warnick, Brian Jeffs

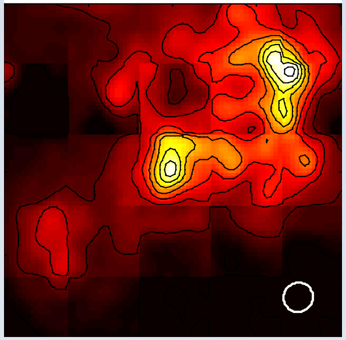
High Impact Research Contributions

- Major experiments at national radio observatories
- International recognition for work in array feeds
- Organizers of two journal special issues and many special sessions
- Significant international collaboration
  - Netherlands, Germany, Canada, Australia, Germany
- 13 years of continuous NSF funding

Grad & ugrad students test their array feed at NRAO

Graduate Student Research

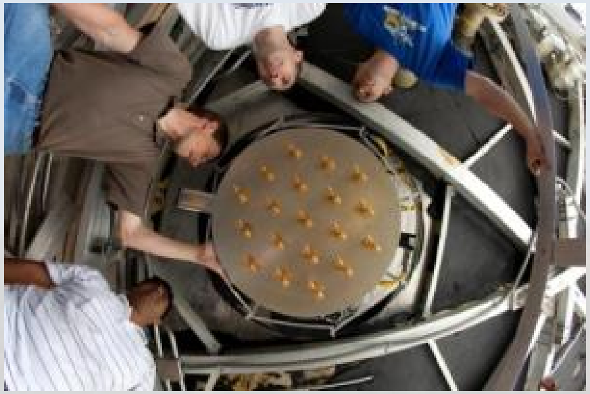
- Students mentored by faculty and scientists
- Excellent placement of MS grads into Ph.D. programs (MIT, Stanford, BYU)
- Student-directed experimental research



(left) Installing the array on the 20m dish (right) Array image of Cygnus radio sources

Undergraduate Mentoring

- Supported by NSF REU
- Mentored by graduate researchers and faculty
- Engaged in instrumentation senior projects



BYU Phased Array Feed on Arecibo Telescope

Outline

- Characteristics of RFI
- Layers of RFI mitigation
- Case studies
- Recent research on RFI mitigation
  - Temporal filtering, spatial filtering
  - Array signal processing
  - Deeper cancellation nulls
  - Progress towards adoption
- Strategy and Implementation

Disclaimer: this presentation is biased towards the latest research on RFI mitigation, less focus on current “in the trenches” best practice

Characteristics of RFI and Layers of Mitigation

Characteristics of RFI

- ITU Report RA.2126
- Non-thermal
  - Thermal noise has stable temporal stochastic properties
  - RFI is temporally, spatially, or spectrally structured
- Can obscure a deep space signal or produce a fall positive detection
- Interference to noise ratio (INR) > 0 dB: Above thermal noise floor
  - Totally obscures the signal
  - Easier to flag
  - Can be subtracted or nulled in some cases
- INR < 0 dB: Below the noise floor, but above the signal power level (-30 to – 50 dB SNR)
  - Harder to flag
  - Much more challenging to mitigate
- Trends
  - Modern, broadband science is more vulnerable to RFI than narrowband spectral line observations
  - Dynamic spectrum allocation will further complicate the RFI environement

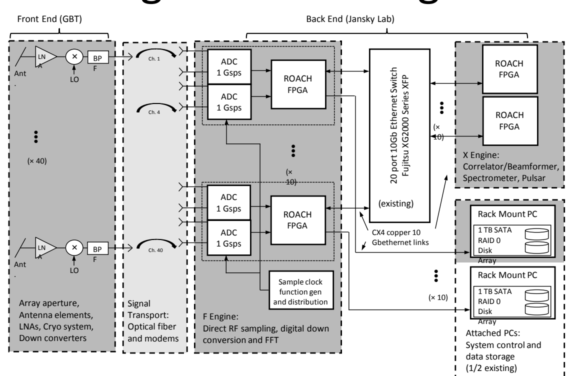
RFI Examples

- The usual:
  - Satellite downlinks, cellular networks, broadcast radio/television, and hundreds of other active radio services
- Other more “interesting” sources:
  - Spark plugs in gasoline engines
  - Blimp-mounted drug interdiction radar (Arecibo)
  - Radar reflections from aircraft (Green Bank)
  - Digital TV (broadband, spectrally noise-like)
  - GLONASS – Russian positioning system
  - Digital cameras
  - Incandescent light bulb (R. Fisher, personal communication)
- Self-RFI
  - Connectors, cables, digital hardware, leaky racks, LO distribution

Layers of RFI Mitigation

Raw Data

Signal Processing



Integrated Data

Layers of RFI Mitigation (Process)

Pre-observation

- Prevent RFI signals from entering astronomical data
- Spectrum management
- Coordination with active sources
- Reducing the observatory's vulnerability

During observation

- Flagging and/or removing RFI signals from data in real time

After observation

- Post-correlation methods to remove RFI after data integration or buffering
- Excising, removing or reducing the impact of RFI off line after observation

Layers of RFI Mitigation (Impact on Data)

Category I - Data never corrupted

- **Pro-active** measures to change RFI environment, coordination, management

Category II – Discard corrupted data

- **Excision –** Identify, flag, and remove corrupted data

Category III – Reduce RFI impact on corrupted data

- **Spatial nulling** or adaptive spatial filtering
- **Waveform subtraction**, subtracting RFI from telescope output
- **Anti-coincidence –** Exploit the fact that widely separated antennas receive identical astronomical signals but different RFI

Category I – Standards, Regulation, Coordination

- This meeting…
- ITU Standards
  - Thresholds for detrimental interference in RA bands are given in ITU-R RA.769
  - Percentage of permissible data loss ITU-R RA.1513
  - In exclusive primary bands (RR footnote No. 5.340), all emissions are prohibited
  - Other bands – administrations are urged to take all practical steps to protect RA from interference
- Coordination zones, radio quiet zones
  - Mid West Radio Quiet Zone (Western Australia)
  - National Radio Quiet Zone (Green Bank, WV, USA)
  - Puerto Rico Coordination Zone (Arecibo, PR)
- Keep up with changes in local licensing rules, identify prospective new transmitters, spectrum monitoring

Category II – Flagging/excision

- Typical implementation
  - Bandpass or high/low pass filters (insertion loss raises Tsys)
  - High linearity electronics (reduce mixing products in harsh RFI environments)
  - Monitoring stations to characterize RFI environment
  - RFI detection and data flagging (stochastic detection, out of range flags, etc.)
  - Temporal or spectral excision of corrupted data
- Issues:
  - Unrecognized RFI
  - Data loss
  - Replacing manual post-observation editing with automated editing

Category III – RFI removal/cancellation

BYU
Radio Astronomy Systems Research Group

- Common approaches
  - For aperture synthesis arrays, "fringe stopping" decorrelates RFI at widely separated antennas (Thompson, 1982)
  - Post-correlation mitigation, anti-coincidence (i.e., RFI moves out of field of view)
  - Pulsar de-dispersion over a wide bandwidth tends to reduce RFI
- Recent research
  - Temporal filtering, waveform subtraction (Bradley, Jeffs - LMS filter, Ellingson - signal model)
  - Wiener filter, linearly constrained minimum variance fitler, multiple sidelobe canceling
  - Spatial filtering, subspace projection (Jeffs, et al.)
  - Post-correlation beamforming
  - Auxiliary antennas, reference beams
  - In process of implementation at LOFAR, MWA, focal plane arrays, etc.
- Issues:
  - Interference to noise ratio (INR), interference rejection ratio (IRR), or INR_{in}/INR_{out}
  - Hardware requirement
  - Implementation complexity
  - Expert user capability vs. transparency to user
  - The idea is that data that would otherwise be discarded is retained in the science – scary!

Category II/III RFI Mitigation Methods – Flagging, blanking, cancellation

Temporal Blanking

- Oldest, best-known strategy for pulsed RFI
- Typical case:
  - Ground-based aviation radars (1215-1400 MHz)
  - 2-400 usec pulses, 1-27 msec period, 1 MHz BW
  - Multipath leads to additional copies of pulse, strong enough to corrupt data, but too weak to be reliably detected – long blanking interval needed
- Examples:
  - NAIC – real time blanking of local airport radar pulses at Arecibo
  - Ellingson & Hampson (2003), Fisher et al. (2005), Zheng et al. (2005) – distance measuring equipment (DME)
- Recent improvements
  - Advanced detection using cyclostationarity
  - Kalman tracking
  - Optimal detection thresholds and blanking window lengths

Other Excision Methods

- Real time DSP for transient RFI detection
  - Thresholding in temporal and/or frequency domains: Ratan (Berlin & Fridman 1996), WSRT – (Baan et al. 2004), Pulsar data (Fridman 2009)
  - RFI leads to chi-square distribution, adds kurtosis – RFI discriminant (Fridman & Baan, Nita, Gary, Deller)
  - Median filtering (Kalberla, Flöer)
- Digital excision at correlation
  - Kurtosis based flagging after FX, cyclostationarity indicator
  - LOFAR (Bentum 2008)
- Post-correlation (imaging)
  - Automated flagging (Middleberg 2006, Offringa 2010, Keating 2010)
  - Closure relations (Briggs 2000)
  - Fringe-stopping, delay compensation – moves RFI out of image (Wijnholds 2004, Cornwell 2004, Athreya 2009), included in AIPS

Is there a need for more powerful (and expensive) techniques?

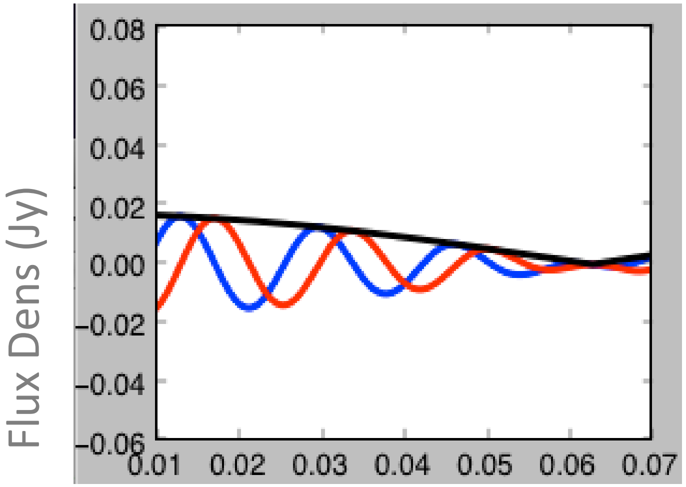
…Case Studies

Craig Anderson: RFI effect on ATCA Spectropolarimetry

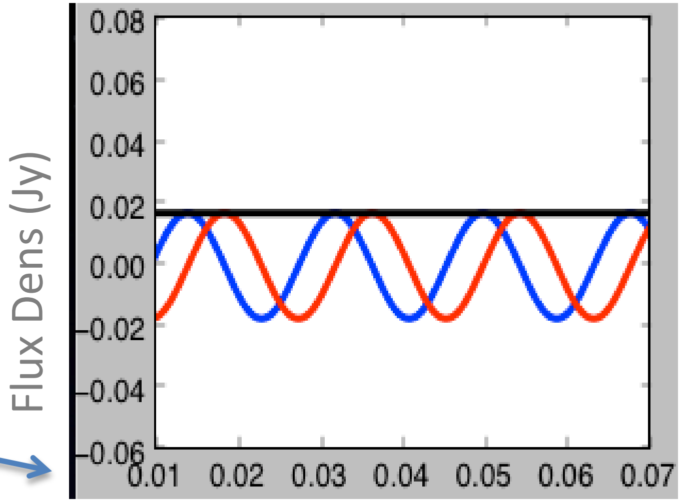
BYU
Radio Astronomy Systems Research Group

Science: magnetized plasmas encode B/density in frequency dependence of pol angle

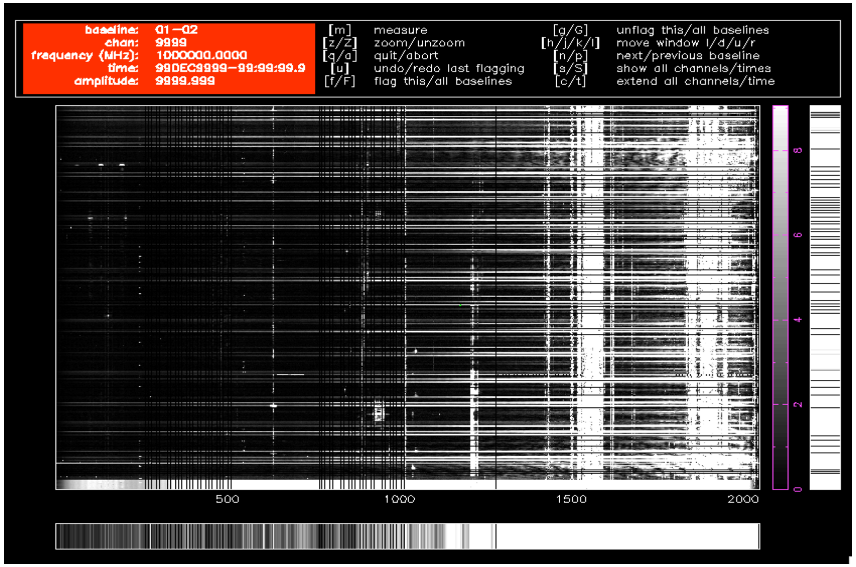
Multiple Faraday-thin components



Uniform external Faraday screen



RFI:



λ^2

Craig Anderson: RFI effect on ATCA Spectropolarimetry

BYU
Radio Astronomy Systems Research Group

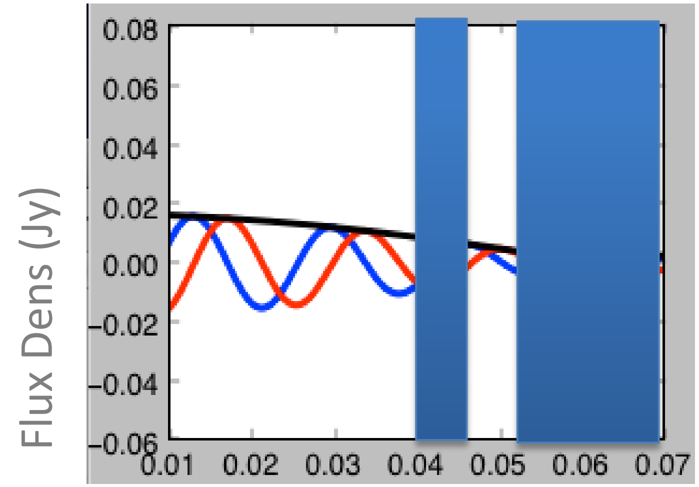
RFI hurts in several ways:

(1) 40% coverage loss due to flagging

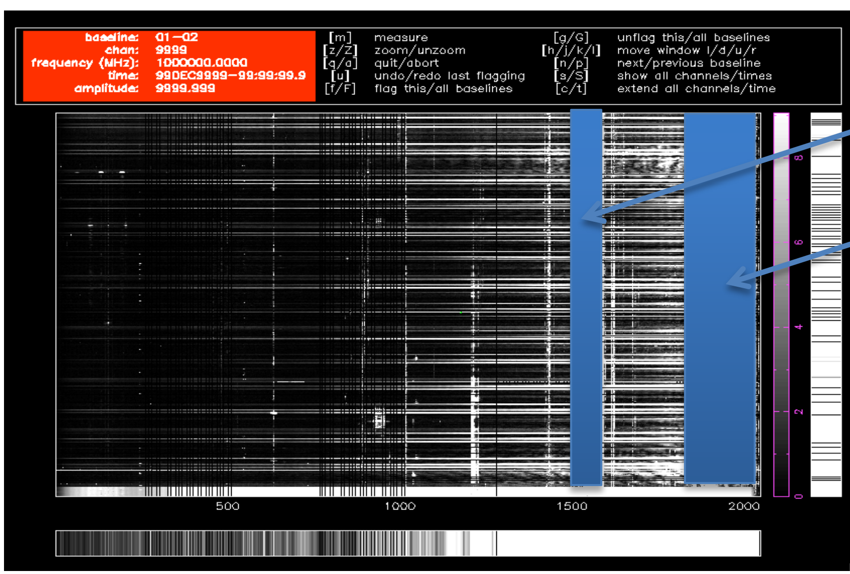
(2) Flagging leads to biased flux densities

(3) Polarimetric calibration requires solving at each 128MHz, can't handle large spectral gaps

Multiple Faraday-thin components



RFI:

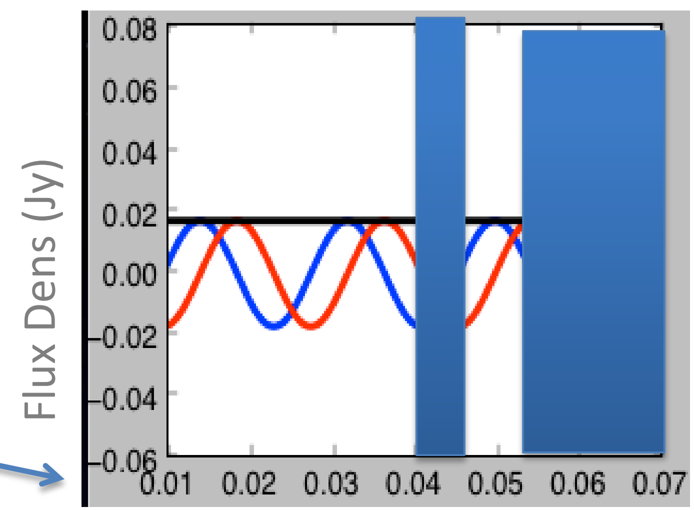


1.45 GHz

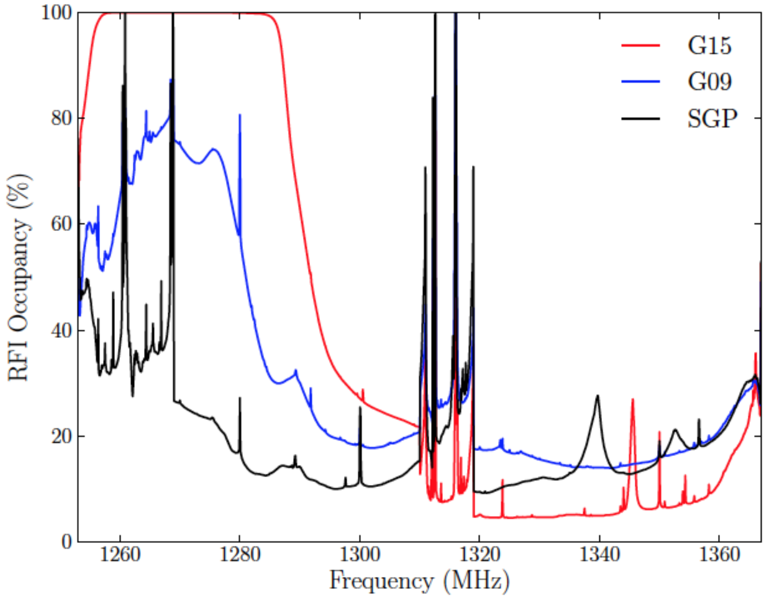
1.2 GHz

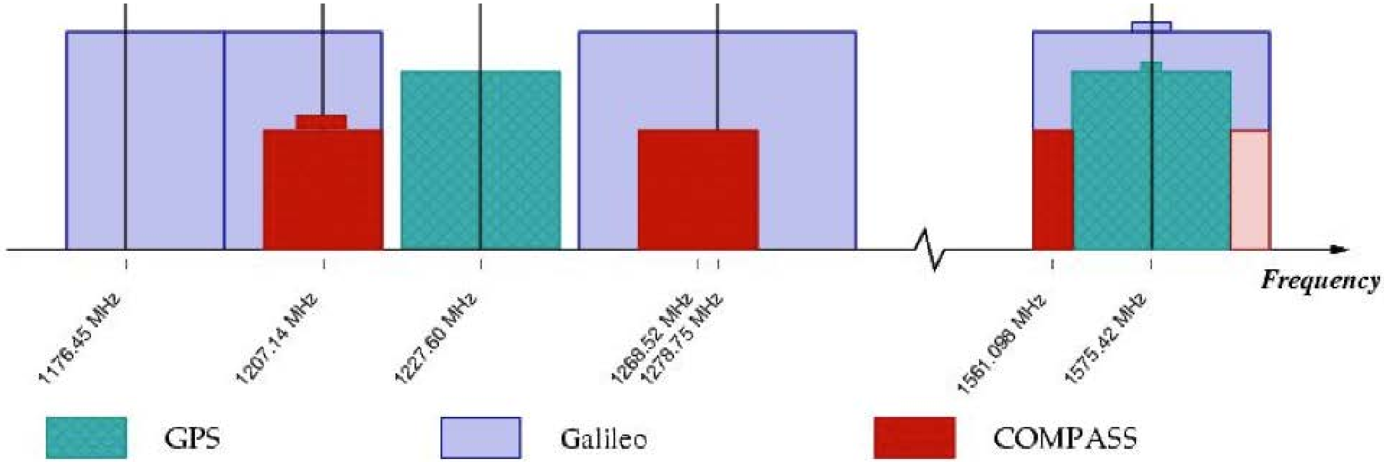
λ^2

Uniform external Faraday screen



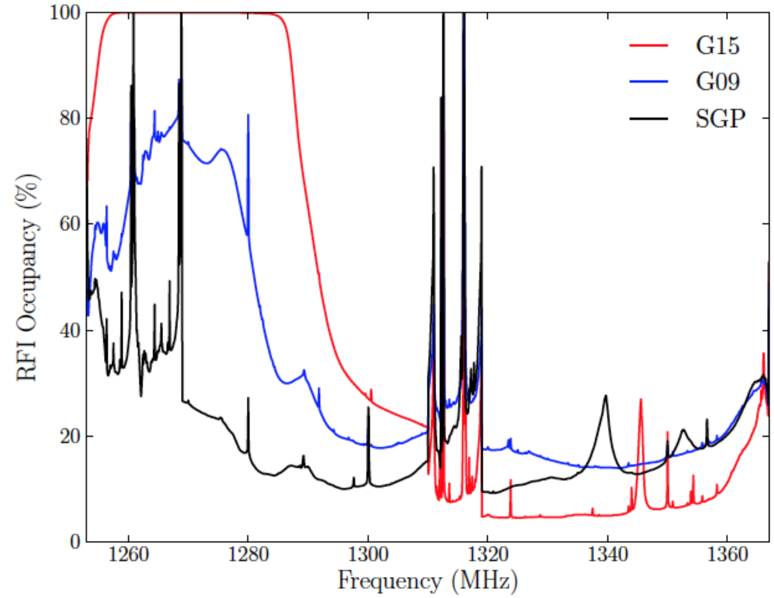
Science: Radio survey of a sample of galaxies are shifted to put HI at rest frame frequency, then averaged to locate HI emission features.

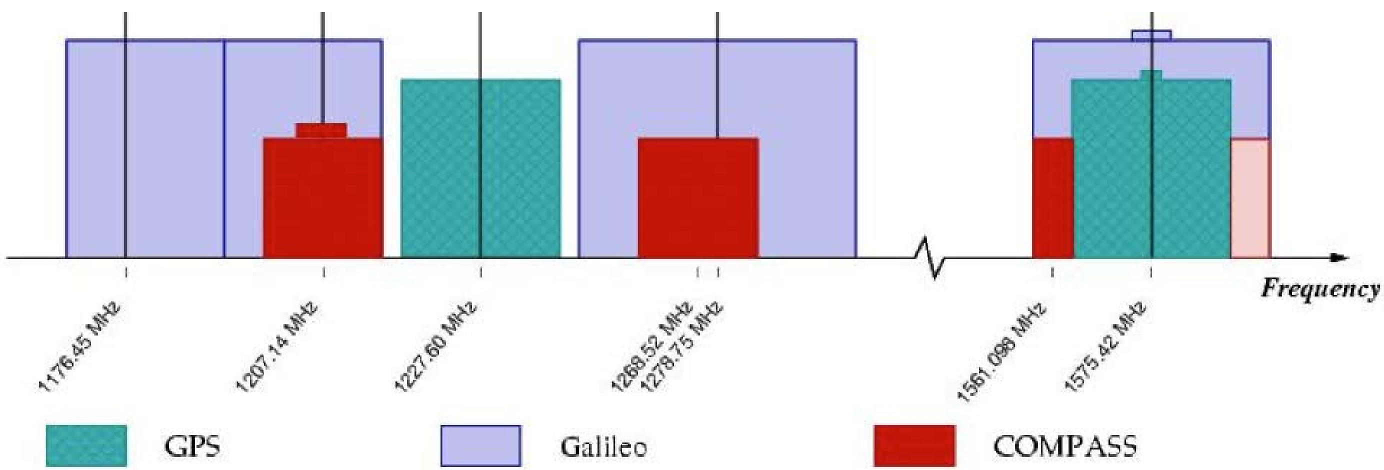




RFI Issues

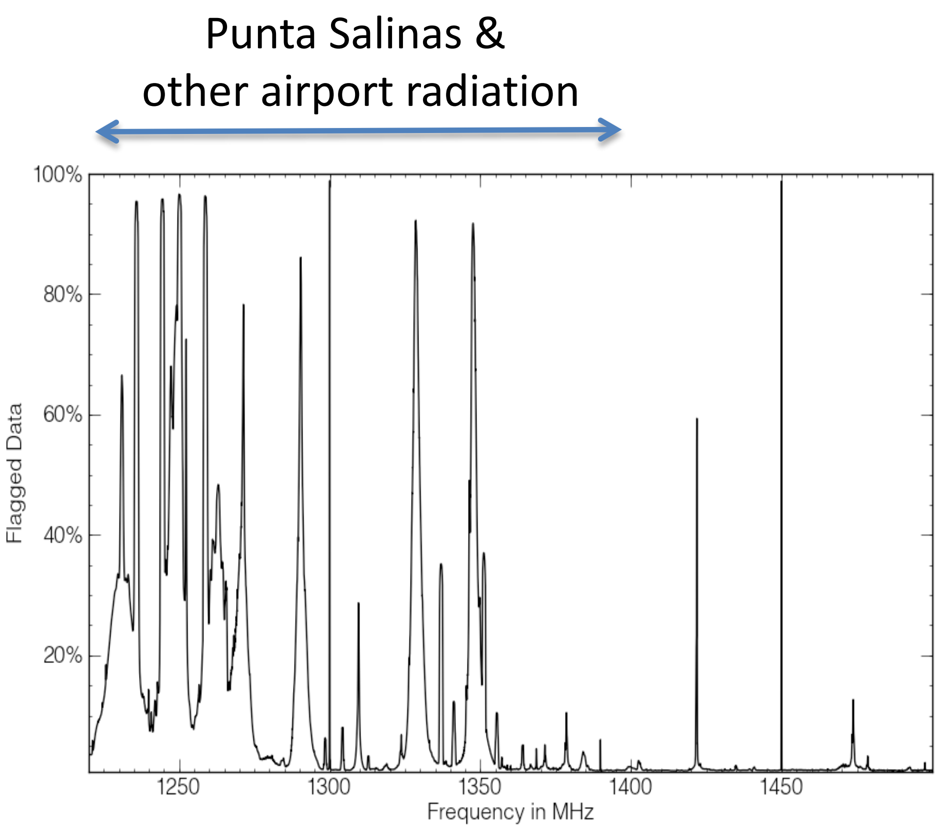
- RFI increased significantly at Parkes between 2008-2012
- Observed at Parkes and ATCA
- RFI prevents interesting science at z > 0.1
- Many fewer usable sources for stacking, lower SNR
- Asymmetric baselines, inaccurate flux
- With new nav. satellites, a large contiguous band will be gone





Laura Hoppmann: Arecibo and RFI

BYU
Radio Astronomy Systems
Research Group



- Arecibo does good science, BUT is strongly affected by RFI
- High redshift surveys are especially affected
- Flagging, 3-sigma clipping help
- Problems with flagging
  - Different types of RFI are flagged differently
  - Problems with bandpass
  - Causes negative artifacts

Take-away Points:

- RFI is getting worse
- Navigation satellites, COMPASS, Galileo, GLONASS, and GPS are chewing up a large contiguous band below the HI line
- Some moderately to highly red shifted HI science is threatened or impossible
- Flagging is essential, but can be inadequate; too much data loss
- We are approaching some "critical cases" where important science will need spatial array processing to have any hope of success

Survey of Recent Research on RFI Cancellation (Category III)

Array Signal Processing Basics

- Temporal filtering
  - Applicable to single signal path
- Spatial filtering
  - Applicable to:
    - Synthesis Arrays
    - Aperture Arrays
    - Phased Array Feeds
  - Can incorporate auxiliary antennas
- In essence, array-based RFI cancellation methods adjust the array beam pattern to place a null on the interferer, or a null in a generalized orthogonality sense (e.g., interferer with multipath)
- Interferers and telescopes move – spatial filtering requires fast integration, fast correlation, fast signal processing

Waveform Subtraction

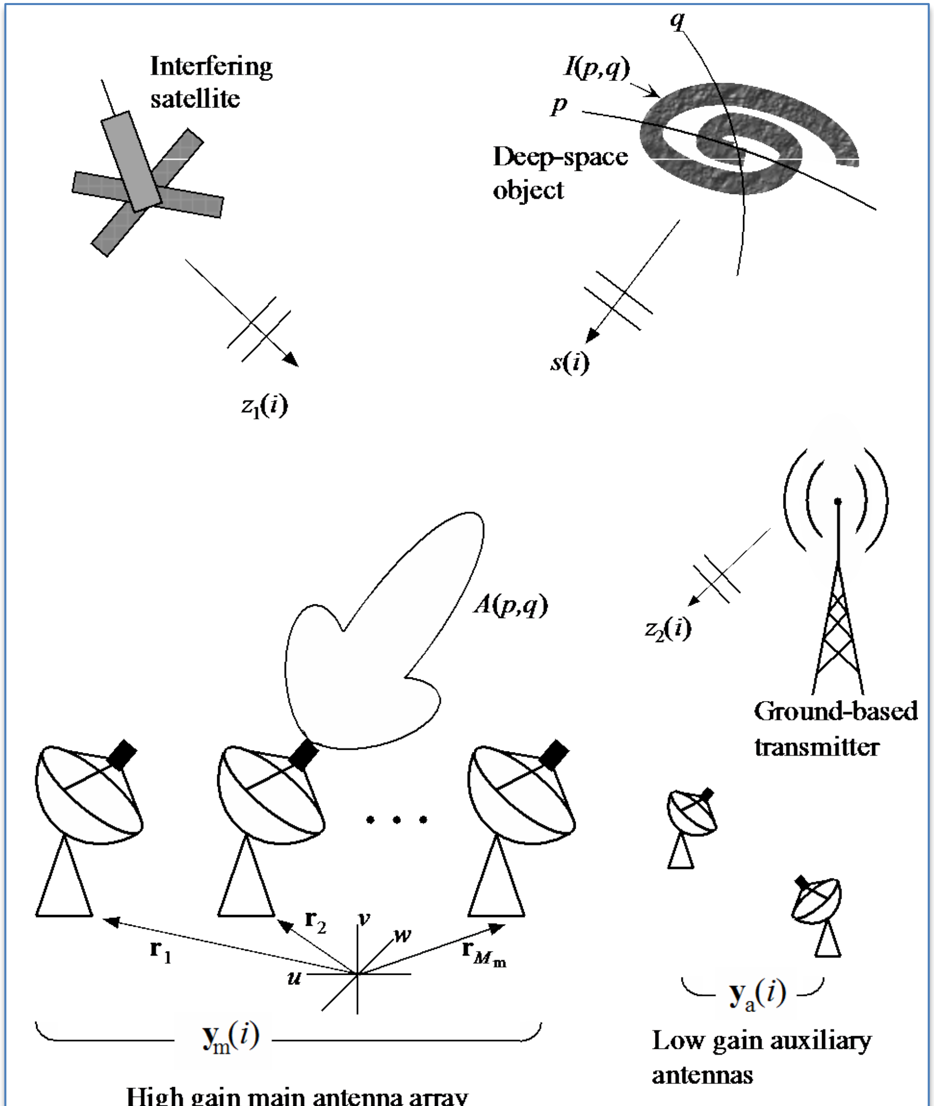
- Steps:
  - Detect and estimate RFI waveform
  - Synthesize noise-free version of RFI waveform
  - Subtract from corrupted data
- Techniques
  - Wiener filtering / temporal adaptive filtering – FFT, adapt to corrupted frequency bins, inverse FFT
  - Least Mean Squares (LMS) - Barnbaum & Bradley (1998)
  - Auxiliary antennas significantly improve performance (Jeffs et al., 2005)
  - Theoretical limits on suppression (Ellingson, 2002)
  - Exploit *a priori* knowledge of waveform characteristics (Ellingson et al.,, 2001)
  - Real time implementation (Poulsen, 2003)
- Real data results
  - 12 dB suppression of analog TV (Roshi, 2002),
  - 16 dB suppression of radar pulses (Ellingson & Hampson, 2002)
  - Pulsar adaptive cancellation (Kesteven, 2005)

Synthesis Imaging Array Spatial Filtering

- Arrays such as the ASKAP, JVLA, WSRT, GMRT, etc. are well suited for adaptive array processing.
- Full array can be treated as a nulling post-correlation beamformer.
- Array elements are the single dishes, or a station beam.

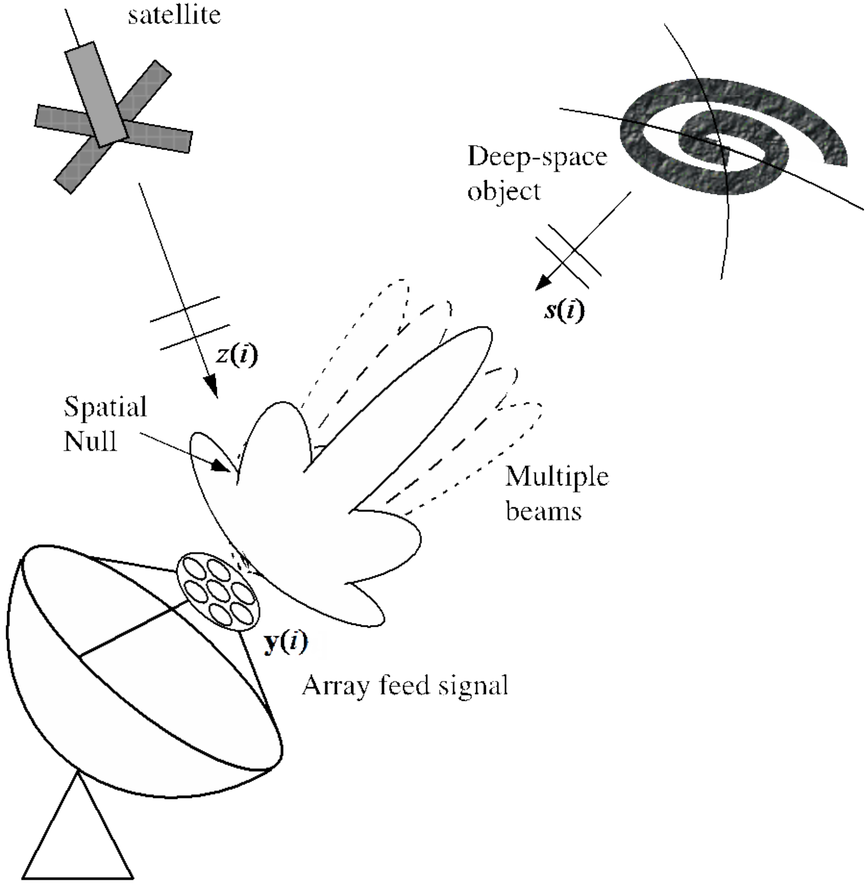
Image credit: Dave Finely, National Radio Astronomy Observatory / Associated Universities, Inc. / National Science Foundation.

Synthesis Array Spatial Filtering



- Post-correlation processing removes interference from visibilities.
- Large aperture means tracking speed is an issue. Need short integration dump times.
- Dish directivity helps and hurts: partially rejects RFI, but reduces INR needed to estimate interference subspace.
- Auxiliary antennas help.

Phased Array Feed Spatial Filtering



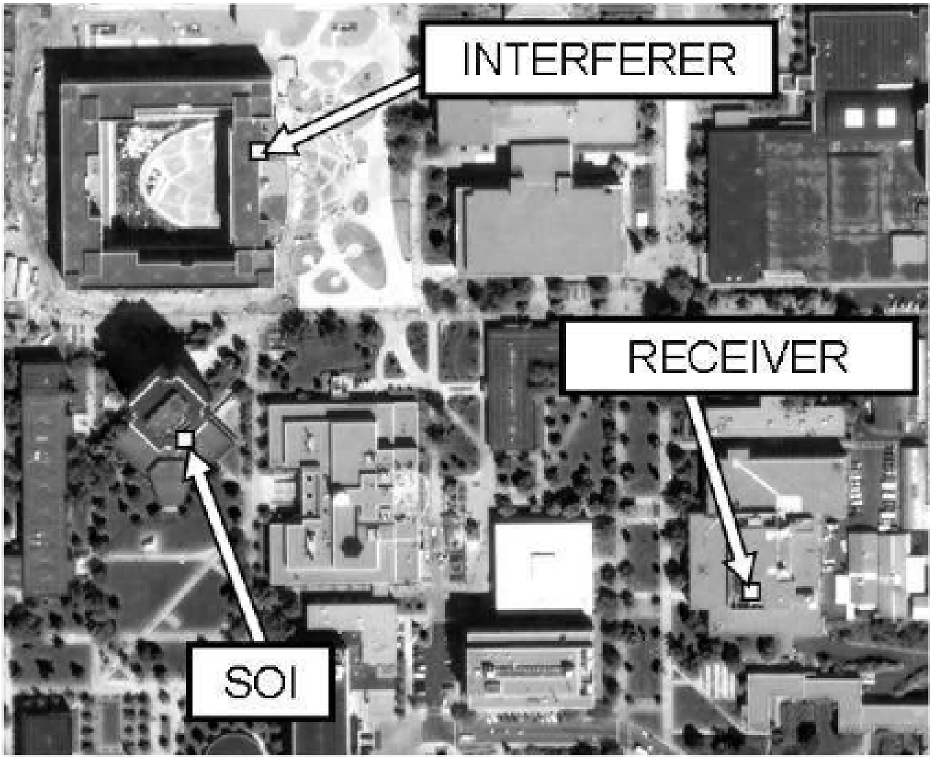
Radio telescope dish with a phased array feed

- Newly deployed (ASKAP, APERTIF, AO19, GBT).
- Small aperture helps with moving interferer tracking.
- Beamshape distortions.
- Dish directivity helps and hurts cancelation.
- Must cancel sources outside the FOV in dish sidelobes.
  - Response in this region is uncalibrated!
  - Null pre-steering not possible.

Early PAF RFI Experiments (2006)

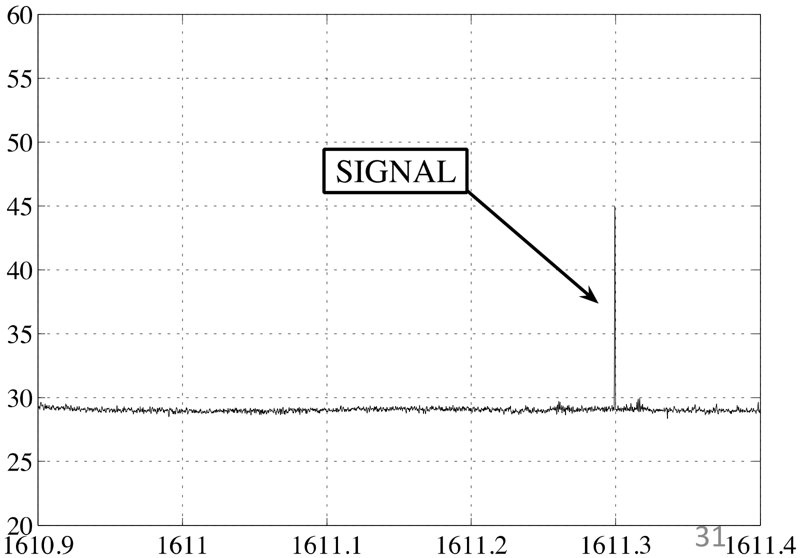
19 element L band PAF on 3m dish
Moving RFI (hand held)
BYU campus

Early PAF RFI Experiments (2006)

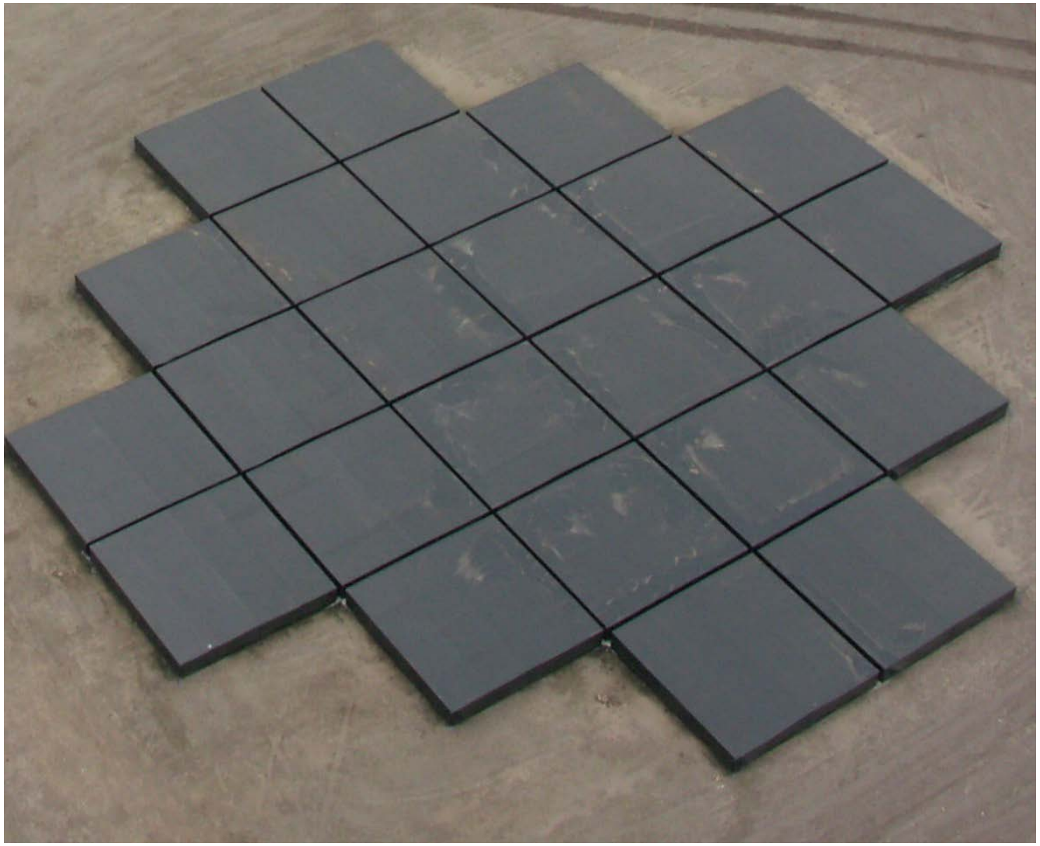


Moving FM sweep RFI, 10 second integration

Subspace Projection and max SNR beamforming

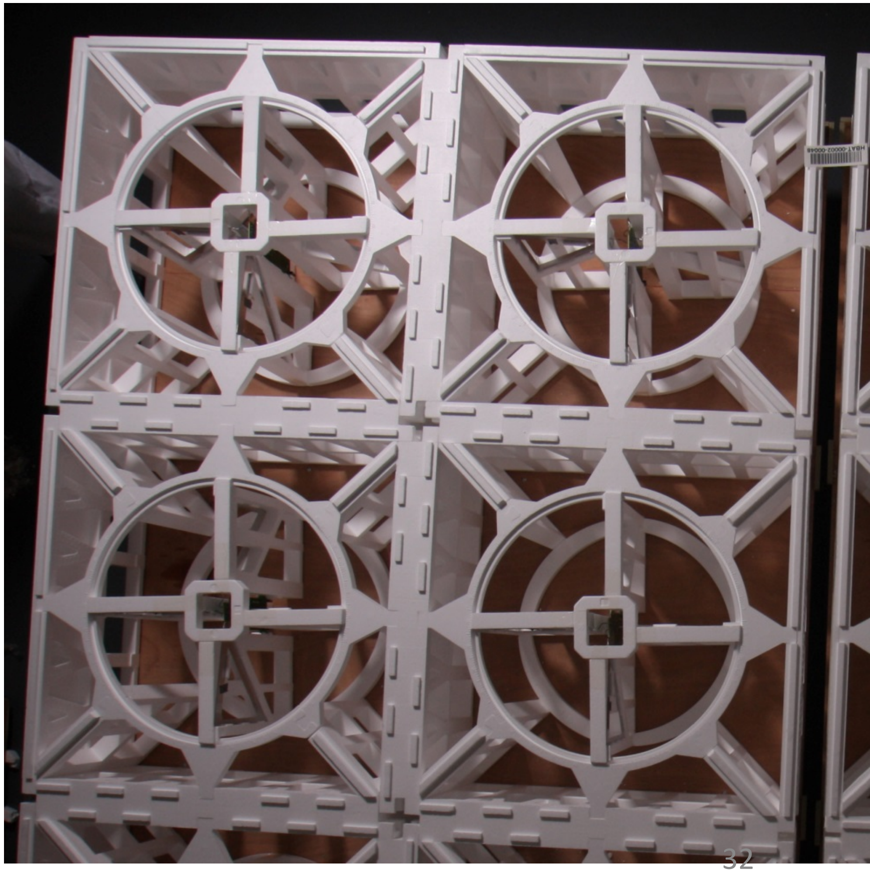


Aperture Arrays



A LOFAR single station aperture array with 96 antennas. The Netherlands

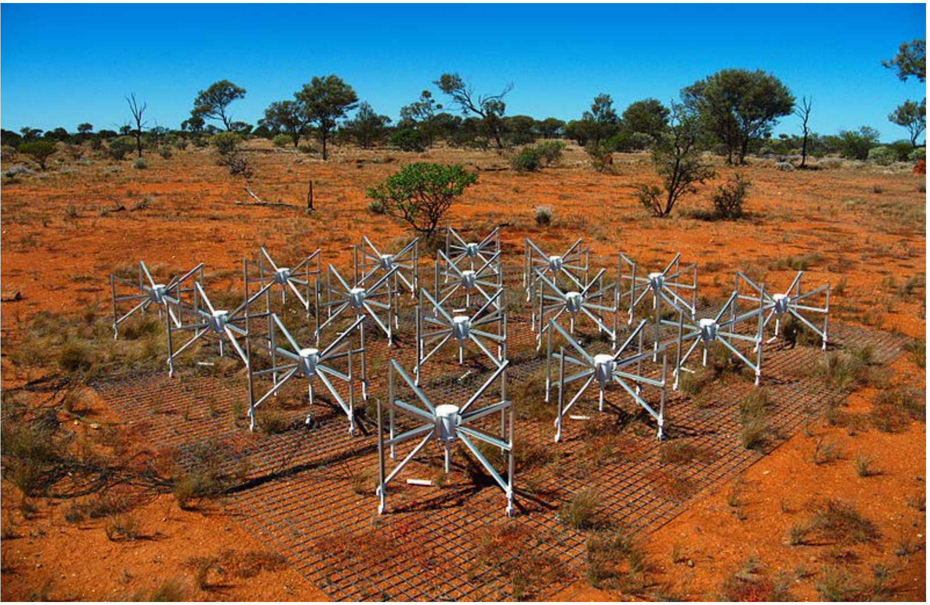
Interior view showing four dual- pol broadband dipole elements



BYU
Radio Astronomy Systems Research Group

Long Wavelength Array (LWA)

Image credit: Helene Dickel Photos, Picasa, LWA web site.



Murchison Widefield Array (MWA) one of 128 tiles

Image credit: Natasha Hurley Walker

Aperture Array RFI Mitigation Characteristics

- Low frequency: LOFAR, LWA, MWA, PAPER, etc.
- Parabolic dish collecting area is replaced with a beamforming “station” of closely packed simple antennas
- Wide fields of view for station elements make them highly susceptible to RFI from horizon to horizon
- Non SOI deep space objects must be treated as RFI and cancelled (or peeled)
- Tracking is slow for station beams, fast for full array

Spatial Filtering - Practical Considerations

Array processing RFI mitigation is a big, costly, complex step.

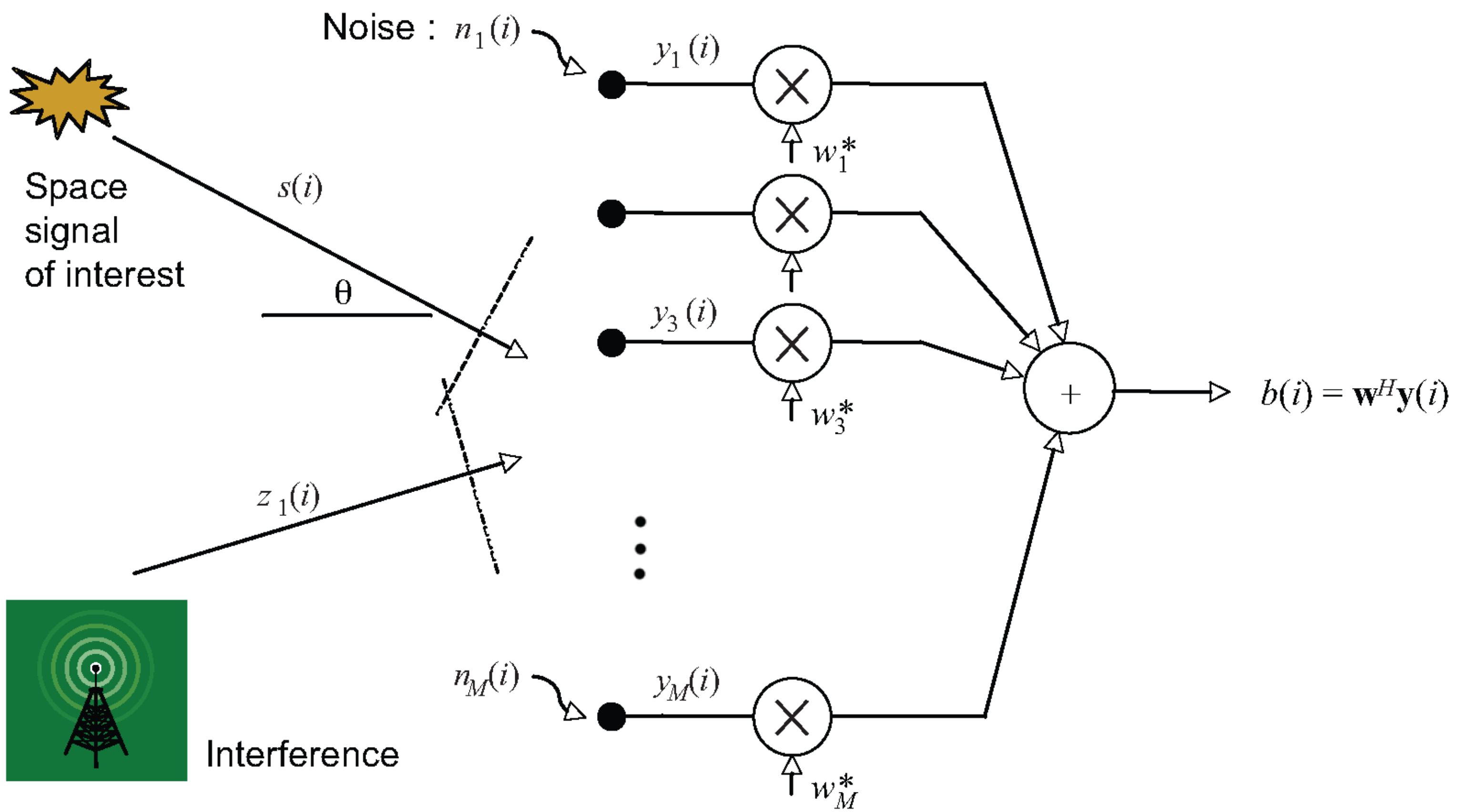
Will it work well enough?

Is it necessary?

- Integral part of aperture array processing (low gain)
- Optional part of phased array feed and synthesis array processing (high gain)

Signal Processing Structures and Implementation

The Narrowband Beamformer



- Repeat for each frequency channel.
- $\mathbf{w}$ is (weakly) frequency dependent.

- Signal Model:

$$\mathbf{y}(i) = \mathbf{a}\, s(i) + \sum_{d=1}^{D} \mathbf{v}_d(i) z_d(i) + \mathbf{n}(i)$$

Time-dependent Covariance Estimation

- Calculating $\mathbf{w}$ for spatial nulling relies critically on array covariance estimation.
  - Definitions: $$\mathbf{R} = E\{\mathbf{y}(i)\mathbf{y}^H(i)\} = \mathbf{R}_s + \mathbf{R}_n + \mathbf{R}_z$$
    $$\hat{\mathbf{R}}_k = \frac{1}{N}\sum_{i=kN}^{(k+1)N-1} \mathbf{y}(i)\mathbf{y}^H(i)$$
  - Must identify the interferer vector subspace portion $\mathbf{R}_z$
  - Computed at the PAF, station, and central correlator levels.

- Must update frequently to track interferer motion
  - Compute $\hat{\mathbf{R}}_k$ for all short term integrations (STI), k.
  - STI windows are N_{sti} samples long, which depends on motion rate and aperture size.

- Maximum SNR beamformer
  - Maximize signal to noise plus interference power ratio:

$$\mathbf{w}_{\text{snr}} = \arg\max_{\mathbf{w}} \frac{\mathbf{w}^H \mathbf{R}_s \mathbf{w}}{\mathbf{w}^H (\mathbf{R}_z + \mathbf{R}_n)\mathbf{w}} \quad \rightarrow \quad \mathbf{R}_s \mathbf{w}_{\text{snr}} = \lambda_{\max} (\hat{\mathbf{R}}_z + \hat{\mathbf{R}}_n)\mathbf{w}_{\text{snr}}$$

  - Point source case yields the MVDR solution:

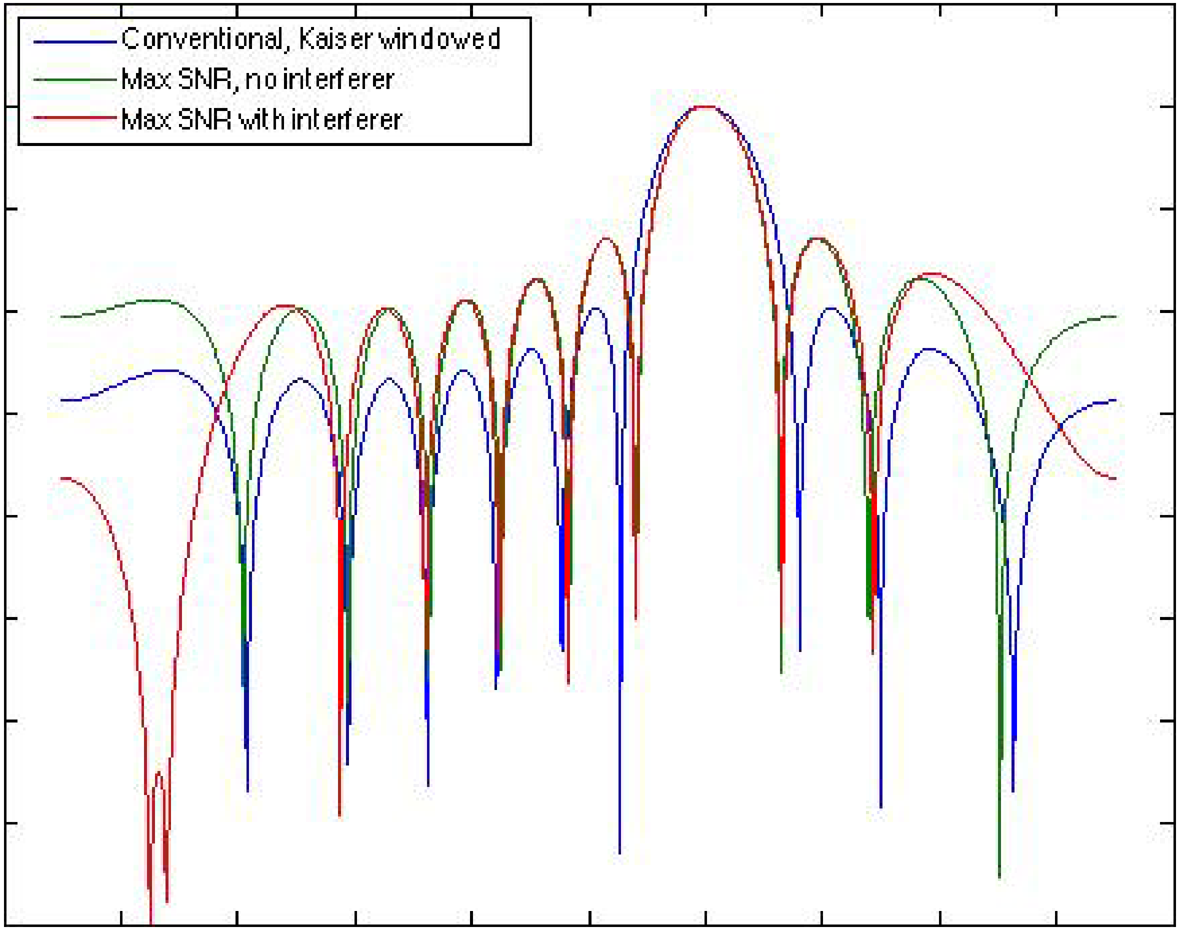
$$\mathbf{w}_{\text{mvdr}} = (\hat{\mathbf{R}}_z + \hat{\mathbf{R}}_n)^{-1} \mathbf{a}$$

- LCMV beamformer
  - Minimize total output power subject to linear constraints:

$$\mathbf{w}_{\text{lcmv}} = \arg\min_{\mathbf{w}} \mathbf{w}^H \hat{\mathbf{R}} \mathbf{w} \text{ s.t. } \mathbf{C}^H \mathbf{w} = \mathbf{f} \rightarrow \mathbf{w}_{\text{lcmv}} = \hat{\mathbf{R}}^{-1} \mathbf{C} [\mathbf{C}^H \hat{\mathbf{R}} \mathbf{C}]^{-1} \mathbf{f}$$

  - Direct control of response pattern at points specified by $\mathbf{C}$.
  - Can also constrain derivatives (slope) or eigenvectors.

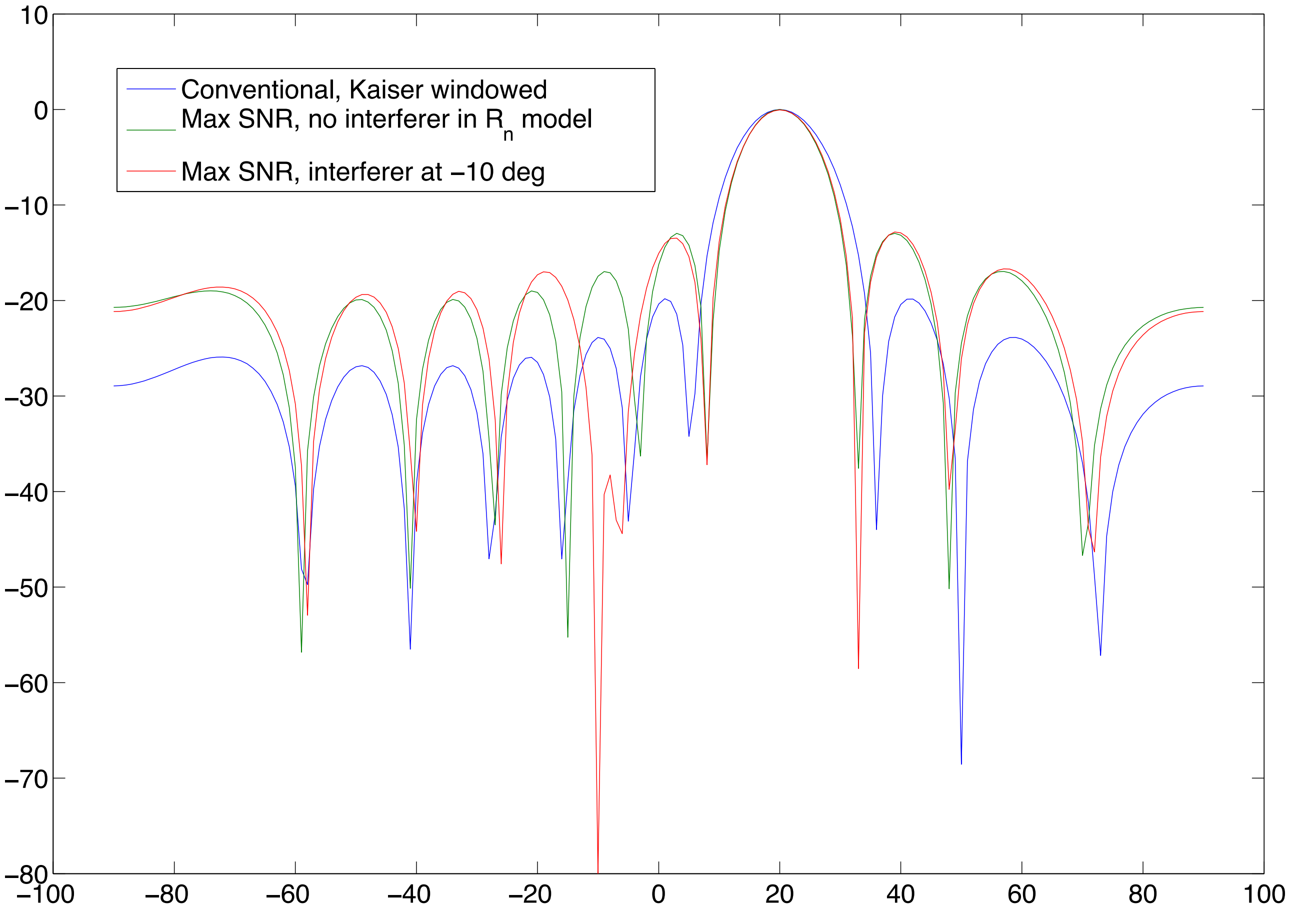
An Example of MaxSNR Canceling (High INR)



- 10 element ULA
- Moving interferer
- Exact covariances

- Very high INR case, +70 dB.
- SNR = +40 dB
- Max SNR output SINR = 50 dB

An Example of MaxSNR Canceling (High SNR/INR)



- 10 element ULA
- Exact covariances
- Output SIR is 139 dB!

- Very high INR case, +70 dB.
- SNR = +40 dB

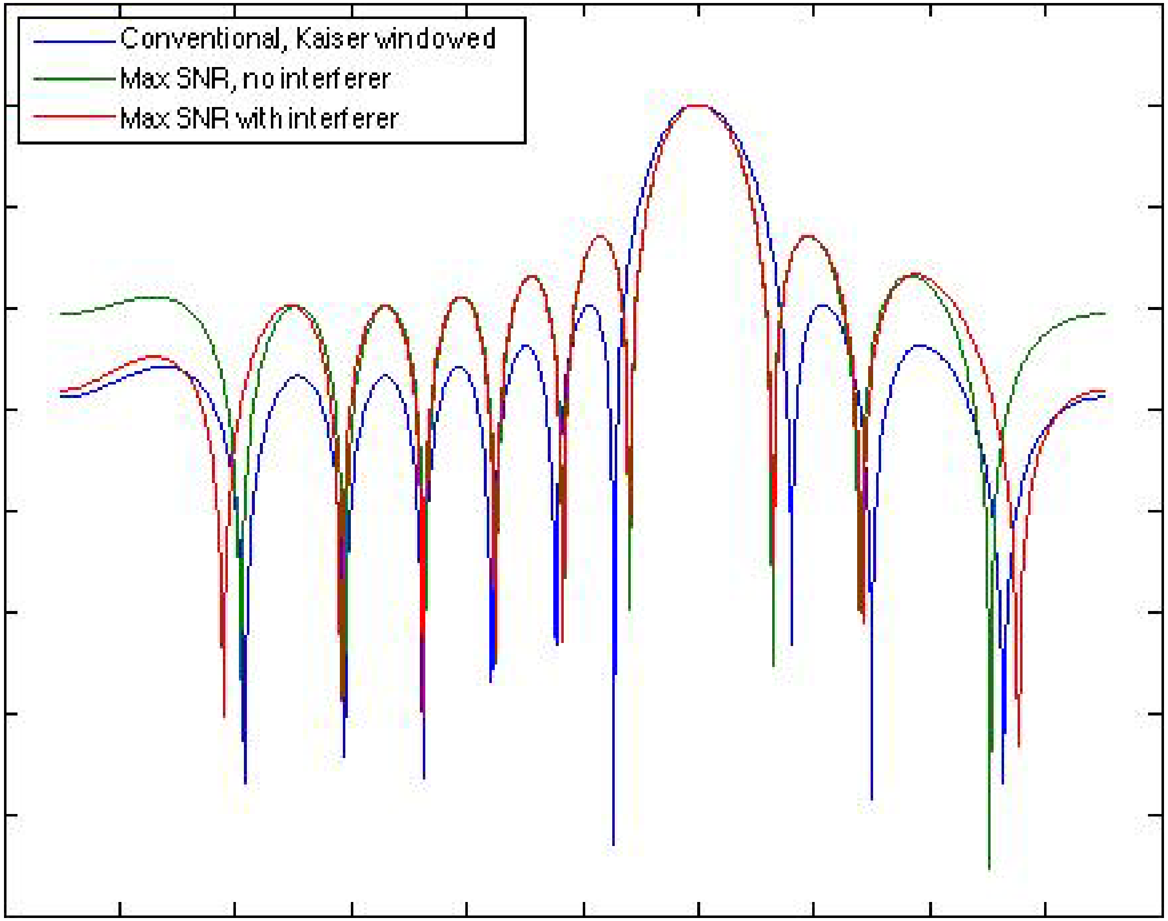
- Max SNR output SINR = 50 dB
- Similar to comm example

Problems with the RA Signal Scenario

- SOI and interferer are well bellow the noise floor.
  - SNR of -30 dB or worse is common.
  - INR <0 dB can still severely corrupt SOI.
  - Extremely hard to estimate $\mathbf{R}_z$ from $\mathbf{R}$.
- Motion limits integration time, increases sample estimation error in $\mathbf{R}_z$.
- Weak but troublesome interferers yield shallow nulls.
- Canceling distorts beam patterns.
  - Raises confusion limit in sidelobes.
  - Main beam may not have known shape.

More Realistic Example of MaxSNR Canceling

BYU
Radio Astronomy Systems
Research Group

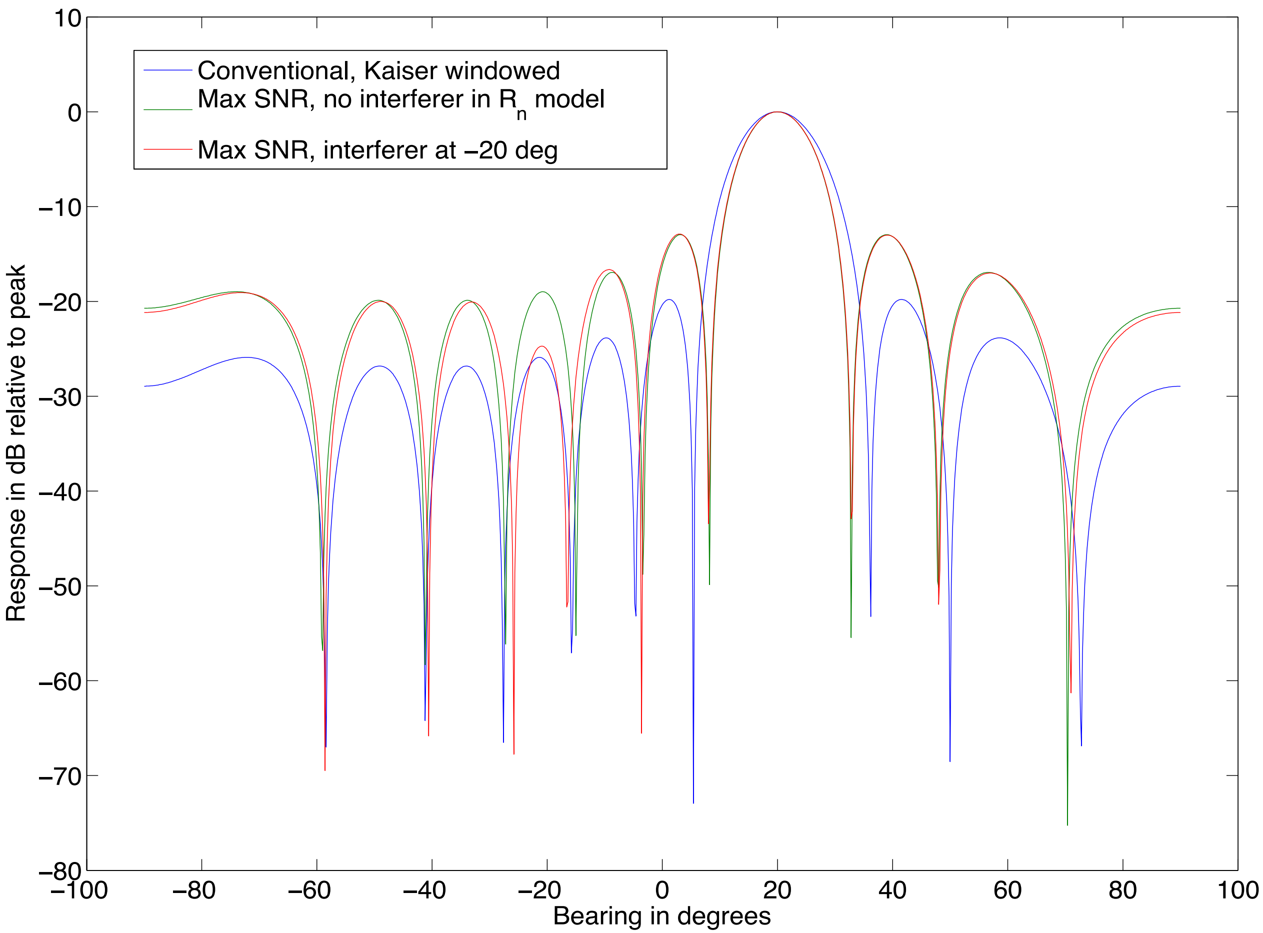


- 10 element ULA
- Exact covariances

- Low INR case, -10 dB.
- SNR = -40 dB

- Input SINR = -40 dB
- Max SNR output SINR = -30 dB

More Realistic Example of MaxSNR Canceling



- 10 element ULA
- Exact covariances
- *Output SIR is only -5 dB*

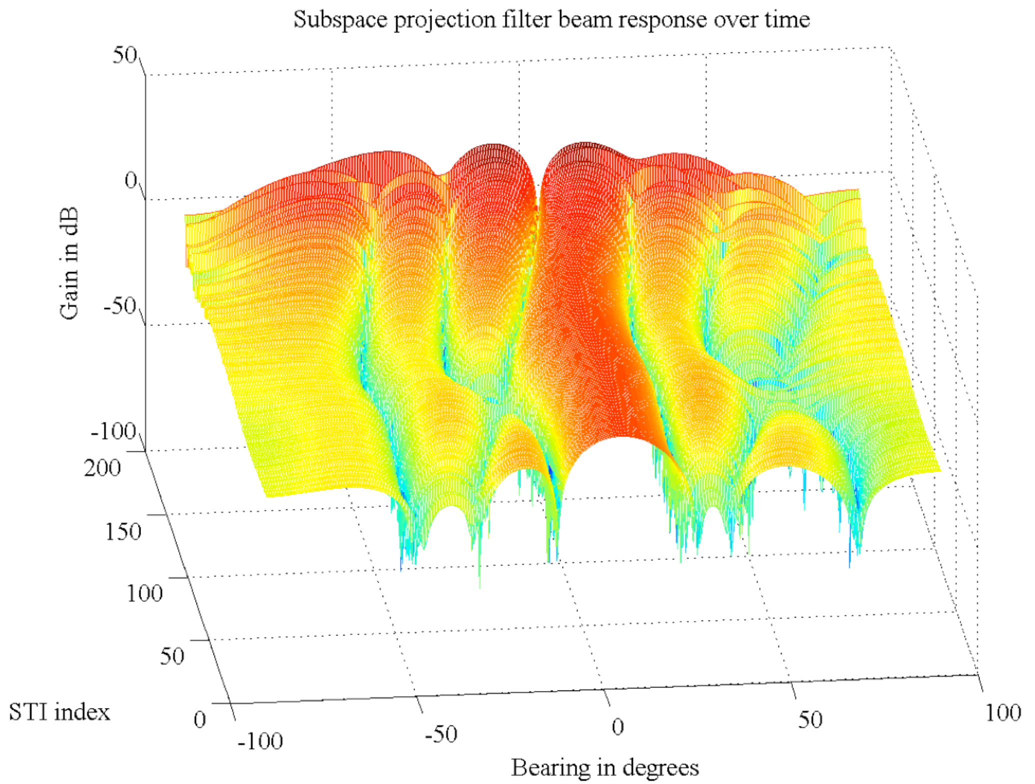
- Low INR case, -10 dB.
- SNR = -40 dB

- Input SINR = -40 dB
- Max SNR output SINR = -30 dB

Pattern Distortion with Moving RFI

BYU
Radio Astronomy Systems
Research Group

- In addition to poor rejection, with a moving interferer, sidelobe structure is unpredictable.
- Becomes severe as null approaches the main lobe.
- Sidelobe “rumble” increases confusion noise, hampers on/off subtraction.



- Uniform line array.
- 2 moving interferers, starting at +33 and -35 degrees, then moving to the right.
- 0 dB INR

Achieving Deeper Cancellation Nulls

The Good News

- Real-time correlators are already needed for all array types (interferometers, aperture, PAF)
  - Used to calculate visibilities or calibrate beams.
  - Rapid dump times needed to handle motion
  - Additional computational for spatial filtering is small
- Much progress has been made to address null depth limitations in the RA scenario.

Subspace Projection Method

BYU
Radio Astronomy Systems Research Group

- Well suited for synthesis arrays, aperture arrays, PAFs, and post correlation processing.
- Zero forcing, deeper nulls than with total variance minimization.
- Must assume interference is the dominant source.
- Use eigenvector decomposition to identify the interference subspace.
- Partition eigenspace. Largest eigenvalues(s) correspond to interference.

$$\hat{\mathbf{R}}_k [\mathbf{U}_{\text{int}} \,|\, \mathbf{U}_{\text{sig+noise}}] = [\mathbf{U}_{\text{int}} \,|\, \mathbf{U}_{\text{sig+noise}}] \Lambda$$

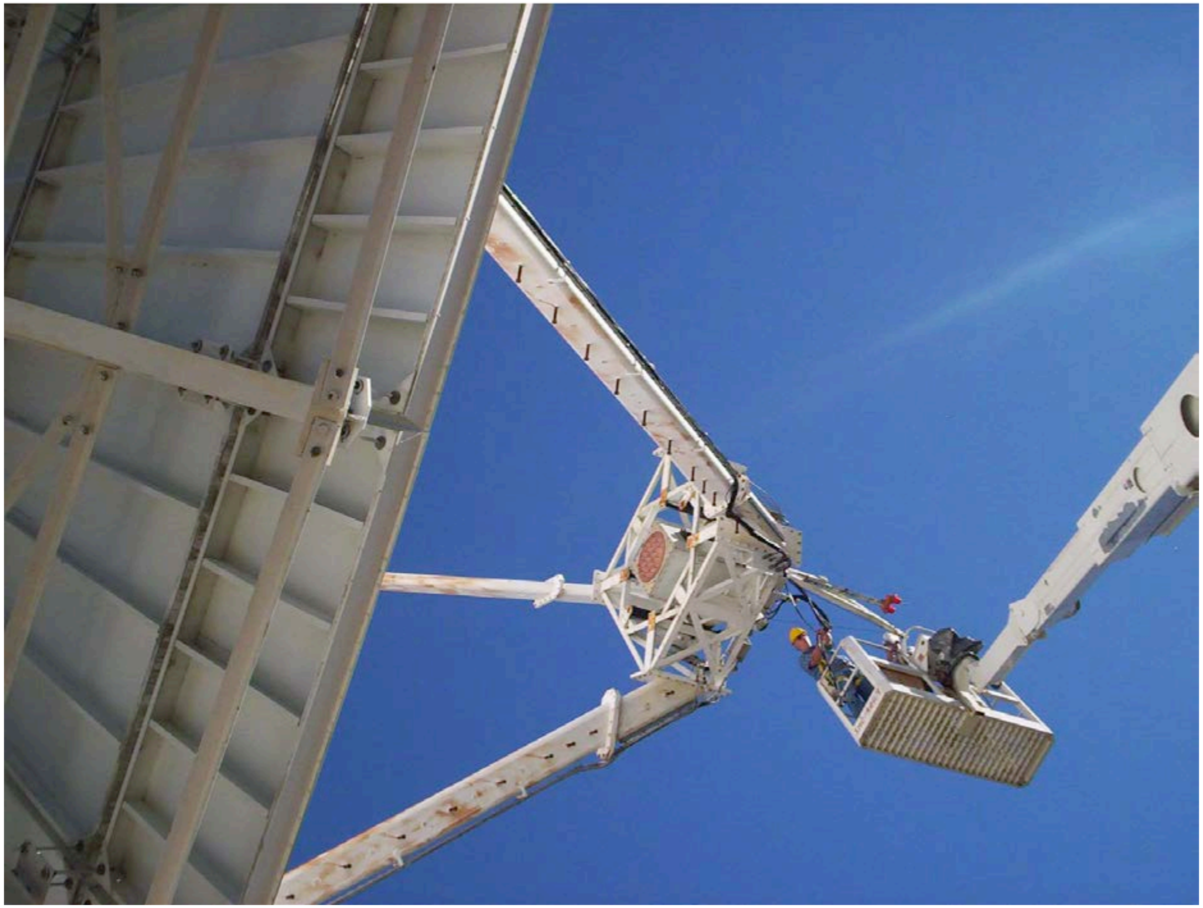
- Form perpendicular subspace projection matrix:

$$\mathbf{P}_k = \mathbf{I} - \mathbf{U}_{\text{int}} \mathbf{U}_{\text{int}}^H$$

- Compute weights and beamform over each STI:

$$\mathbf{w}_{\text{SSP},k} = \mathbf{P}_k \mathbf{w}_{\text{nominal}}, \quad b(i) = \mathbf{w}_{\text{SSP},k}^H \mathbf{y}(i), \quad k = \left\lfloor \frac{i}{N} \right\rfloor$$

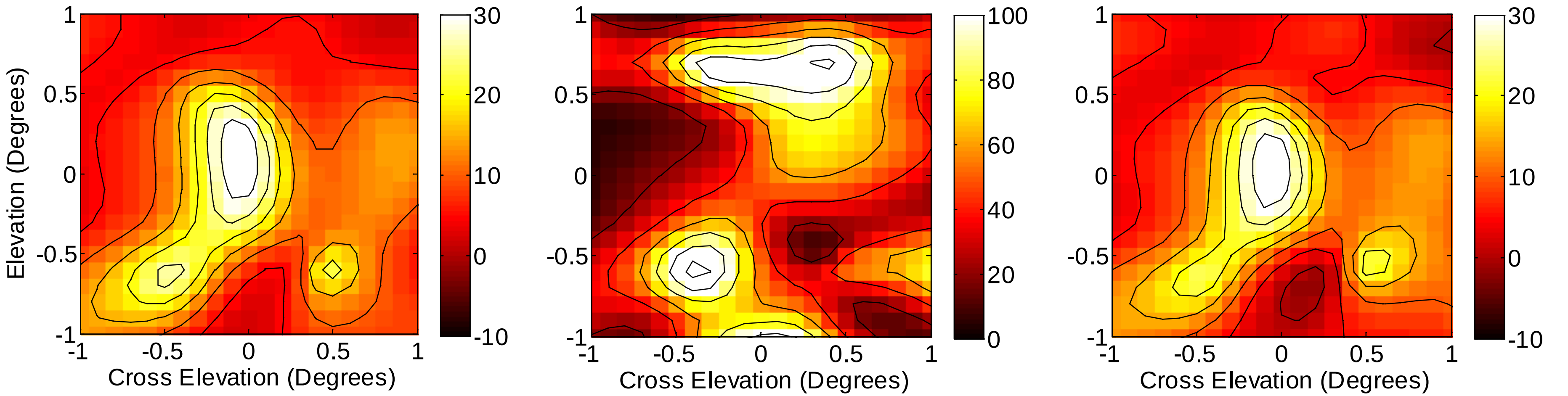
Real-World PAF Subspace Projection



- 19 element L band PAF on Green Bank 20 Meter Telescope.

Real-World PAF Subspace Projection

BYU
Radio Astronomy Systems Research Group



W3OH, no RFI

RFI corrupted image (moving function generator and antenna on the ground)

Adaptive spatial filtering Subspace projection algorithm

- 19 element L band PAF on Green Bank 20 Meter Telescope.
- Snapshot radio camera image, 21 by 21, 441 simultaneous beams.
- CW interference, hand held antenna and signal generator walking in front of Jansky Lab.

Subspace Bias Correction

- Projecting out interference subspace distorts the beampattern and causes a bias in the "off" integrated noise baseline level
- Leshem and van der Veen proposed a correction for moving interference over the N sample long term integration (LTI).

$$\breve{\mathbf{R}}_k = \mathbf{P}_k \hat{\mathbf{R}}_k \mathbf{P}_k^H = \text{unvec}\left\{(\mathbf{P}_k^* \otimes \mathbf{P}_k)\text{vec}\left(\hat{\mathbf{R}}_k\right)\right\}$$

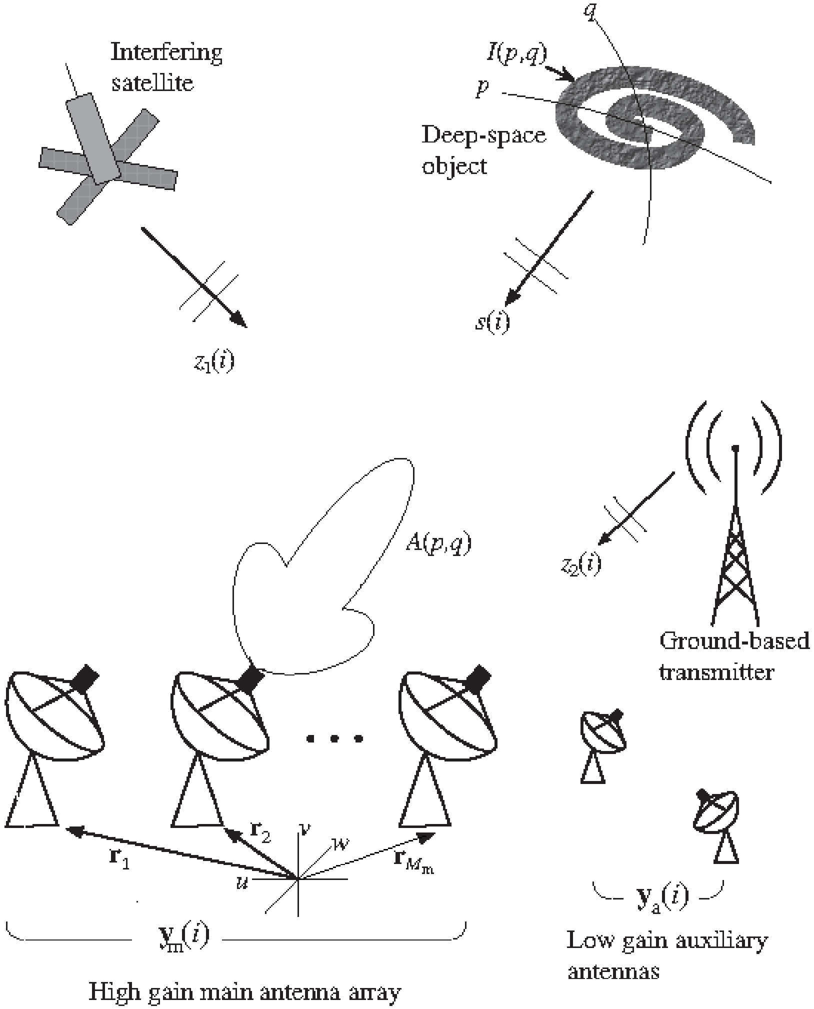
$$\bar{\mathbf{R}}_j = \text{unvec}\left\{\mathbf{B}^{-1}\sum_{k=0}^{J-1}\text{vec}\left(\breve{\mathbf{R}}_k\right)\right\}$$

$$\mathbf{B} = \sum_{k=0}^{J-1}\mathbf{P}_k^* \otimes \mathbf{P}_k, \quad J = \lfloor N / N_{\text{sti}} \rfloor$$

- Canceling happens at fast STI rate, k, correction at LTI rate, j.
- Use $\bar{\mathbf{R}}_j$ directly as an imaging visibility matrix.
- Works because each STI has a different subspace removed. Over the LTI, we can recover the full space.

Auxiliary Antenna Methods

- Improve interference subspace estimate $\hat{\mathbf{R}}_z$ and increase null depth.
- Aux antennas return higher INR signal than ~0 dBi dish sidelobe.
- Must track moving interferers.
- One antenna per interferer.



Aux Antenna Performance Analysis

Cross Subspace Projection

- Extend array vector to include auxiliaries.

$$\mathbf{y}(i) = \begin{bmatrix} \mathbf{y}_{\mathrm{m}}(i) \\ \mathbf{y}_{\mathrm{a}}(i) \end{bmatrix}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{\mathrm{mm}} & \mathbf{R}_{\mathrm{ma}} \\ \mathbf{R}_{\mathrm{am}} & \mathbf{R}_{\mathrm{aa}} \end{bmatrix}$$

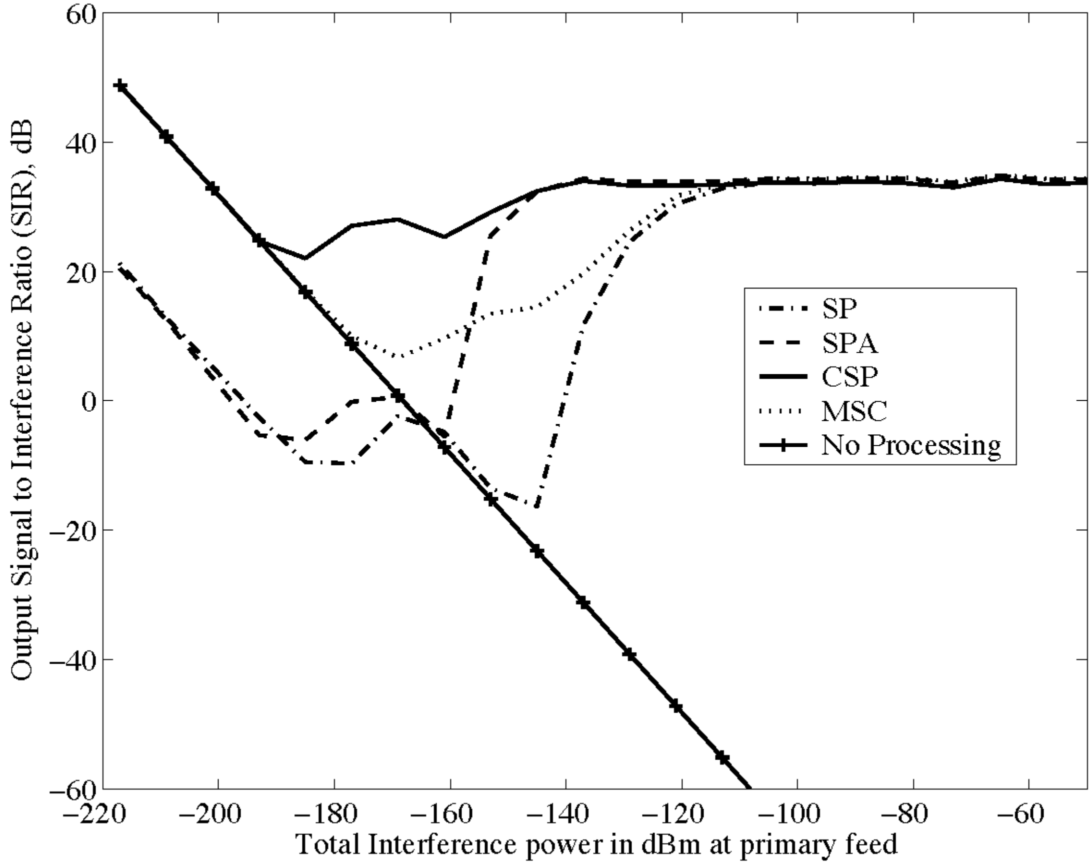
- Compute "projection" matrix with SVD on $\hat{\mathbf{R}}_{\mathrm{ma}}$

$$\hat{\mathbf{R}}_{\mathrm{ma}} = \mathbf{U}\Sigma\mathbf{V}^H$$

$$\mathbf{U}_{\mathrm{s}} = [\mathbf{u}_{D+1}, \cdots, \mathbf{u}_{M_{\mathrm{m}}}]$$

$$\mathbf{P}_{\mathrm{CSP}} = \left[\mathbf{U}_{\mathrm{s}}\mathbf{U}_{\mathrm{s}}^H, \mathbf{0}_{M_{\mathrm{m}}}\right]$$

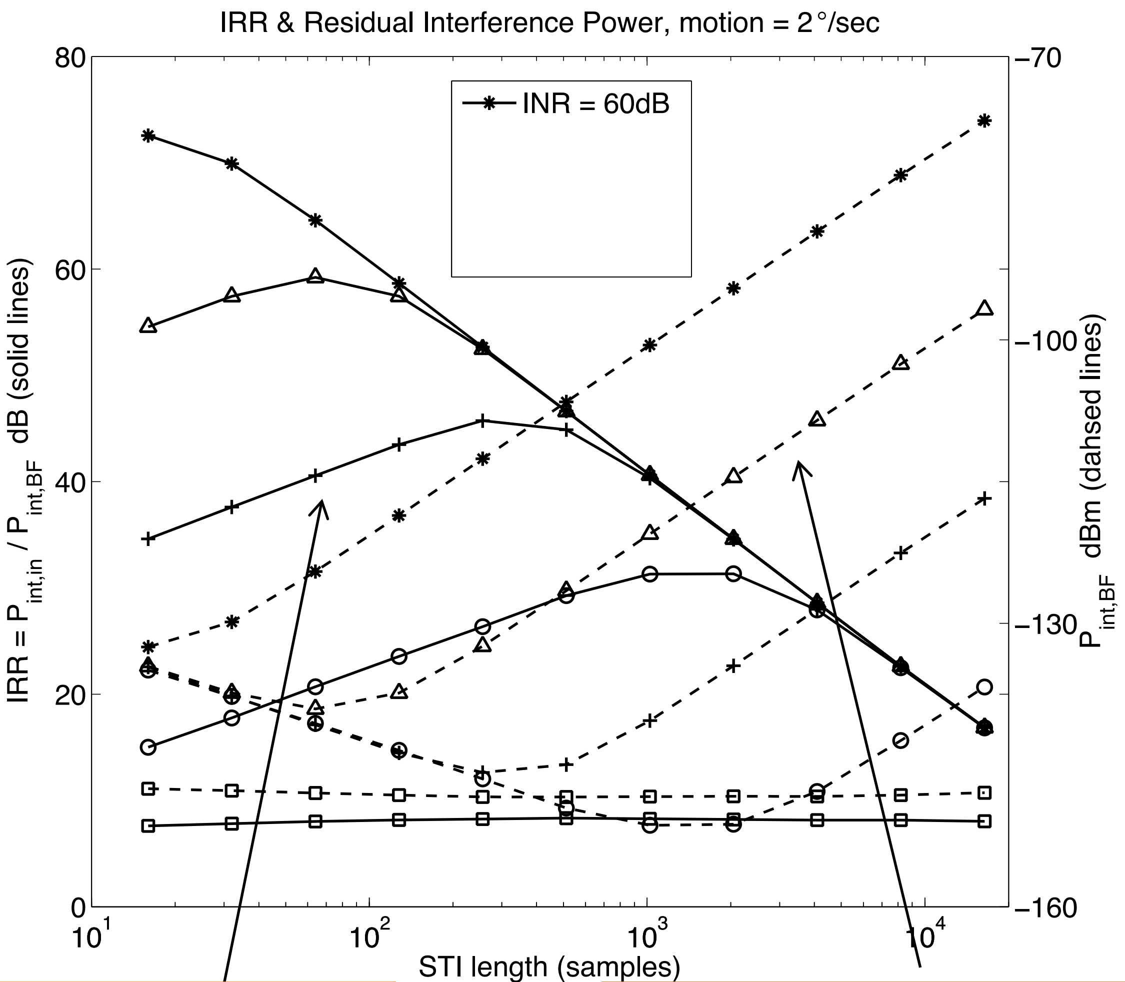
$$\hat{\mathbf{R}}_{\mathrm{CSP}} = \mathbf{P}_{\mathrm{CSP}}\hat{\mathbf{R}}\mathbf{P}_{\mathrm{CSP}}^H$$



VLA simulation for two stationary interferers and two small auxiliary dish antennas. Source is 1 Jy OH emission. INR at primary feeds is 146 dB above the plotted dBm interferer power level.

Conventional SSP Limitations – Moving Interferer

- Detailed simulation of 19-element PAF on 20m reflector, 0.43f/D
- Correlated spillover noise, mutual coupling, modeled 33K LNAs.
- **Short STI: Poor subspace estimation**
- **Long STI: Subspace smearing due to interferer motion**
- **Performance approaches adequate only in a "sweet spot" for STI length**



Subspace estimation error due to sample noise from short STI

Subspace smearing error due to motion, with no sample estimation error.

Low Order Parametric Models for SSP (J. Landon)

BYU
Radio Astronomy Systems Research Group

- Fit a series of STI covariances $\hat{\mathbf{R}}_k$ to a polynomial that can be evaluated at arbitrary timescale.
  - Beamformer weights can be updated *every* time sample.
  - Use entire data window to fit polynomial for less sample estimation error.
- Minimize the squared error between STI sample covariances and the polynomial model $\mathbf{C}_{\mathrm{LS}}$:

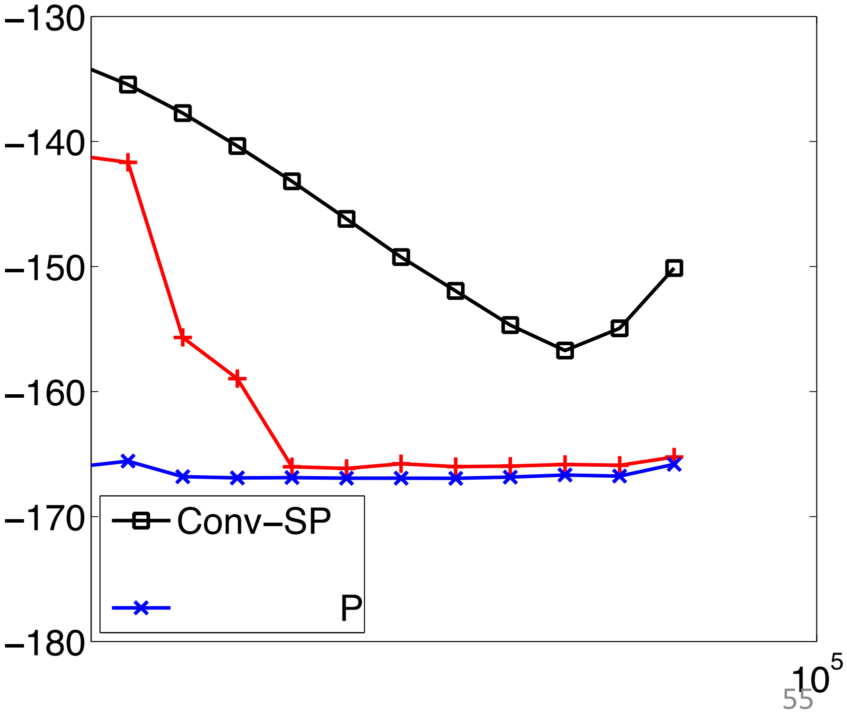
$$\mathbf{C}_{\mathrm{LS}} = \arg\min_{\mathbf{C}} \sum_{k=1}^{K} \left\| \hat{\mathbf{R}}_k - \tilde{\mathbf{R}}_{\mathrm{int}}(t_k, \mathbf{C}) \right\|_F^2 ,$$

where $t_k = kN_{\mathrm{sti}}T_s$

$$\tilde{\mathbf{R}}_{\mathrm{int}}(t, \mathbf{C}) = \mathbf{a}_{\mathrm{poly}}(t, \mathbf{C})\mathbf{a}_{\mathrm{poly}}^H(t, \mathbf{C})\Big|_{t=nT_s}$$

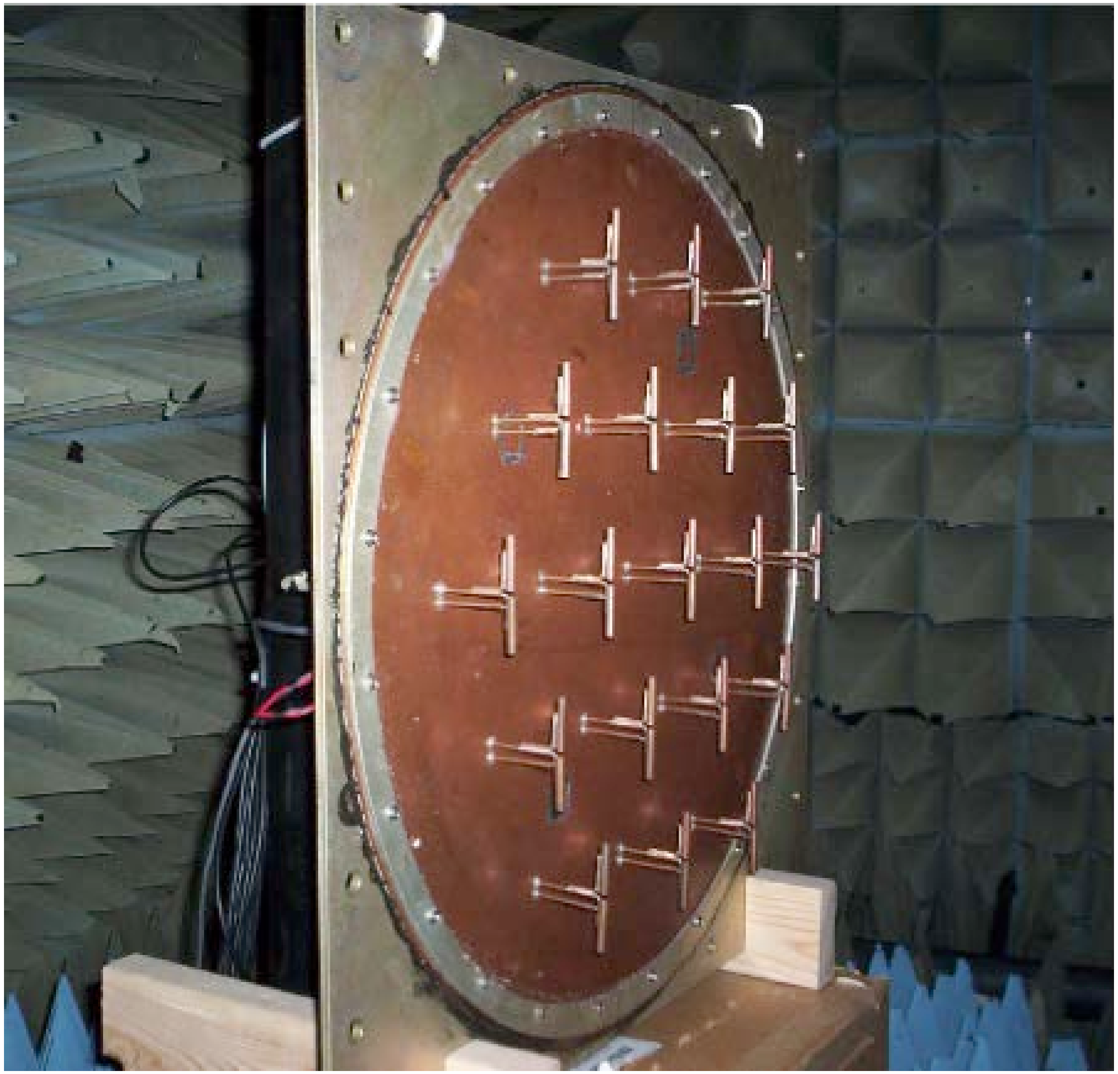
where $\mathbf{C} = [\mathbf{c}_0 \cdots \mathbf{c}_r]$

$$\mathbf{a}_{\mathrm{poly}}(t, \mathbf{C}) = \mathbf{c}_0 + \mathbf{c}_1 t + \cdots + \mathbf{c}_r t^r$$



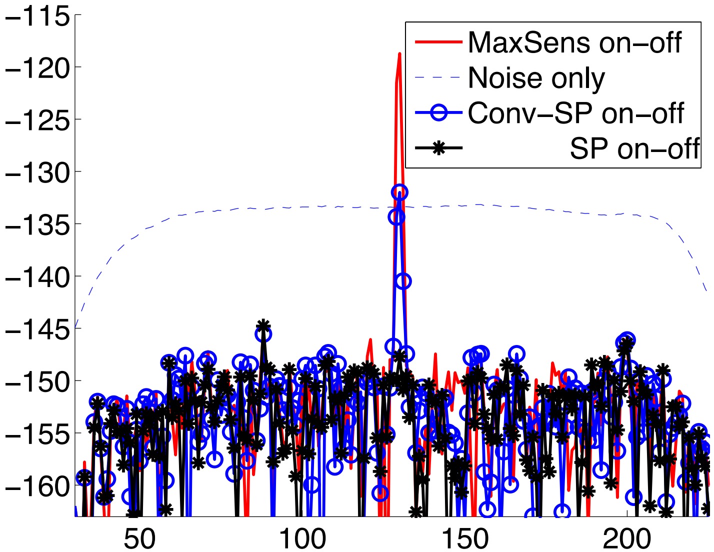
Real Data Cancelation Results

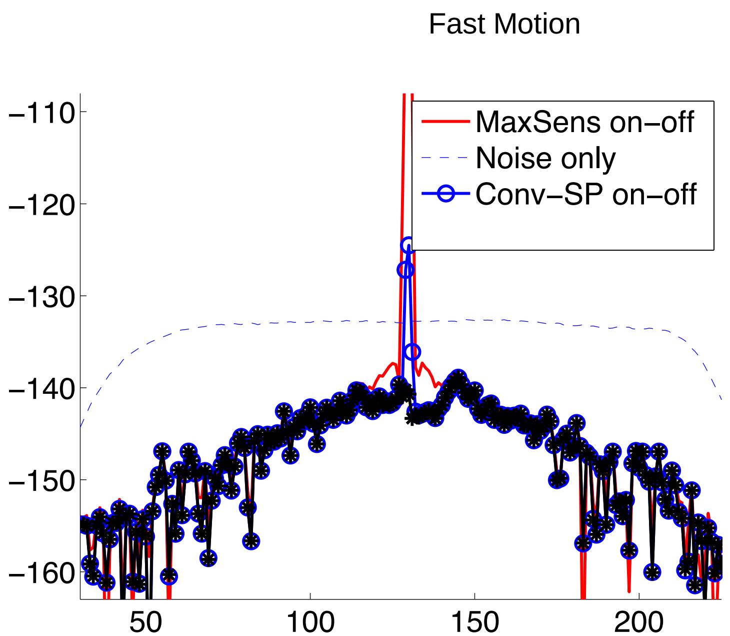
BYU
Radio Astronomy Systems
Research Group

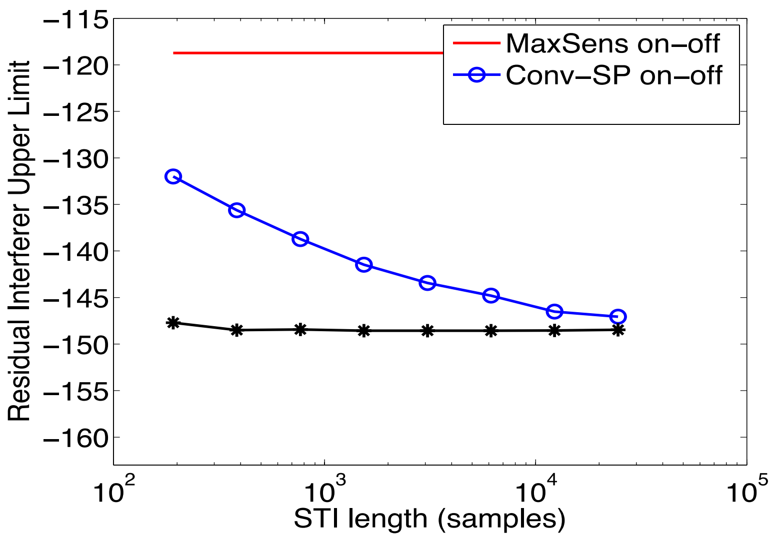


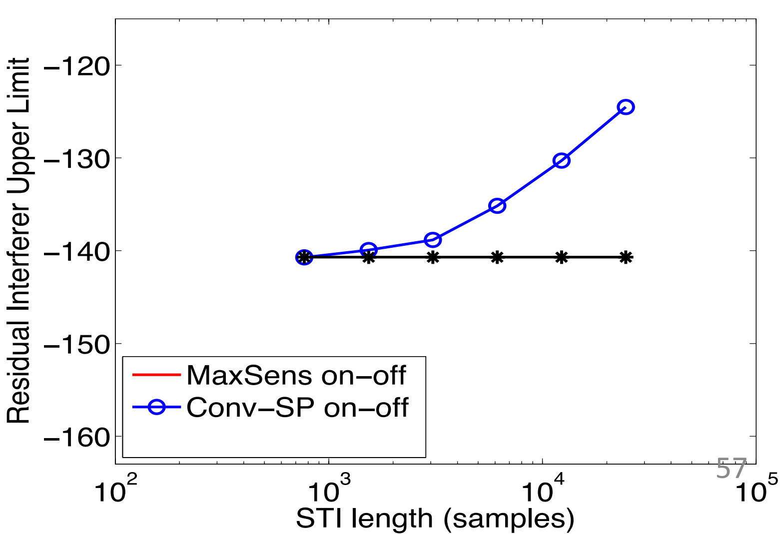
- Test Platform in the anechoic chamber.
- Used an early 19 element L-band PAF array.
- Interference motion is induced by controlled rotation of the array.

Real Data Cancelation Results









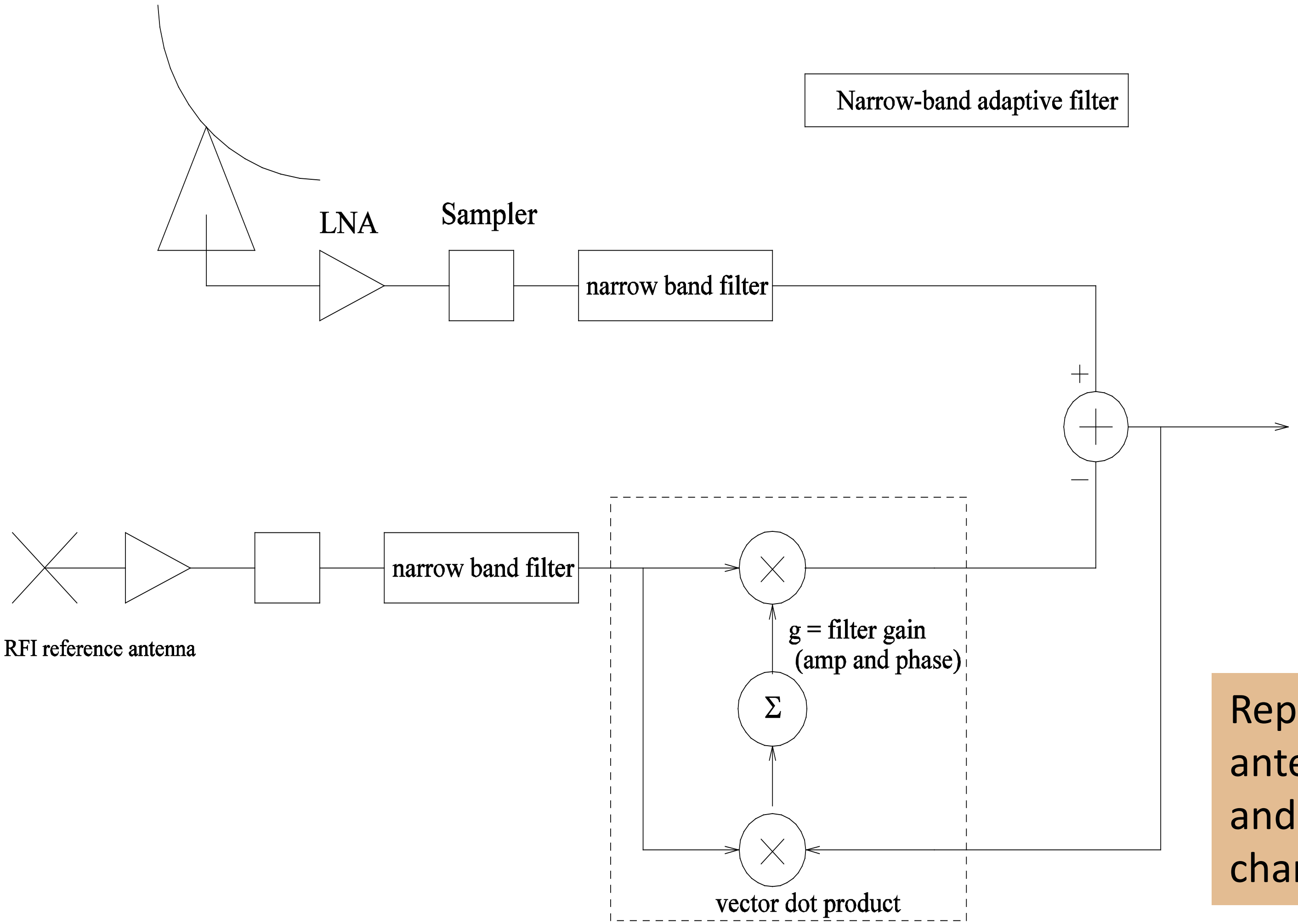
Additional Array Signal Processing Methods

- Robust beamforming
  - Helpful if array calibration has errors. Keeps SOI from being canceled.
- Spectral scooping correction (Jeffs, Warnick)
  - Block mode covariance matrix processing for beamformer weight updates, narrowband RFI
  - Surprising behavior: the time-varying spatial filter places a spectral null in PSD estimates (spatial filter becomes a temporal filter!)
  - Noticed by a grad student (James Nagel), who we didn't believe at first
  - The cause of this bias has been described analytically.
  - A straightforward correction has been proposed.
- **Many** other methods, techniques, algorithms are available in the array signal processing literature - very mature field (at least theoretically, but perhaps not in terms of practical implementation)

Progress Towards Adoption

Kesteven Adaptive Filter: Parkes and ATCA

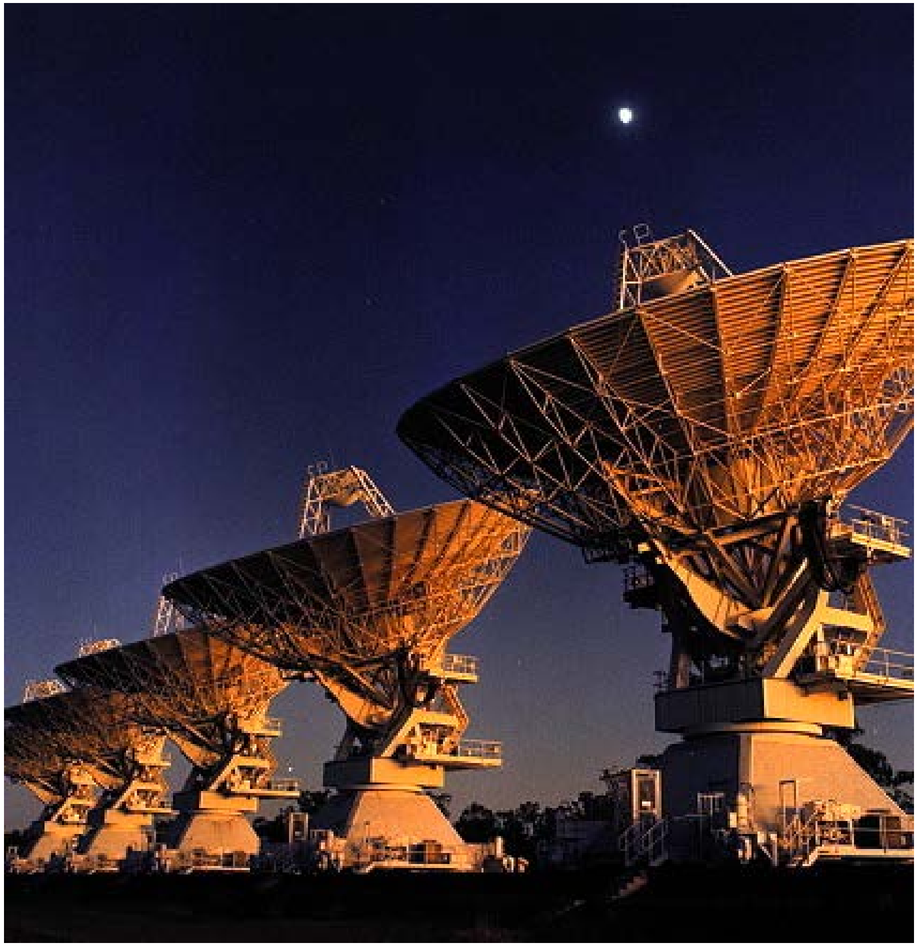
BYU
Radio Astronomy Systems Research Group



Repeat for each antenna and frequency channel

Kesteven Adaptive Filter: Parkes and ATCA

- Fully operational at Parkes.
- Initial test at Narrabri on CABB July 2013.
  - RFI was from radio tower on Mount Kaputar, 55 km due East.
  - Narrowband, modulated source.
  - 1.5 GHz.
  - Seen in dish pattern sidelobes.
  - One dish of 6 steered near RFI used as reference.
  - RFI Attenuation of 10-20 dB.
- Also tried at GMRT.



Other Activities

- Low frequency aperture arrays are currently using array processing mitigation in normal operations.
  - With no dish, ultra wide element patterns “see it all.”
  - Spatial filtering is essentially mandatory.
  - Used at station beamformer level.
- CSIRO has made this a priority for ASKAP.
  - B. Jeffs on sabbatical at CSIRO.
  - Funded a 3-year post doctoral position to study PAF RFI mitigation.
  - Aliakbar Gorji joins the group in October.
  - Will collaborate with Aaron Chippendale, Michael Kesteven, Stuart Hay, Aidan Hotan, and Brian Jeffs.
  - System requirements for ADE PAF, ACM correlator, beamformer, and central correlator will be studied.
  - New algorithms will be pursued.

Spatial Filtering - Progress Towards Adoption

- Despite significant promise and potential, adoption has been slow.
- Perhaps astronomers are reluctant to move from the tried and true.
- We now have critical science cases to motivate adoption.
- Computational and infrastructure costs are incremental, but non-trivial.
- We hope presented progress in overcoming spatial filtering limitations will spur adoption.

Layers of RFI Mitigation - Implementation Strategy

- New generation backends
  - Allow mitigation at different processing stages
  - Accommodate auxiliary antennas
- Each mitigation method requires an INR threshold – removal of most RFI requires layered application of methods to exploit progressive integration of data and increasing INR
- Human intervention required to select between filtering for known, fixed transmitters and adaptive real time processing
- Interferometers – less vulnerable, but station level mitigation still required
- Implement more sophisticated methods over time – spatial filtering, adaptive cancellation, higher order statistical detection methods

Conclusions

- "Category I and II" RFI mitigation methods are well established
- "Category III" RFI cancellation methods are available now for some instruments and are on the horizon for others
- RFI spatial filtering for array feeds, synthesis arrays, and aperture arrays offers another mode of mitigation beyond time blanking, frequency excision, and avoidance
- Challenges include low INR, interferer motion, hardware/software complexity, user adoption/user confidence
- Algorithms common to wireless comm, radar, and sonar do not drive deep enough nulls, and distort beampatterns
- Several algorithm enhancements have been proposed which may solve these limitations

Bibliography

- ITU Report RA.2126
- A. Leshem, A.-J. van der Veen and A.-J. Boonstra, "Multichannel interference mitigation techniques in radio astronomy," *Astrophysical Journal Supplement*, vol. 131, no. 1, 2000.
- A. Leshem and A.-J. van der Veen, "Radio-Astronomical Imaging in the Presence of Strong Radio Interference," *IEEE Jour. on Information Theory,* vol. 46, no. 5, Aug. 2000.
- B.D. Jeffs, L. Li and K.F. Warnick, "Auxiliary antenna assisted interference mitigation for radio astronomy arrays," *IEEE Trans. on SP*, vol. 53, No. 2, February, 2005.
- B.D. Jeffs and K.F. Warnick, "Bias corrected PSD estimation for an adaptive array with moving interference," *IEEE Trans. on SP*, vol. 56, no. 7, July, 2008.
- J. Landon, B.D. Jeffs, and K.F. Warnick, "Model-Based Subspace Projection Beamforming for Deep Interference Nulling," *IEEE Trans. on SP*, vol. 60, no. 3, March 2012.
- B.D. Jeffs and K.F. Warnick, "Spectral bias in adaptive beamforming with narrowband interference," *IEEE Trans. on SP*, vol. 57, no. 4, Apr., 2009.
- J. R. Nagel, K. F. Warnick, B. D. Jeffs, J. R. Fisher, and R. Bradley, "Experimental verification of radio frequency interference mitigation with a focal plane array feed," *Radio Science*, vol. 42, RS6013, doi 10.1029/2007RS003630, 2007.
- S. van der Tol and A.-J. van der Veen, "Application of robust Capon beamforming to radio astronomical Imaging," *Proceedings of ICASSP 2005,* vol. iv, pp. 1089-1092, March 2005.
- S. van der Tol and A.-J. van der Veen, "Performance analysis of spatial filtering of RF interference in radio astronomy," *IEEE Trans. on SP*, vol. 53, no. 3, Mar. 2005.