National Radio Astronomy Observatory

# The Very Large Array and RFI Mitigation


Presented by:

Adam Kimbrough

(N4ADK)

# Radio Telescopes

- Come in two basic forms:



Single Antenna

Arrays

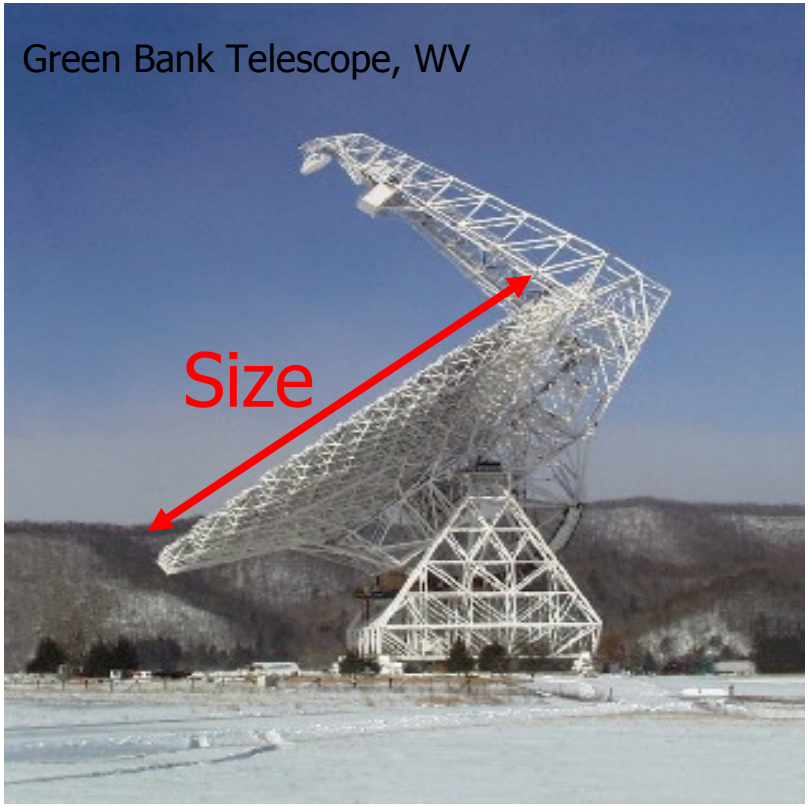
# Benefits of Observing in the Radio

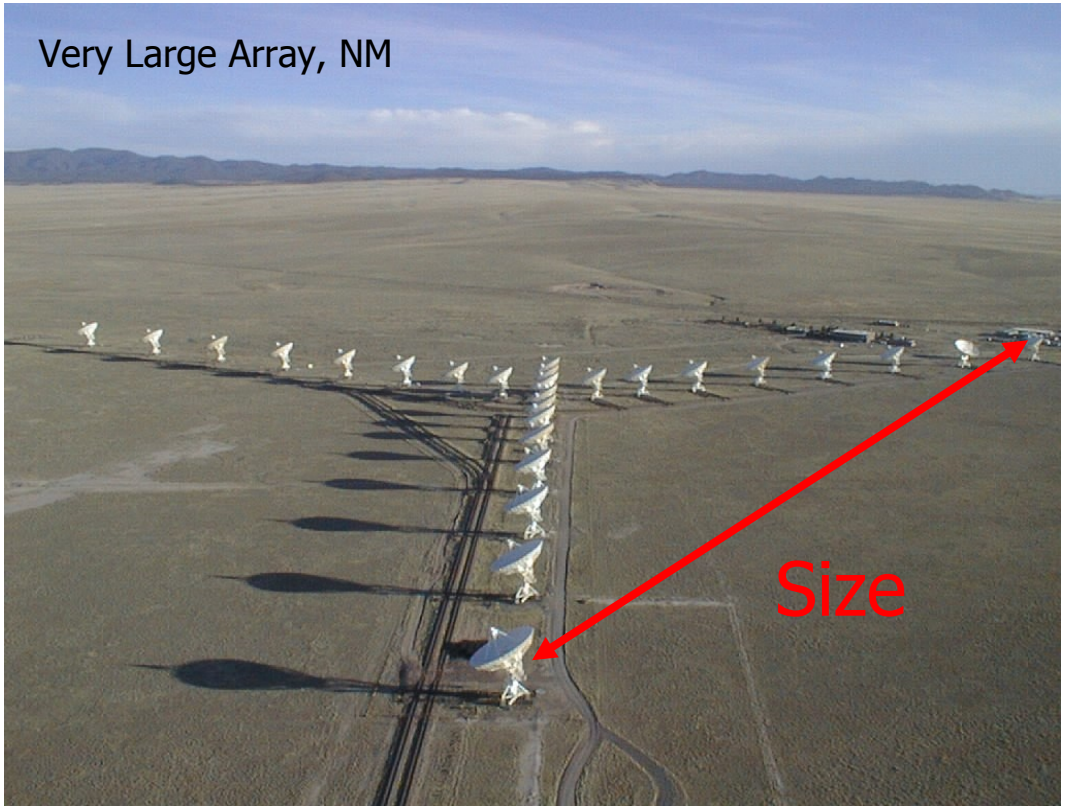
- Track physical processes with no signature at other wavelengths
- Radio waves can travel through dusty regions
- Can provide information on magnetic field strength and orientation
- Can provide information on line-of-sight velocities
- Daytime observing (for cm-scale wavelengths anyway)

# The Very Large Array-- Overview

- The Very Large Array is a 28-element, reconfigurable interferometer array, located in west-central New Mexico, USA. (lat = 34.1, long = 107.6).
- High elevation (2100 m), desert climate (~20 cm yearly precipitation, 76% sunny), means good observing conditions most of the year.
- There are four major configurations, offering a range of over 300 in imaging resolution.
  - e.g. 1.5" to 400" at $\lambda$=21cm
  - The Pete V. Domenici Science Operations Center (DSOC)
  - VLA site
  - Upgraded in 2012, ~$94M

# Radio Telescopes: Resolution




Single Dish

Arrays

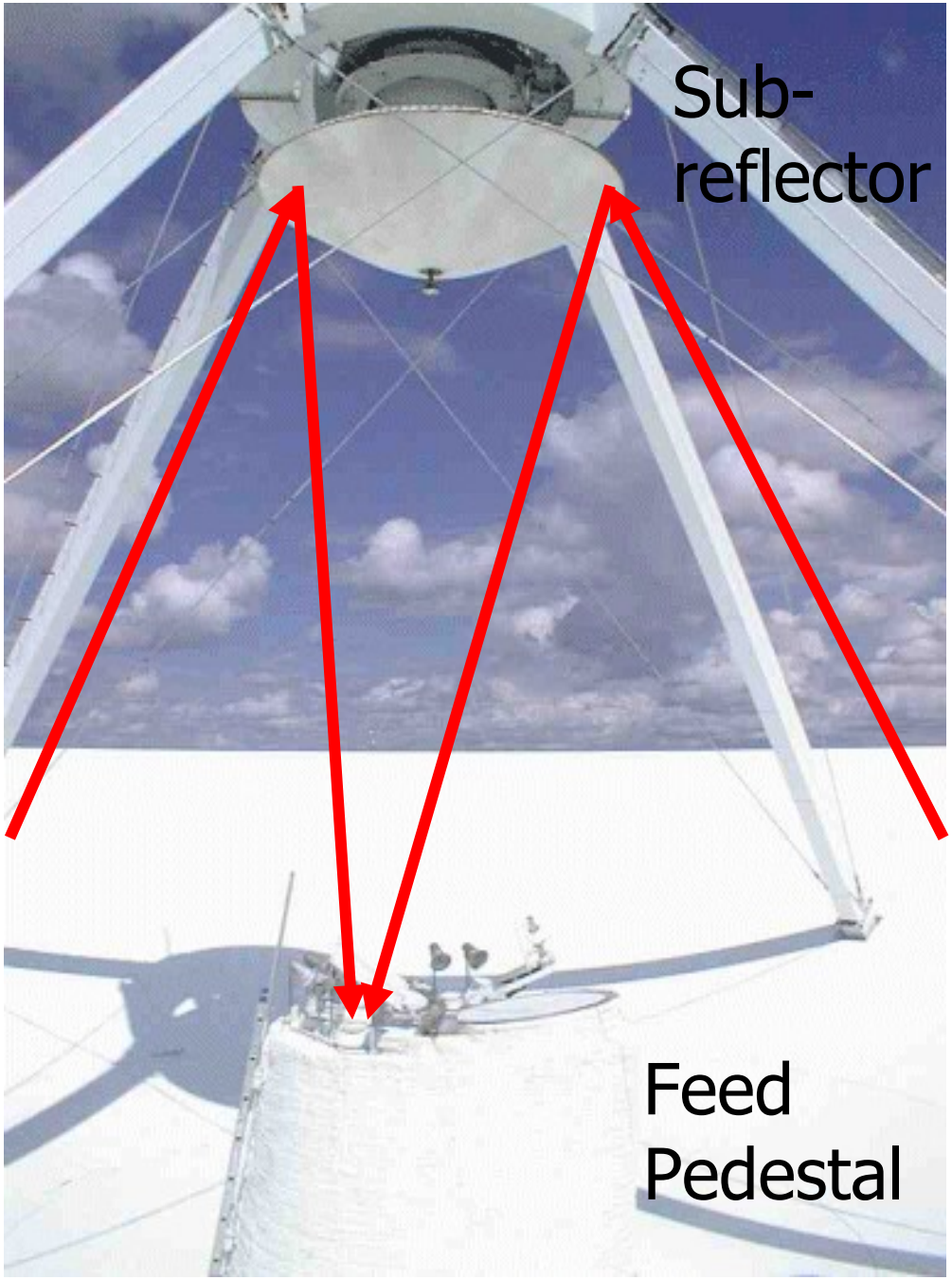
# EVLA aka Jansky VLA Antennas

- The EVLA utilizes 25-meter parabaloids.
  - Off-axis Cassegrain optics. (GBT, Arecibo are Gregorian)
  - Change band by rotating subreflector

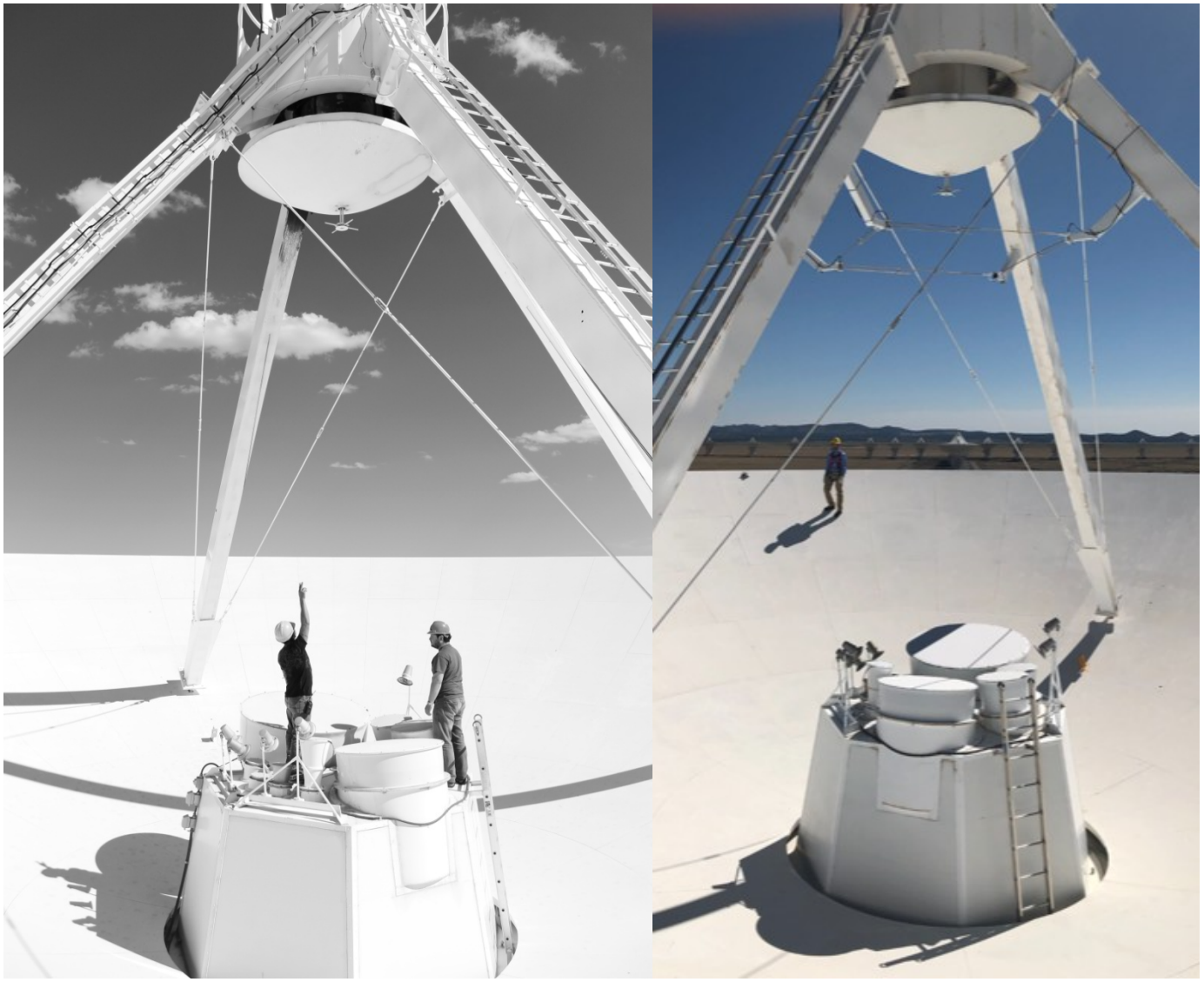
Antenna 24 – the first EVLA antenna outfitted with all eight feeds.

# Sub-reflector

- Re-directs incoming waves to Feed Pedestal
- Can be rotated to redirect radiation to a number of different receivers



# EVLA antennas are big!



# Jansky VLA-VLA Capabilities Comparison

The upgraded EVLA's performance is vastly better than the VLA's:

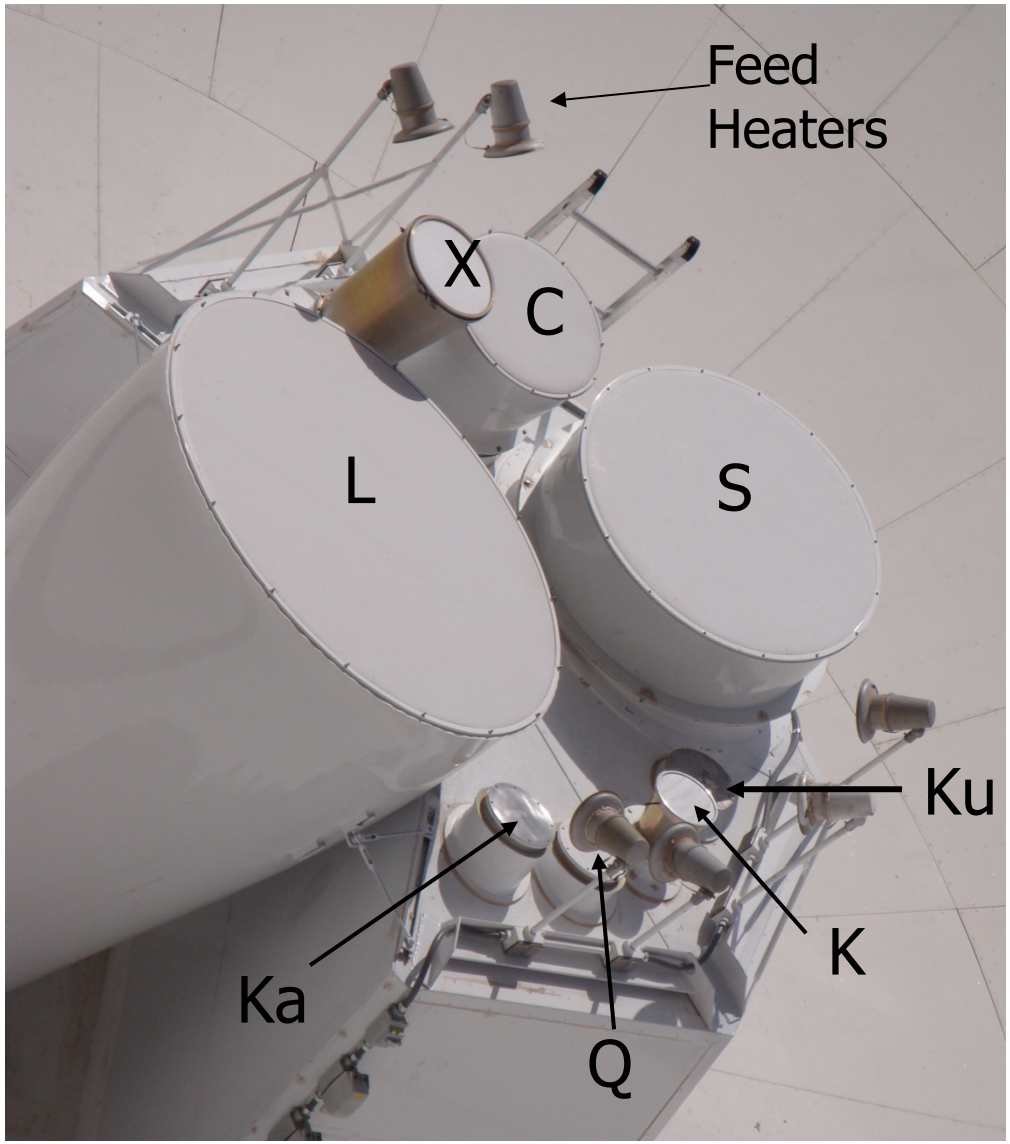
| Parameter | VLA | Jy VLA | Factor | Current |
|---|---|---|---|---|
| Point Source Cont. Sensitivity (1σ,12hr.) | 10 μJy | 1 μJy | **10** | 1 μJy |
| Maximum BW in each polarization | 0.1 GHz | 8 GHz | **80** | 8 GHz |
| # of frequency channels at max. BW | 16 | 16,384 | **1024** | 16384 |
| Maximum number of freq. channels | 512 | 4,194,304 | **8192** | 4,194,304 |
| Coarsest frequency resolution | 50 MHz | 2 MHz | **25** | 2 MHz |
| Finest frequency resolution | 381 Hz | 0.12 Hz | **3180** | 0.12 Hz |
| # of full-polarization spectral windows | 2 | 64 | **32** | 64 |
| (Log) Frequency Coverage (1 – 50 GHz) | 22% | 100% | **5** | 100% |

# Full Frequency Coverage with Outstanding Performance

- There are eight feeds, tightly packed around the secondary focus feed ring.

| Band (GHz) | | $T_{sys}$ |
|---|---|---|
| 1-2 | L | 25 |
| 2-4 | S | 25 |
| 4-8 | C | 25 |
| 8-12 | X | 30 |
| 12-18 | Ku | 40 |
| 18-26.5 | K | 40 |
| 26.5-40 | Ka | 40 |
| 40-50 | Q | 66 |

* -- Initial test values

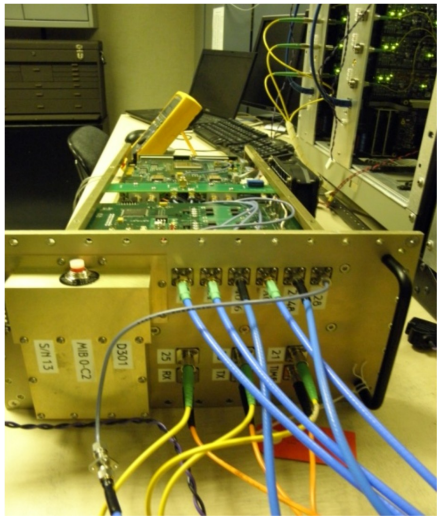


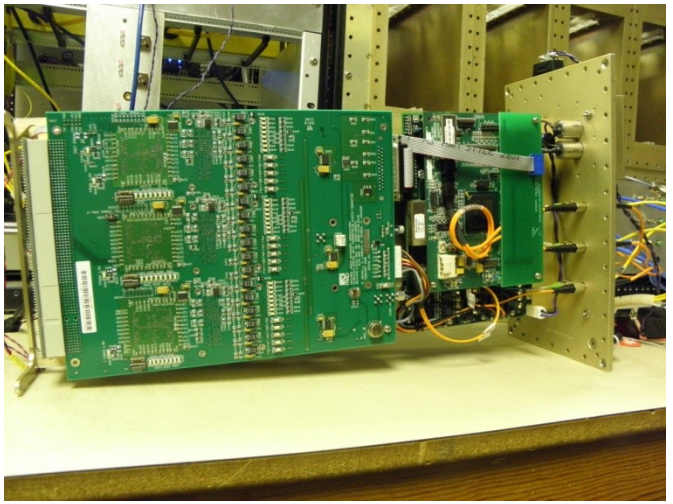
# EVLA Modules

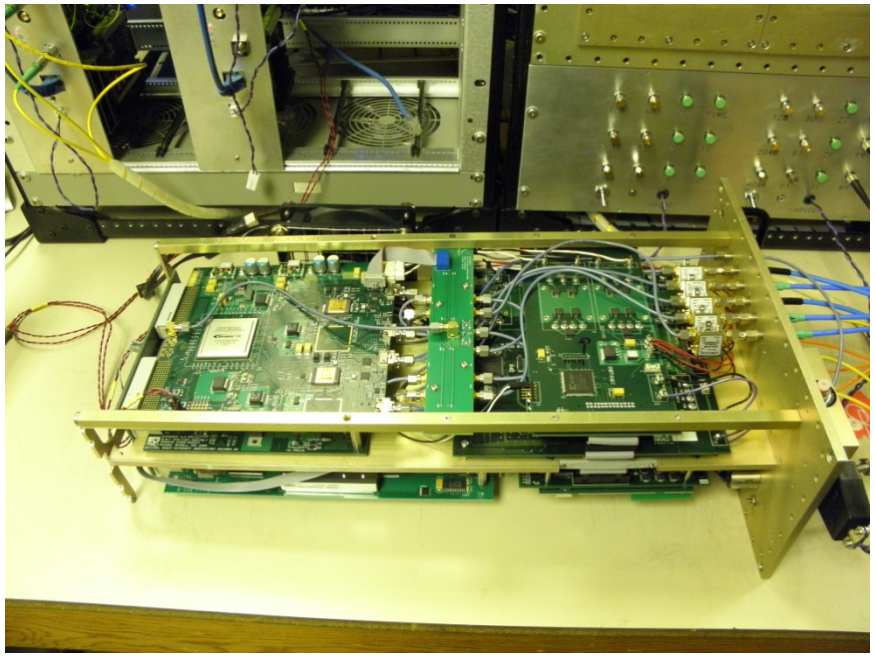
And some Monday morning magic…

# Sampler/DTS Modules

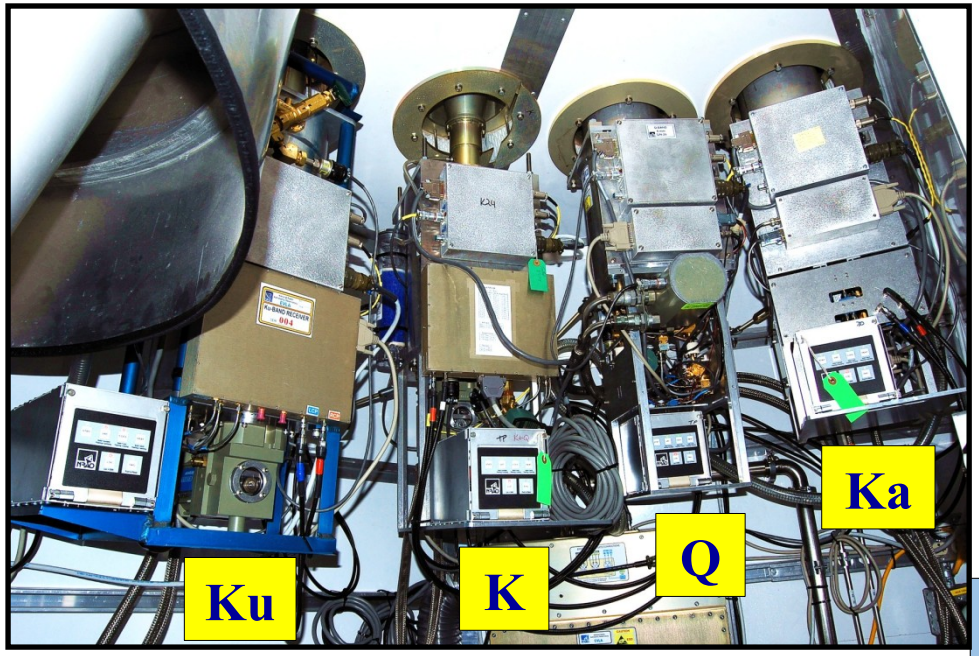
- Two functional modes non-simultaneous
- 8-bit Sampler lower bandwidth/1-2 GHz
- 3-bit Sampler higher band-width/2-4GHz X2
- Transceiver channel fiber modulation for multi-plexing at antenna







# EVLA 1-50 GHz Cryogenic Receivers




**Upper Level**

C = 4 - 8 GHz

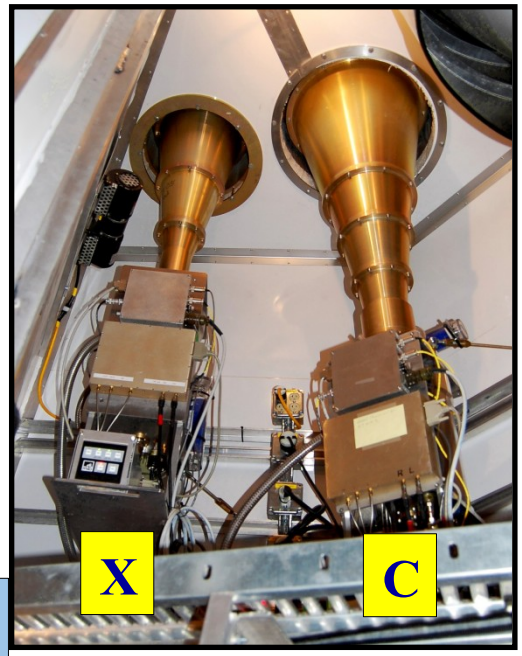
X = 8-12 GHz

Ku = 12-18 GHz

K = 18-26 GHz

Ka = 26-40 GHz

Q = 40-50 GHz



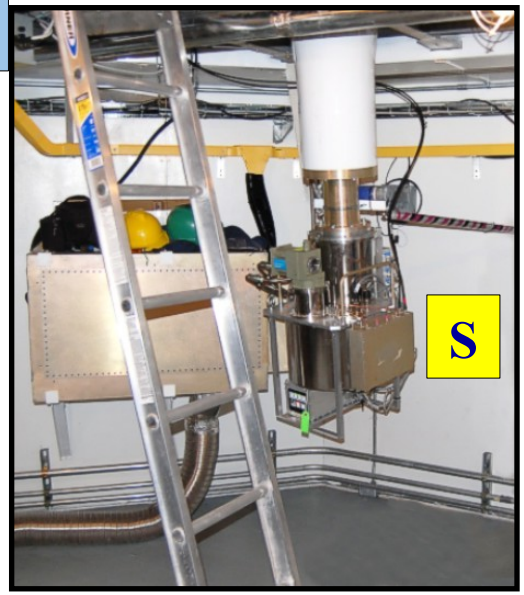

**Vertex Room**


**Lower Level**

L = 1-2 GHz

S = 2-4 GHz

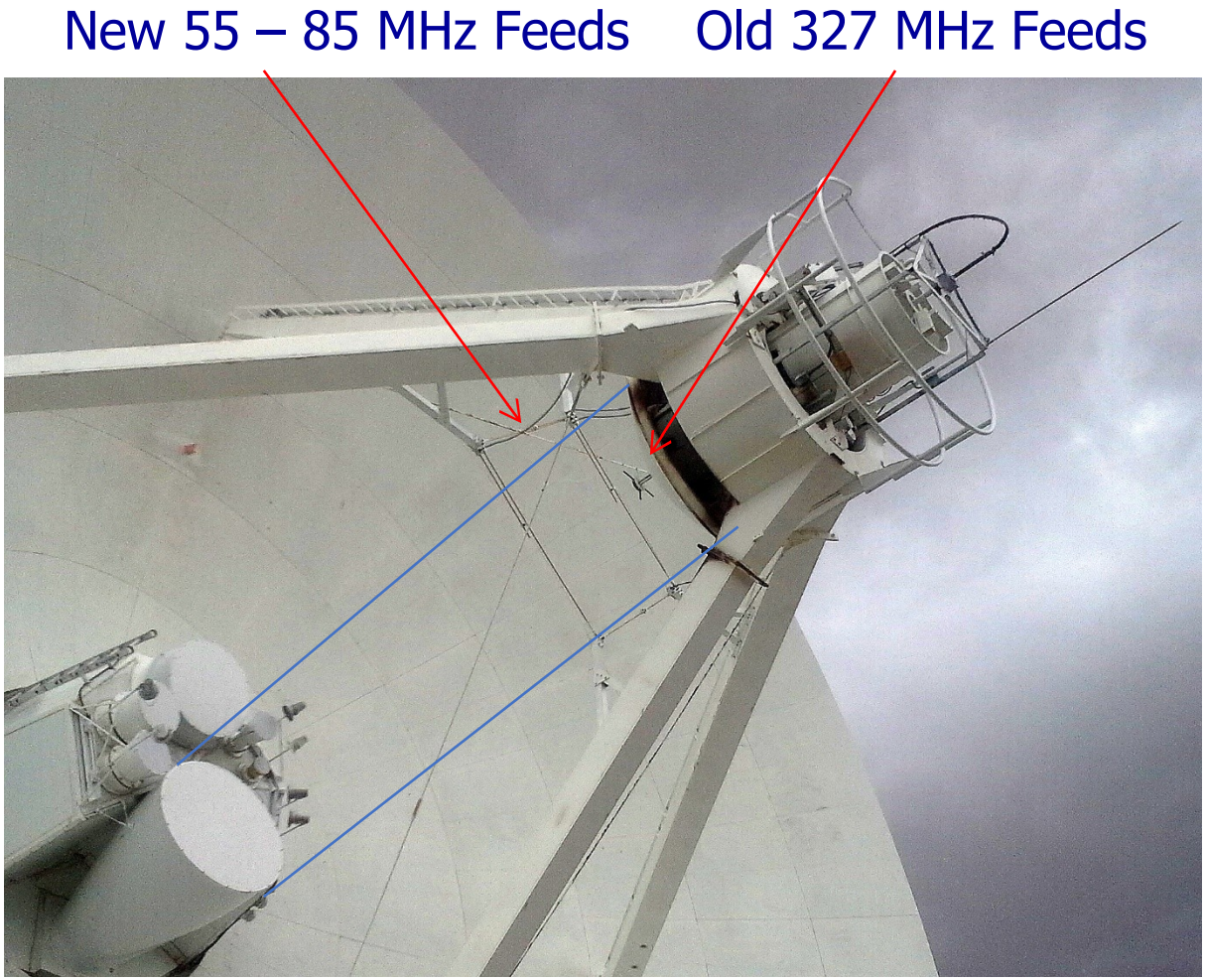
**Total number of EVLA cryogenic receivers = 8 x 30 = 240**




Paul Harden's EVLA Front-End Web Pages - http://www.aoc.nrao.edu/~pharden/fe/fe.htm

# The New Low Band System, and VLITE

- Unlike the Cassegrain bands, the low-frequency system can be operating `24-7'.
- Even though the feed ground plane is 70 cm out of focus, 'decent' sensitivity is available, all the time.
- NRL has led an effort for a full-time commensal low-frequency system on the VLA.

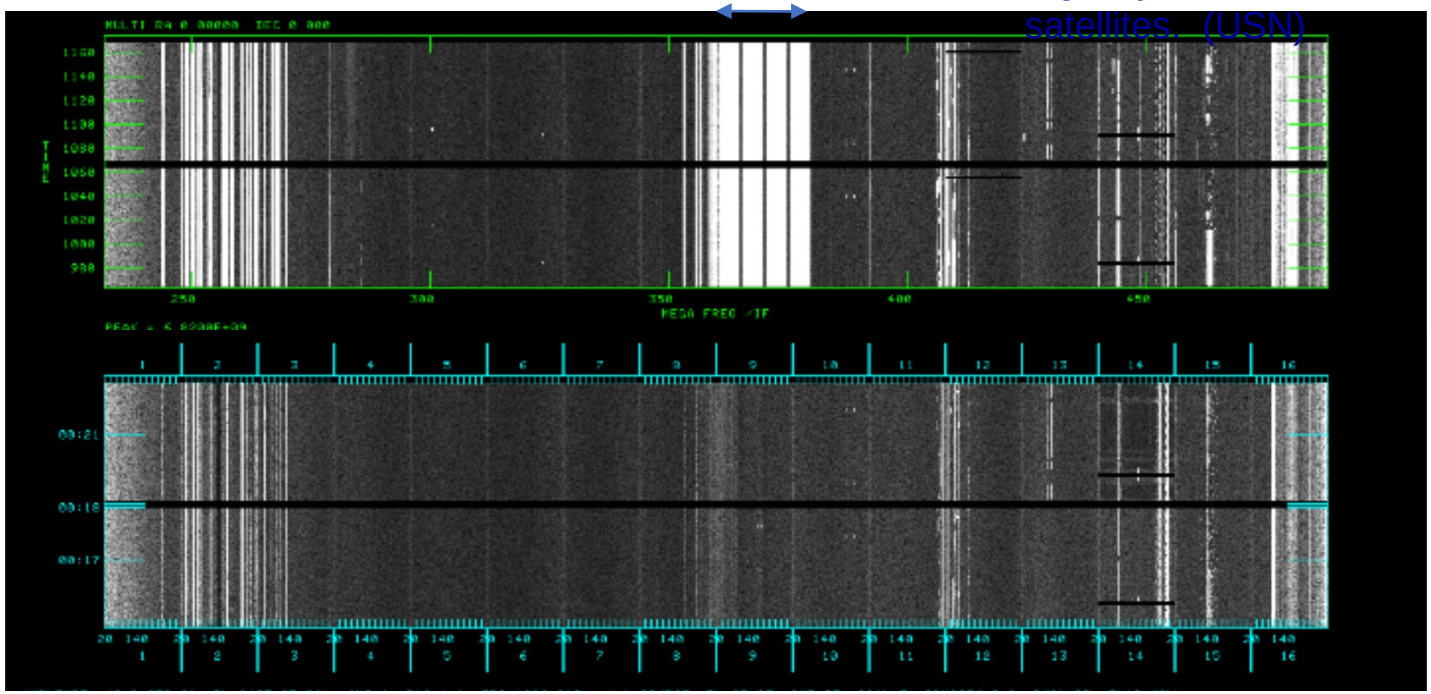


# RFI Spectrum – Not bad …

- No big surprise to learn that the 230 – 486 MHz range contains RFI. Not too bad.
- About 2/3 of the spectrum is useable.
- Two example spectra are shown.

MUOS: Mobile User Objective System.

4 geosynchronous satellites. (USN)



Wideband Interferometric Digital ARchitecture (WIDAR) correlator contributed by Canada

170 KW power, and 120 tons of cooling

17308672 control/monitor bits

1473536 registers

24832 FPGAs

256 boards

16 racks

1 room

Air Conditioners

Ken Sowinski (6'0")

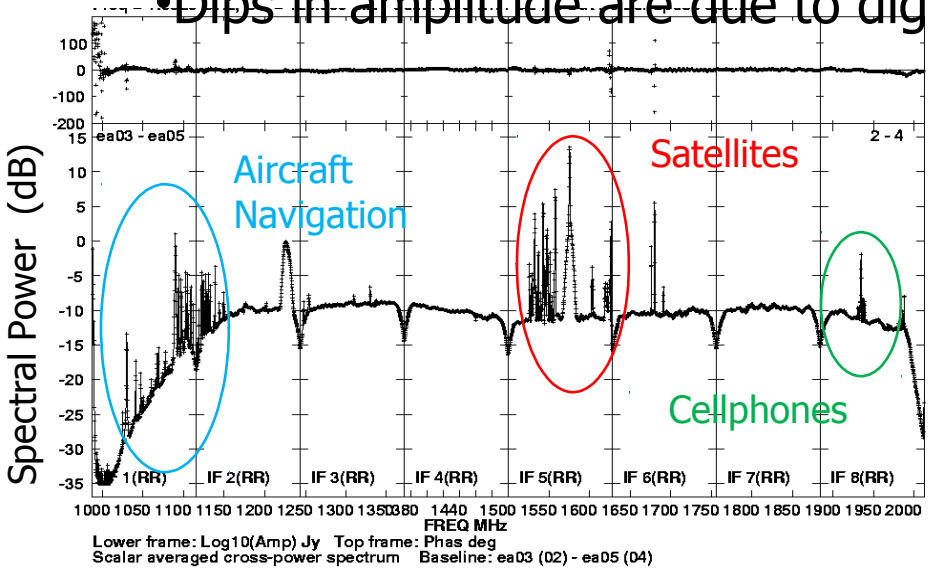
~100 dB Shielded Chamber

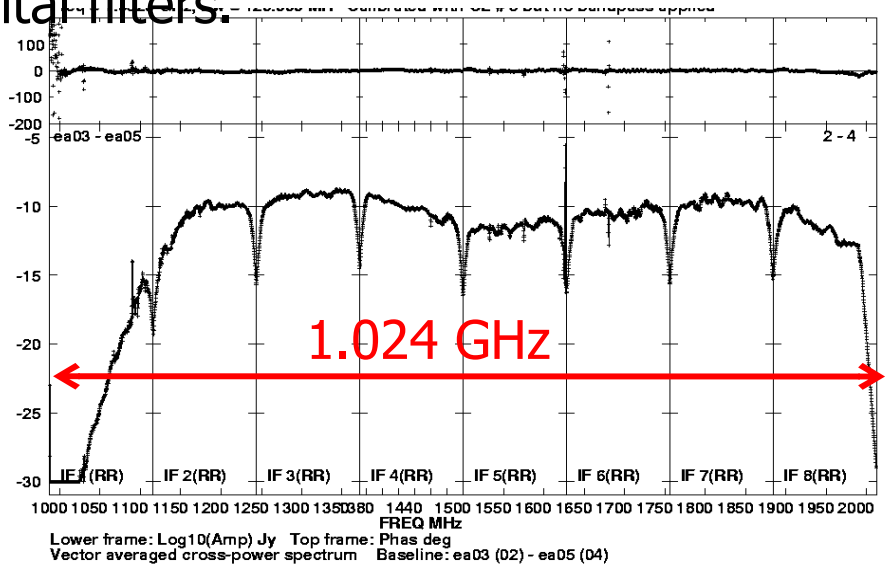
Power Backup/Conditioners

# Spectral Window Continuity

## 8 bit samplers

- Eight continuous subbands, each of 128 MHz, spanning full L-band.
- Only a global delay calibration has been applied.
- Note contiguous phase and amplitudes.
- Dips in amplitude are due to digital filters.



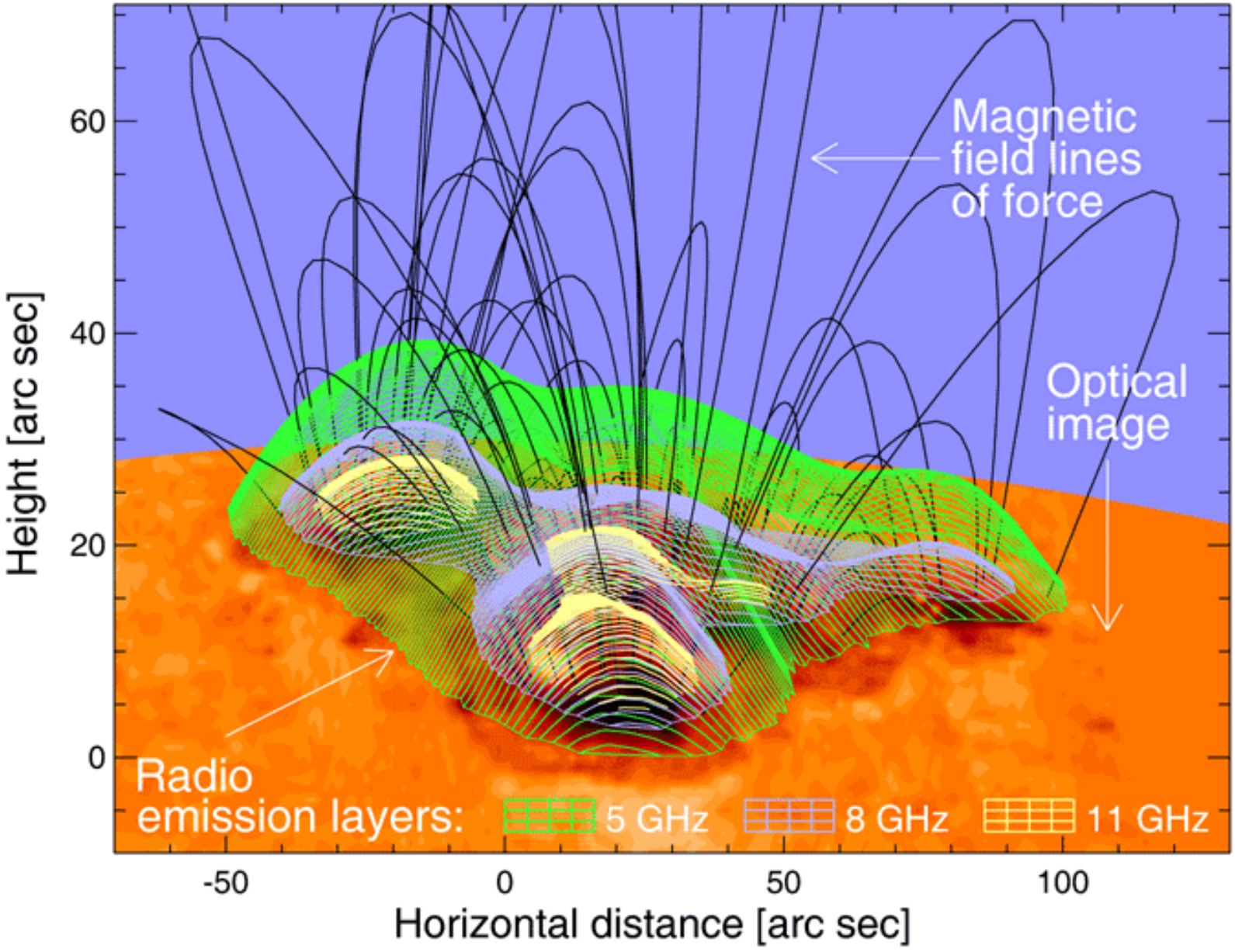




**Ampscalar average** shows the strong RFI: spectral powers nearly a factor of 1000 above noise.

**Vector average** shows how RFI is 'wound down' due to differential phase.

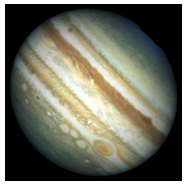
# Brief Tour of the Radio Universe

- Solar System
  - Sun, Planets, Asteroids
- Galactic objects
  - Dark clouds, proto-stellar disks, supernova remnants,
- Galaxies
  - Magnetic fields, neutral hydrogen
- Radio Jets
- The Universe

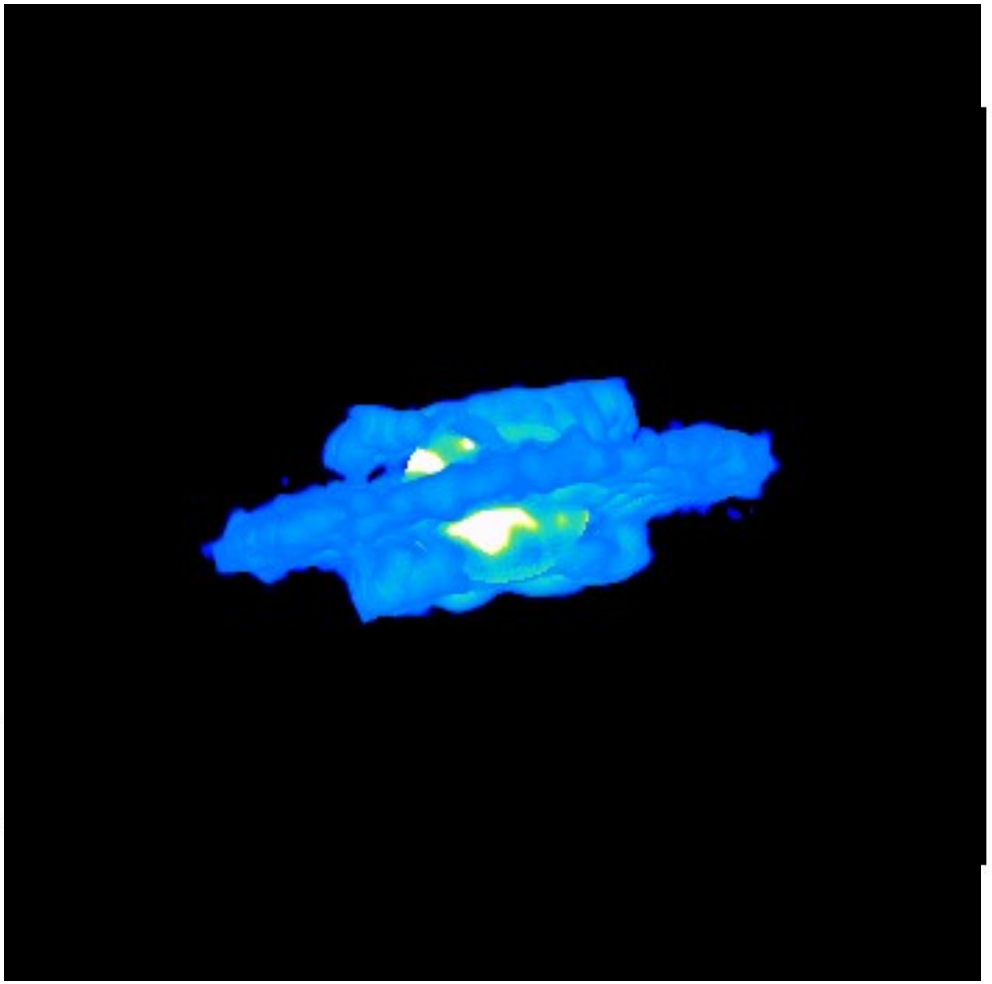

Magnetic
field lines
of force
Optical
image
Radio
emission layers:
5 GHz
8 GHz
11 GHz
Height [arc sec]
60
40
20
0
-50
0
50
100
Horizontal distance [arc sec]

# Jupiter- Synchrotron

Charged particles trapped in Jupiters magnetic field
Similar to earths Van Allen belt



At times, Jupiter outshines the Sun at radio wavelengths – can use this fact for finding extra-solar analogs




Observations: VLA 20 cm

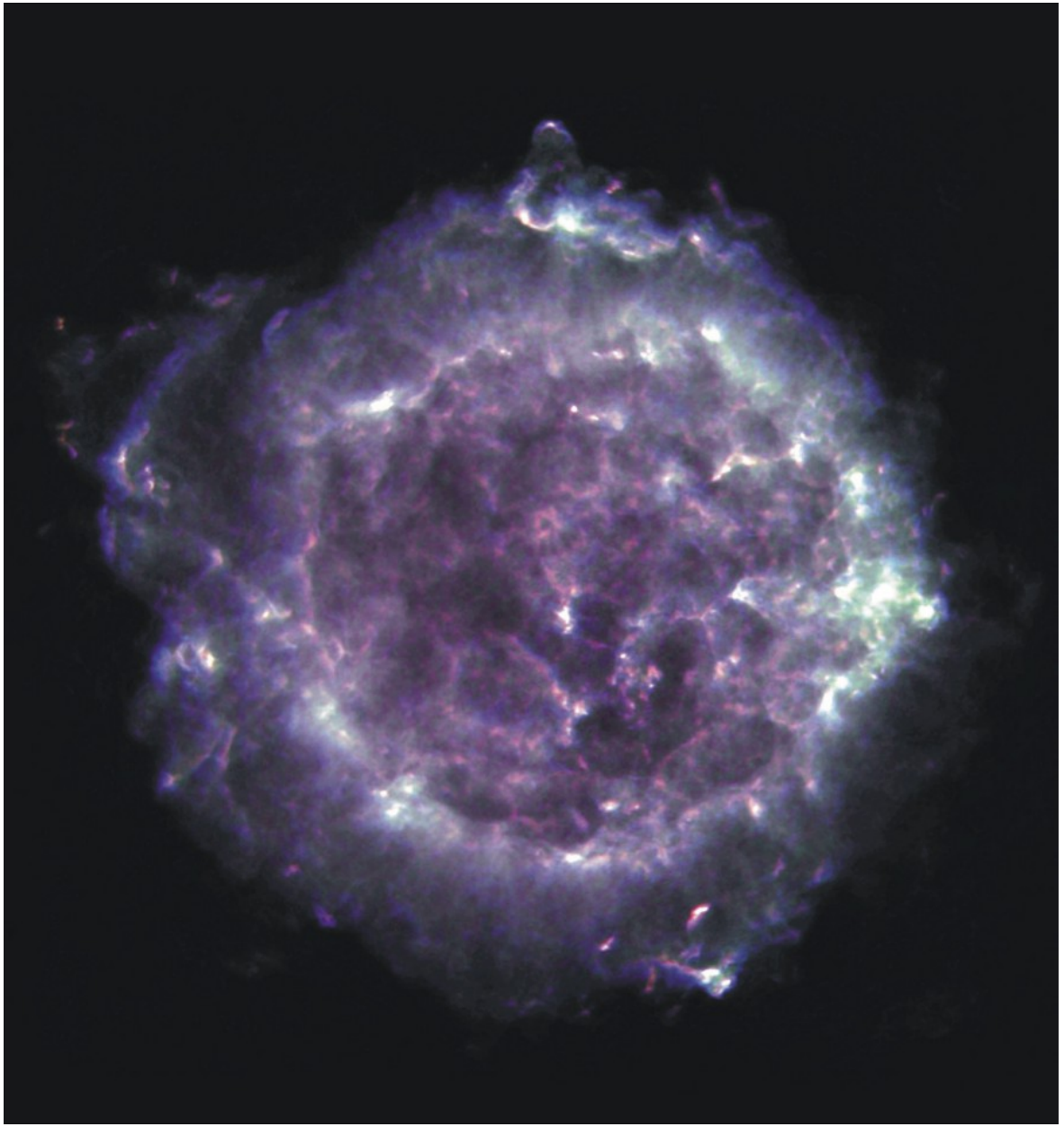
De Pater, Schulz & Brecht 1997

3-D model: Sault et al. 1997; de Pater & Sault 1998

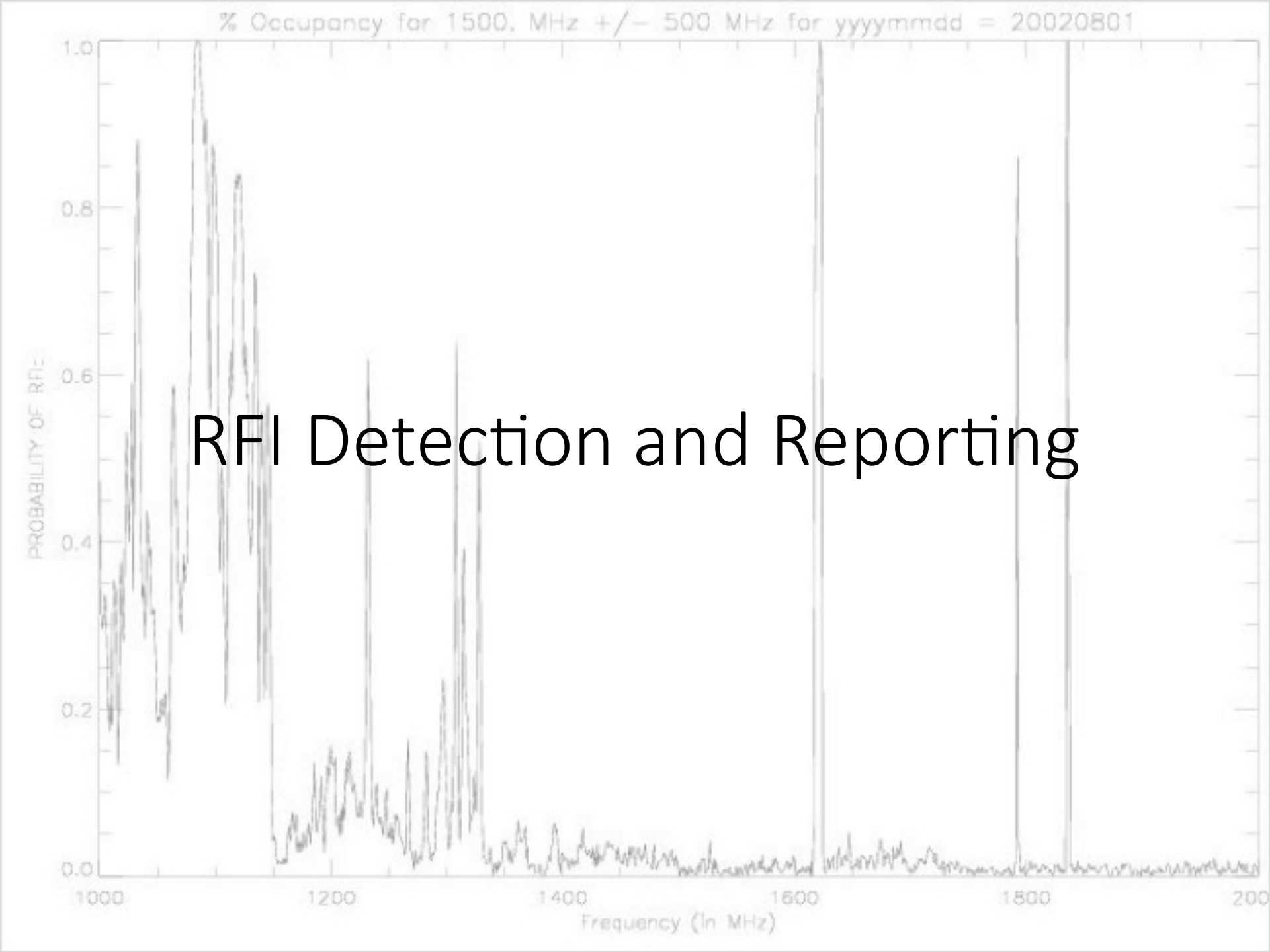
www.atnf.csiro.au/people/rsault/jupiter/movies/

# Cassiopeia A Supernova Remnant

- Remnant of a massive star that exploded ~300 years ago
- VLA image at 1.4, 5, and 8.4 GHz
- Synchrotron emission from tangled magnetic fields



Rudnick et al., Image by T. Rector www.nrao.edu/imagegallery




# RFI Detection and Reporting

September 2018

Power Dividers are Essentials in the Designer's Toolbox p34

Dual-Notch UWB Antenna Suppresses WiMAX, WLAN Noise p46

A Hands-On Look at a New High-Performance Spectrum Analyzer p82

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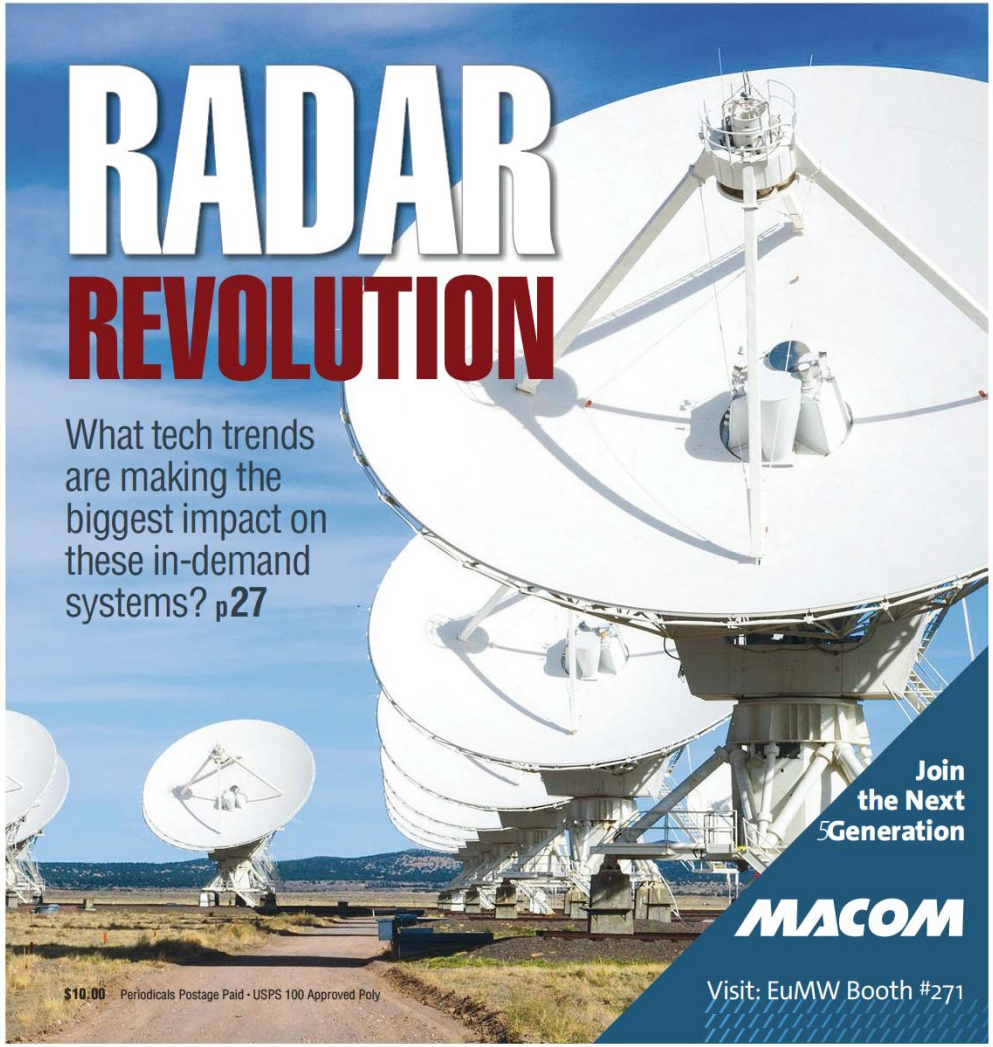


# Protected Bands

First, note that **no** intentional emissions should appear at the VLA from:

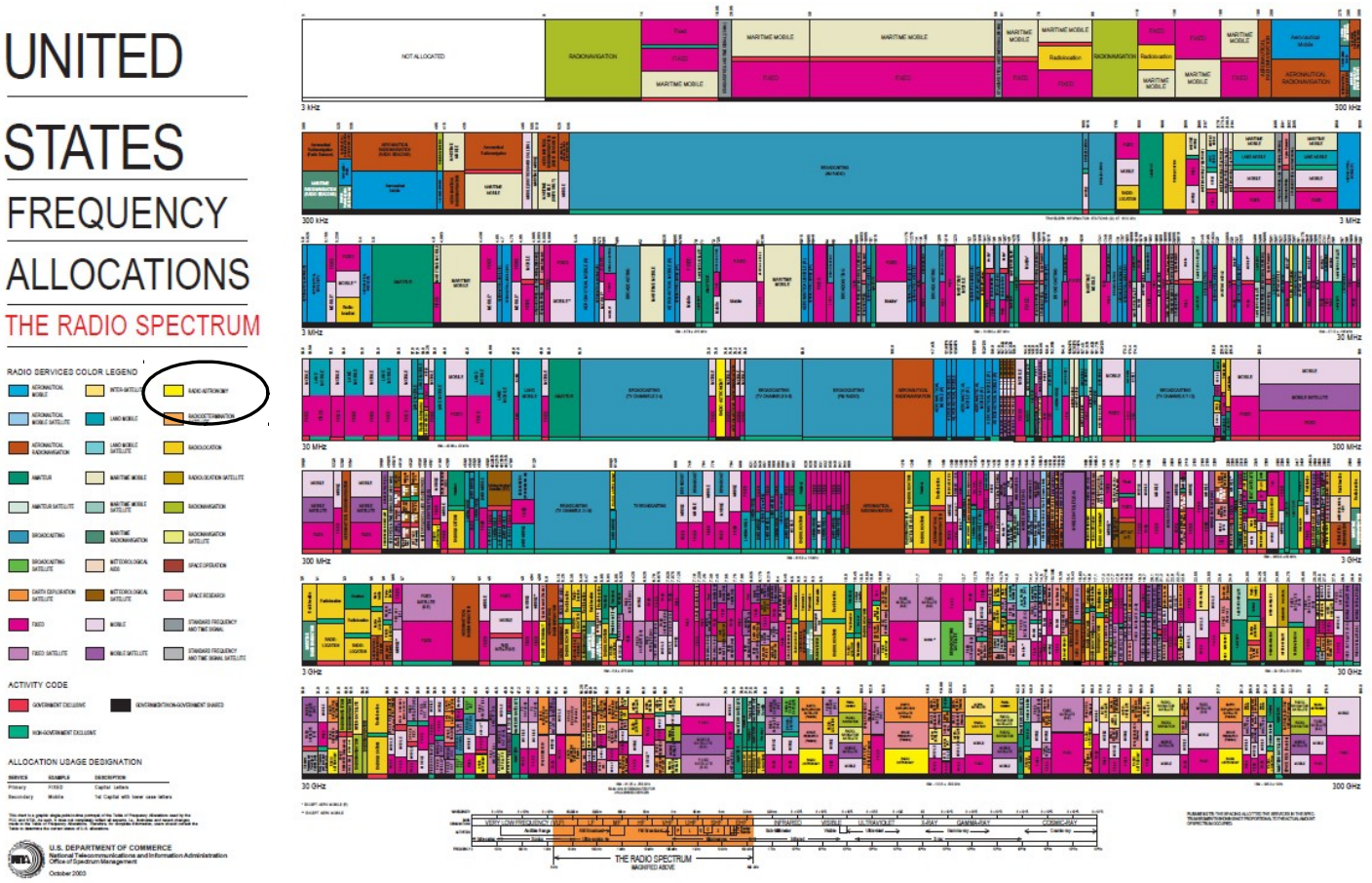
- 73-74.6 MHz (Our "4-band")
- 608-614 MHz ("TV" channel 37)
- 1400-1427 MHz (In our L-band)
- 1610.6-1613.8 MHz (In our L-band)
- 1660.5-1668.4 MHz (In our L-band)
- 2690-2700 MHz (In our S-band)
- 4990-5000 MHz (In our C-band)
- 10,680-10,700 MHz (In our X-band)
- 15,350-15,400 MHz (In our Ku-band)
- 23,600-24,000 MHz (In our K-band)
- 31,300-31,500 MHz (In our Ka-band))

(See 47CFR 2.106 @ http://www.fcc.gov/oet/spectrum/table/fcctable.pdf)

All other frequencies within the EVLA tuning range are allocated to external users!
(However, that doesn't mean that we should expect RFI everywhere else.)

# Protected Bands

(Available @ http://www.ntia.doc.gov/osmhome/allochrt.pdf)

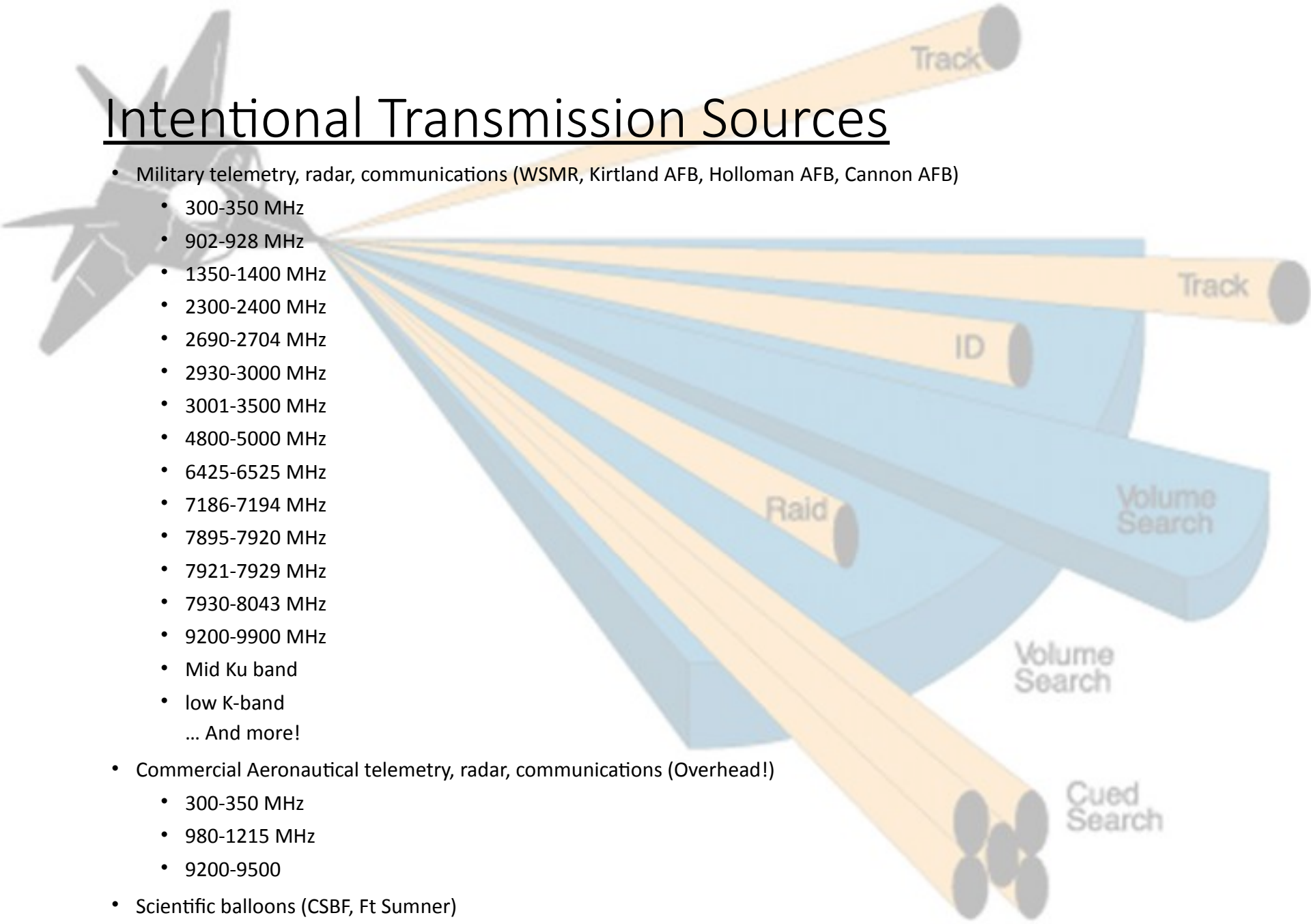


# Davenport Lookout

# Intentional Transmission Sources

- Military telemetry, radar, communications (WSMR, Kirtland AFB, Holloman AFB, Cannon AFB)
  - 300-350 MHz
  - 902-928 MHz
  - 1350-1400 MHz
  - 2300-2400 MHz
  - 2690-2704 MHz
  - 2930-3000 MHz
  - 3001-3500 MHz
  - 4800-5000 MHz
  - 6425-6525 MHz
  - 7186-7194 MHz
  - 7895-7920 MHz
  - 7921-7929 MHz
  - 7930-8043 MHz
  - 9200-9900 MHz
  - Mid Ku band
  - low K-band

    … And more!
- Commercial Aeronautical telemetry, radar, communications (Overhead!)
  - 300-350 MHz
  - 980-1215 MHz
  - 9200-9500
- Scientific balloons (CSBF, Ft Sumner)
  - 1427-1530 MHz + S-band

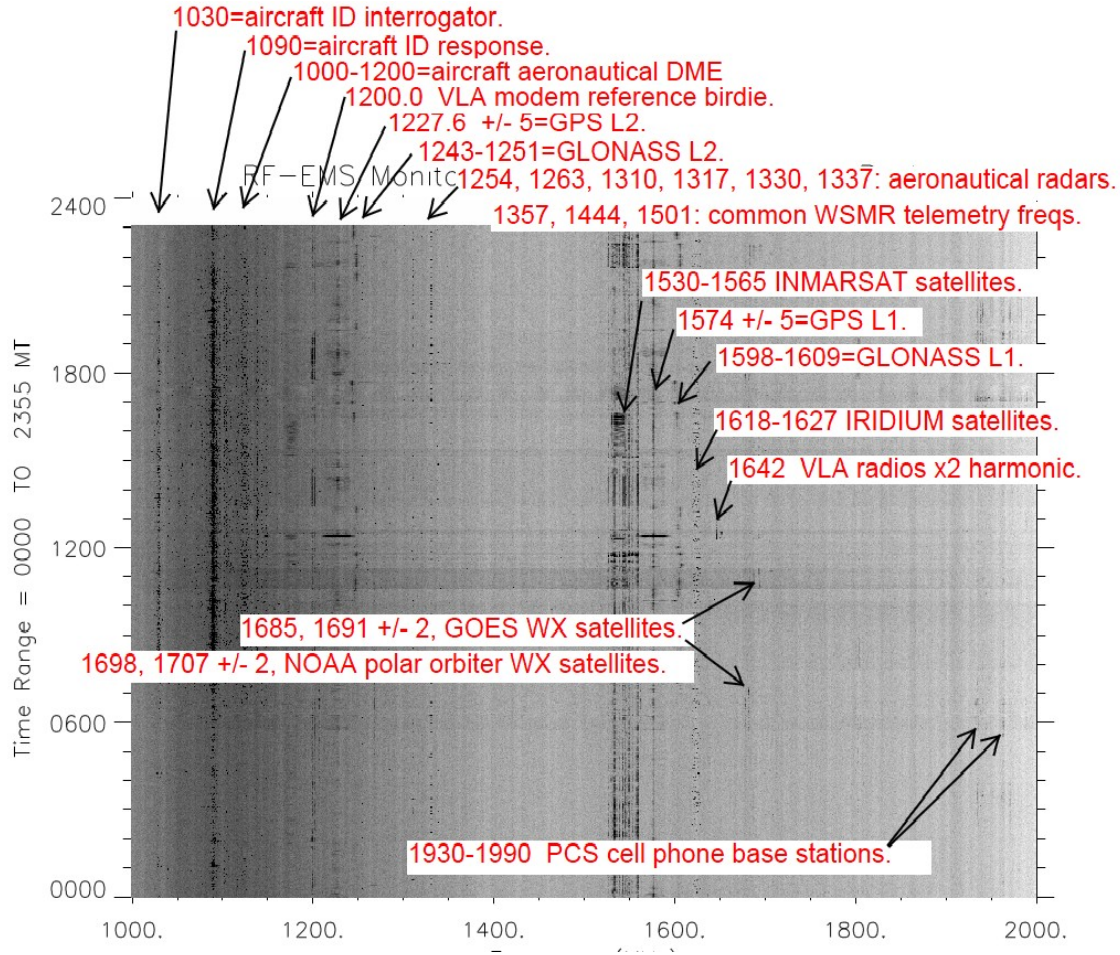


# Intentional Transmission Sources, Continued

- Radiosondes (WX balloons) @ 1670-1680 MHz—Worldwide launch near 00:00 & 12:00 UTC + 1.5 hours.
- Wireless car keys, tire pressure monitoring systems, etc. @ 315±5 MHz—Very intermittent.
- Air Route Surveillance Radars (ARSR), weather radars, etc.—Rotating—very intermittent.
  - 1250—1350 MHz (L-band ARSR)
  - 2700-2900 MHz (S-band Nextrad weather radars)
  - 5600-5650 MHz (C-band Doppler weather radars)
- Border surveillance Radars—TARS—1250 MHz- 1350 MHz.

- Satellites
  - Earth Resource Radars—Very strong. We need to prevent beam-on-beam!
    - CryoSat @ 13,250-13,750 MHz
    - TandemX/TerraSar @ 9300-9800 MHz
    - COSMO-SkyMed @ 9300-9800 MHz
    - RadarSat-2 @ 5350-5460 MHz
  - Radiolocation—Many satellites in low or mid earth orbit
    - GPS @ 1227.6 ±5 MHz, 1381 ± 1 MHz, 1575.4 ±5 MHz
    - GLONASS @ 1242.9375 MHz to 1248.625 MHz, 1598-1605 MHz
  - Communications/Data—space to earth downlink bands:
    - 1525-1560 MHz (MSS-INMARSAT)
    - 1616-1627 MHz (MSS—IRIDIUM, GLOBALSTAR) —Many satellites in low or mid earth orbit
    - 3600-4200 MHz (FSS—Network feeder links)
    - 11,700-12,200 MHz (FSS—Network feeder links)
    - 18,300-20,200 (FSS—Wildblue )
  - Broadcast Satellite Services:
    - 2320-2359 MHz (XM/Sirius radio)

# Intentional Transmission Examples



# Unintentional Transmission Sources

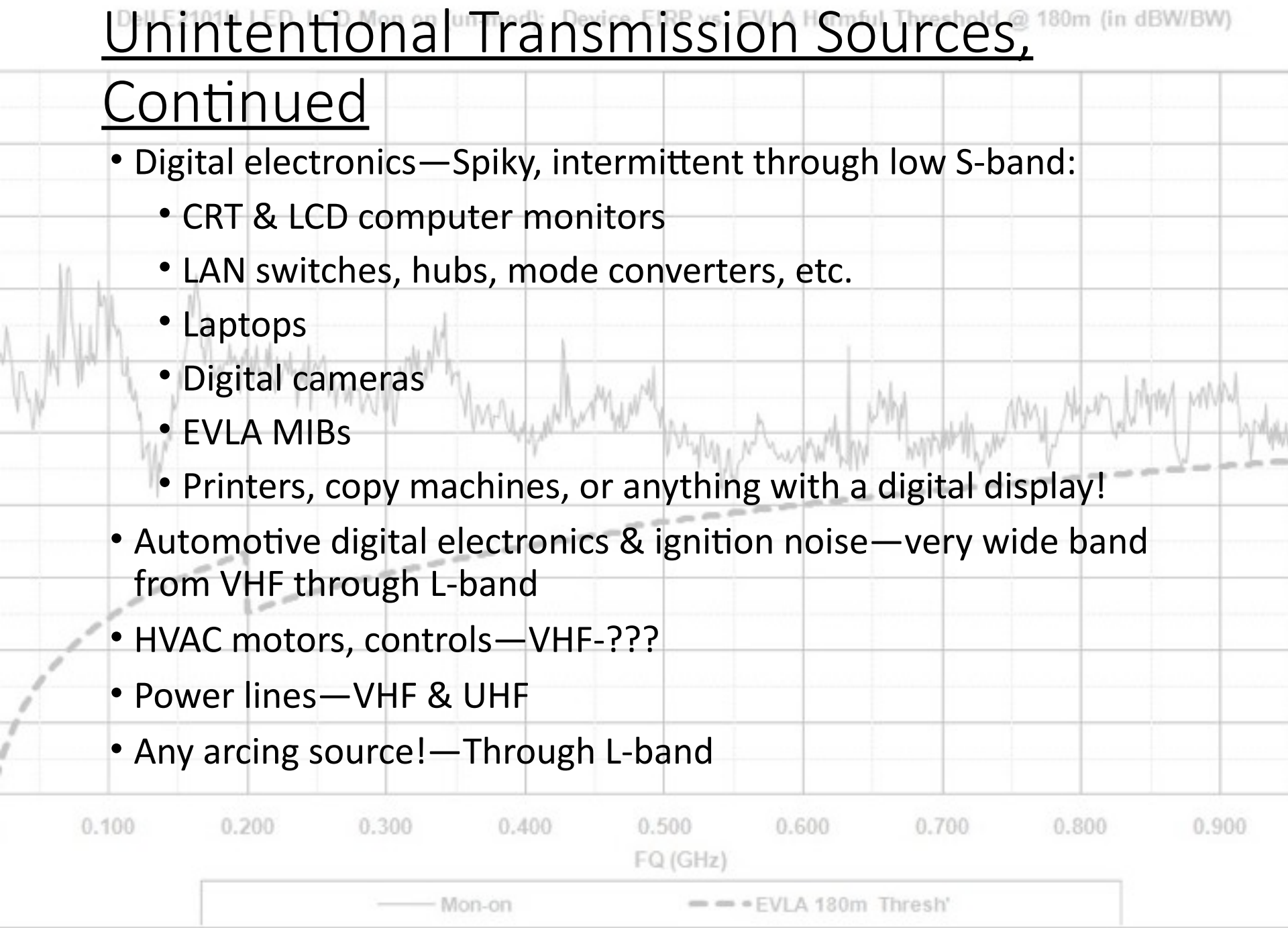
- Harmonics:
  - 2-way radios
  - Broadcast stations (TV, FM Radio)
  - Cell phones
  - LO leakage

  (NOTE: Old site radios @ 154.025 MHz seen @ x9, x10, & x11!)
- Malfunctions—Commercial equipment meant to operate at 1 frequency, within a specified bandwidth (BW) starts to operate out-of-band (OOB), or with a wider BW.
- LO Leakage—Our EVLA frequency conversion electronics occasionally have isolation problems.
- Wild oscillations—LNA & other EVLA circuitry start oscillating far OOB.

(P-band LNA have often radiated in X-band, and X-band LNA have been found to radiate in Ka Band!)

# Unintentional Transmission Sources, Continued

- Digital electronics—Spiky, intermittent through low S-band:
  - CRT & LCD computer monitors
  - LAN switches, hubs, mode converters, etc.
  - Laptops
  - Digital cameras
  - EVLA MIBs
  - Printers, copy machines, or anything with a digital display!
- Automotive digital electronics & ignition noise—very wide band from VHF through L-band
- HVAC motors, controls—VHF-???
- Power lines—VHF & UHF
- Any arcing source!—Through L-band



# Un/Intentional Transmission Characteristics

- Intermittent or varying strength
  (exceptions: carrier harmonics, beacons, etc.).
  Usually noticed by Tsys or total power fluctuations at the T304 .
- Spectrally limited (exceptions: UWB).
  Can be verified using:
  - W8 monitor @ http://www.vla.nrao.edu/cgi-bin/rfi.cgi
  - Bandpass plotter tool @ https://mctest.evla.nrao.edu/cgi-bin/evla/bp1.cgi
- Power varies with antenna, antenna Pointing, or polarization (but not always!).

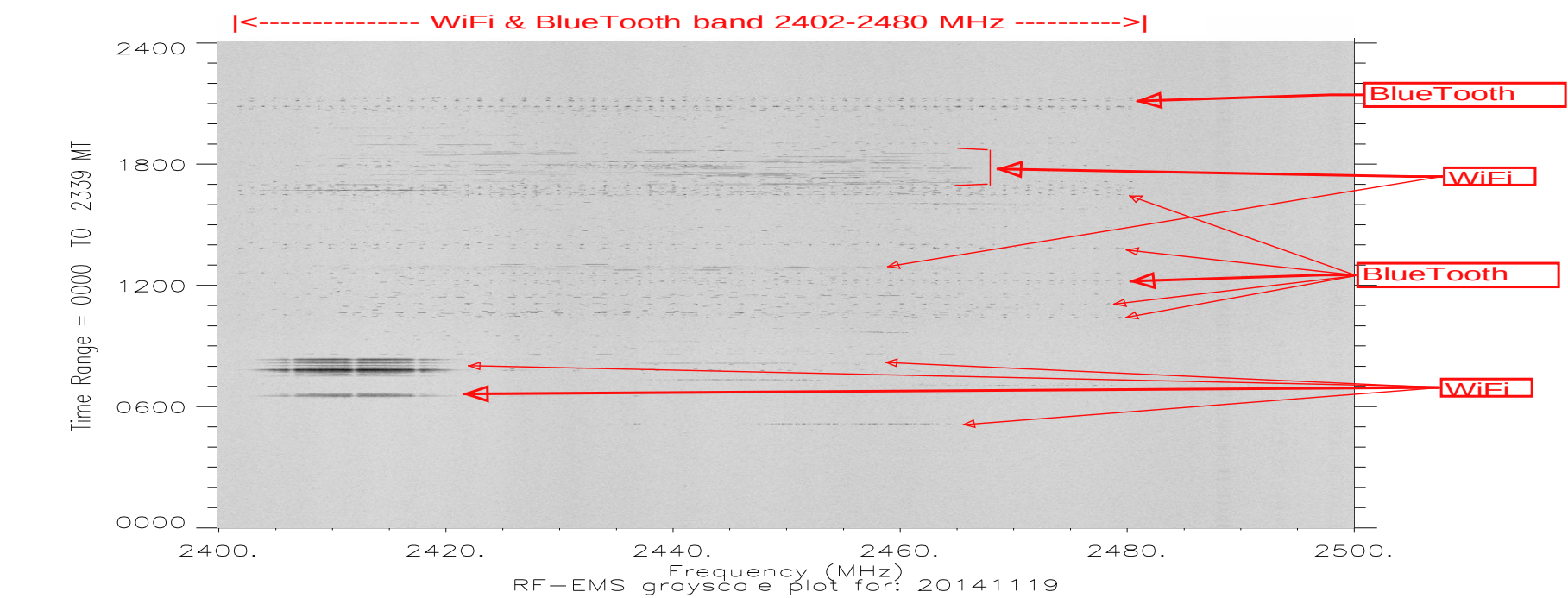
# RFI Reporting

- Needed characteristics:
  - Frequency—Specific, if possible.
  - Band Width—Specific if possible.
  - Strong/weak?—Relatively speaking.
  - Time(s) of detection(s).
  - Duty Cycle—Intermittent or continuous?
  - Pointing???

# RFI Monitoring Stations

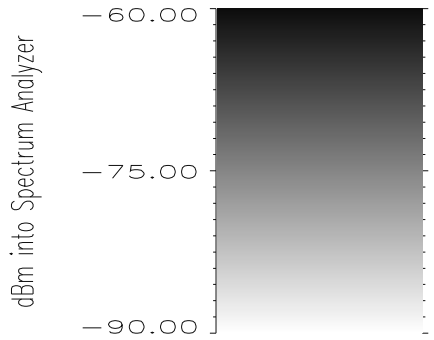
- “RF-EMS Monitor”
- “RF DFS Monitor”
- “W8 Monitor”
- “MK Monitor” (Mauna Kea)

# WiFi & BlueTooth (2.4 GHZ) RFI during the 19 November, 2014 Sky Photography Session at the VLA



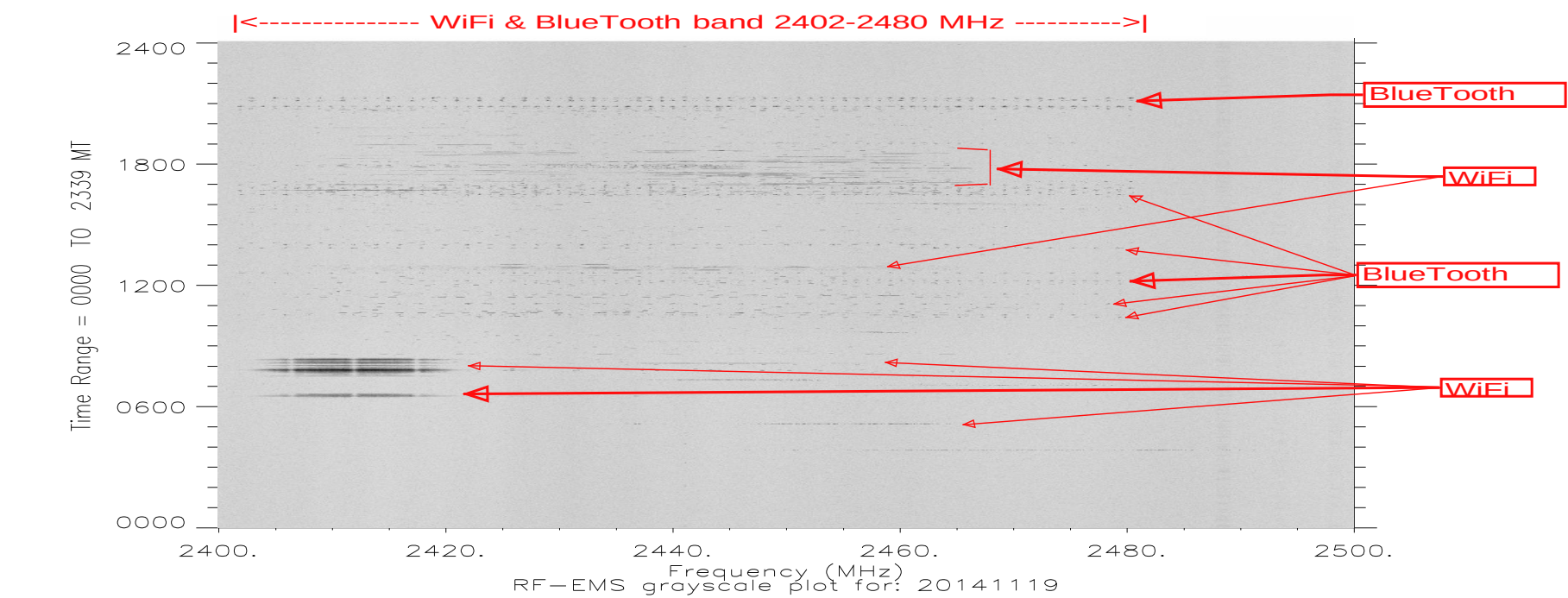






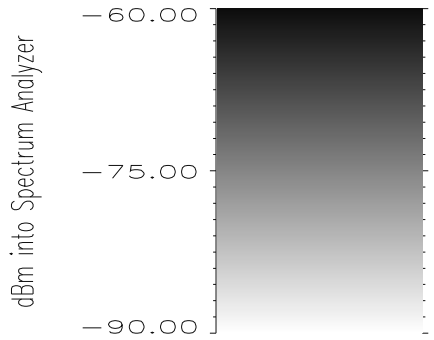

plot center frequency = 2450.0 MHz
Pk Hold or sampling interval period = 1 min
frequency span = 100.0 MHz
resolution bandwidth = 30. KHz
video filter = 30. KHz
input attenuation = 0 dB
notes: None
Special 1. min pk—hold or sampling data acq mode

# WiFi & BlueTooth (2.4 GHZ) RFI during the 19 November, 2014 Sky Photography Session at the VLA







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Special 1. min pk—hold or sampling data acq mode

# RF Emissions Characterization in a RF Reverberation Chamber

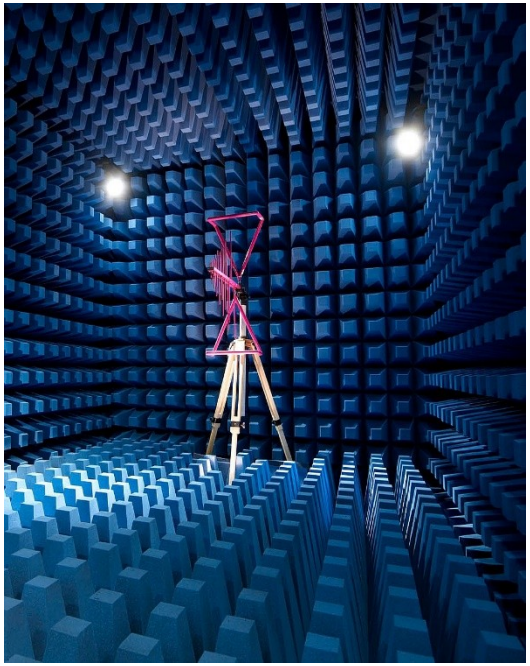
Dimensions: 4.9m x 11m x 3m

# Testing Environment Overview

(Main topic = RF radiated emissions (RE) testing in a Reverberation Chamber (RC), but first …)

A quick review of RF testing environments is usually deemed necessary:

Open Area Test Site ◊ Indoor Acoustic Test Range ◊ Reverberation Chamber



Testing Environment Overview

Open Area Test Site (OATS) for radiated emissions testing:

**Advantages**:

"Free-space" ideal

Accepted results

**Disadvantages:**

RFI confusion (and on/off testing often won't help!)

Environmental—dust, wind, thermal/sun affect results, and equipment!

Scheduling & set-up/breakdown

# Reverberation Chamber for radiated emissions testing:

**Advantages**:

No quiet-zone concern—there is no quiet zone!

Lower cost—no RF absorbing foam to purchase and install

Higher sensitivity—sometimes too much!

Aspect angle insensitivity—excellent for RE & EMC measurements

**Disadvantages**:

Acceptance—no commercial standards currently reference it

Calibration—careful calibration required

Statistically-based results—not easily correlated to OATS or IATR results

Aspect-angle insensitivity—makes shielding debug difficult

# RC facilities and equipment:

TX antenna & feedline

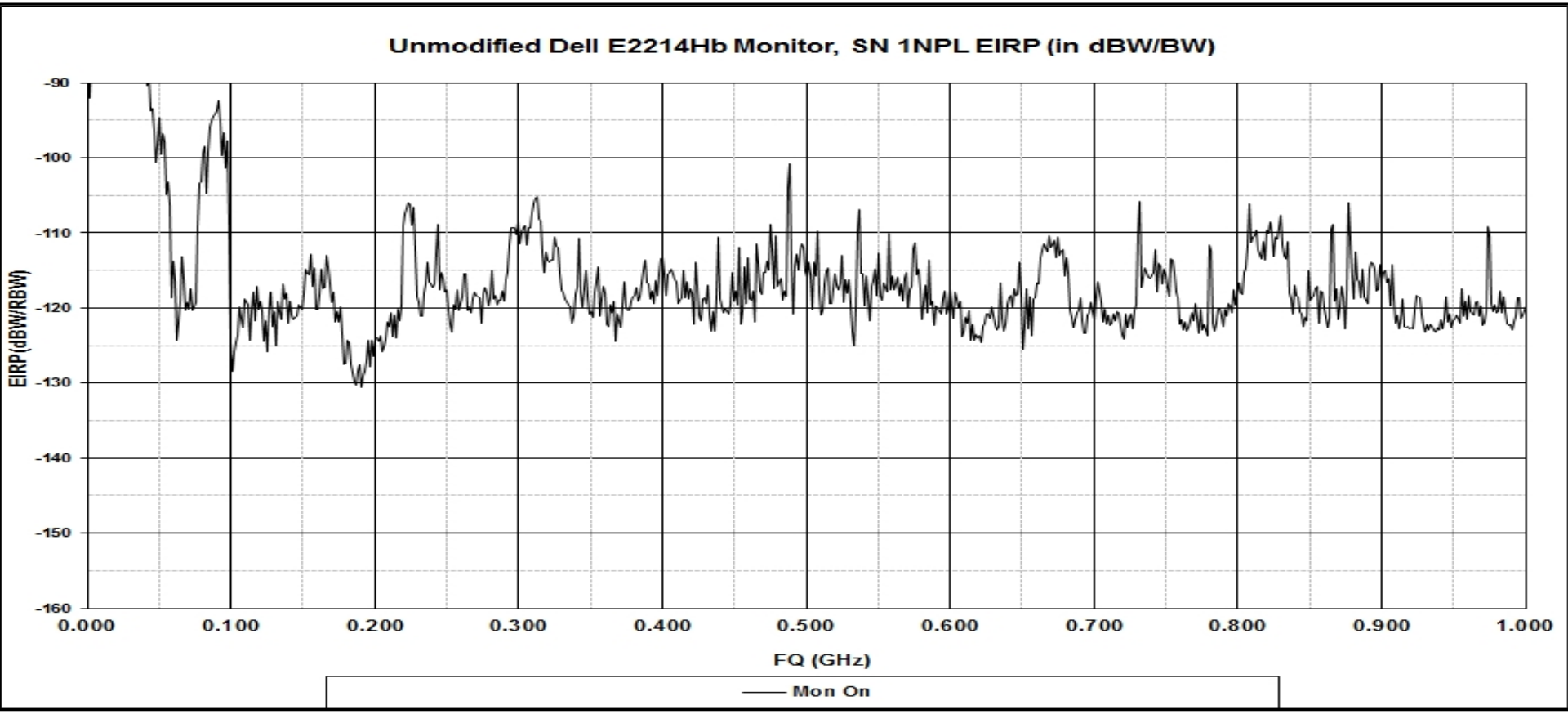
UWB RX antenna & feedline

Mode stirrer

Outside feedthrough

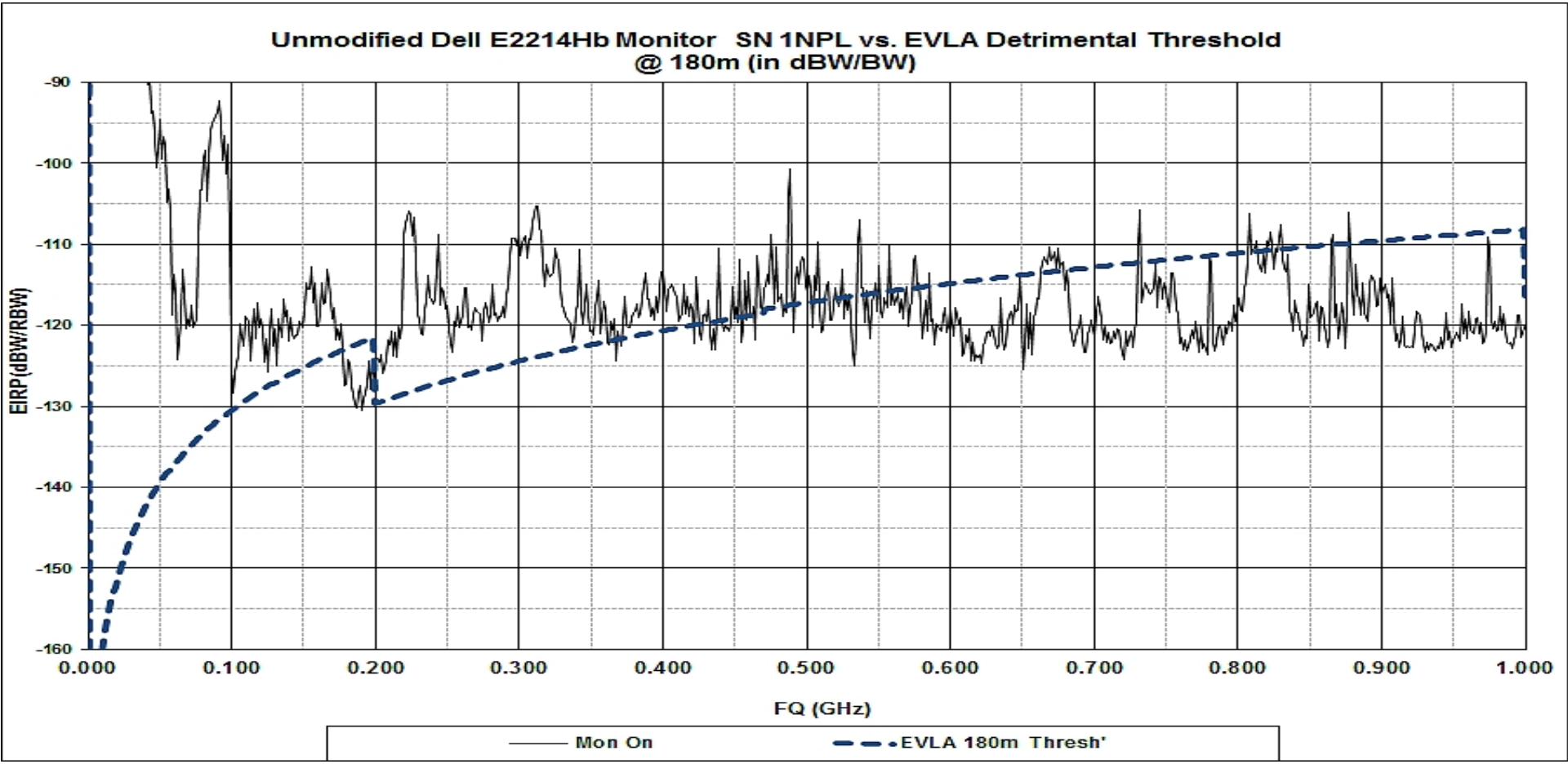
Inside feedthrough + fiber pipe

# RC facilities and equipment, RE measurement: RC RE plot



# Equipment interference potential analysis, … as “simple” as 1, 2, 3:

And finally, plotting the results together,



# So What's Next for Radio Astronomy?

- 2003-2014:
  - EVLA: made the VLA ten times better
  - ALMA: VLA for the sub-millimeter
  - ATA: SETI lives on
  - LOFAR: low frequency array
- 2008-2030+
  - ngVLA
  - SKA: collecting area of 75 VLA's

# Atacama Large Millimeter Array

EuB

A project of the National Science Foundation and the National Research Foundation of Canada through the North American Project for Radio Astronomy via its partners, Associated Universities, Inc. operating the National Radio Astronomy Observatory, and the Herzberg Institute of Astronomy and the European Southern Observatory and its partners The Centre National de la Recherche Scientifique (CNRS), France; Max Planck Gesellschaft (MPG), Germany; The Netherlands Foundation for Research in Astronomy, (NFRA); Nederlandse Onderzoekschool Voor Astronomie, (NOVA); The United Kingdom Particle Physics and Astronomy Research Council, (PPARC);The Swedish Natural Science Research Council, (NFR); and the Ministry de Ciencia y Tecnologia and Instituto Geografico Nacional (IGN,)(Spain)

Array of **66** precision engineered antennas deployed in the Atacama desert in the high Andes in Chile. It is a **configurable array**.

**Elevation:** 5000m(16,000ft)

**Telescope Diameter:** 12m

**Cost:** $1.4B

Al Wootten, ALMA/US Project Scientist

# The Allen Telescope Array

- First telescope designed specifically for the Search for Extra-Terrestrial Intelligence (SETI)
- Array of 350 commercial satellite dishes, 6m in diameter. More collecting area than the GBT
- Speeds SETI targeted searching by 100x
  - Targets from 100,000 to 1 million nearby stars
  - Scans 100 million radio channels

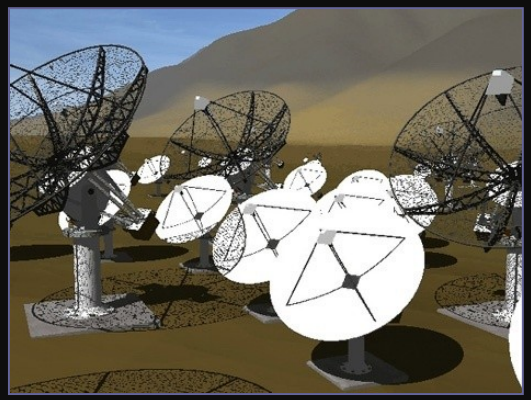
www.seti-inst.edu/seti/our_projects

# More Radio Instruments:


## 2008: Low-Frequency Array (LOFAR)

A low-frequency (10-240 MHz) multi-beam-forming array composed of ~100 antenna "stations" each containing ~100 individual antenna, spread over an area of ~400 km. Completed in 2012

www.lofar.org



## 2009: Frequency Agile Solar Radiotelescope (FASR)

A multi-frequency (~0.1 - 30 GHz) imaging array composed of ~100 antennas for imaging the Sun with high spectral, spatial, and temporal resolution.

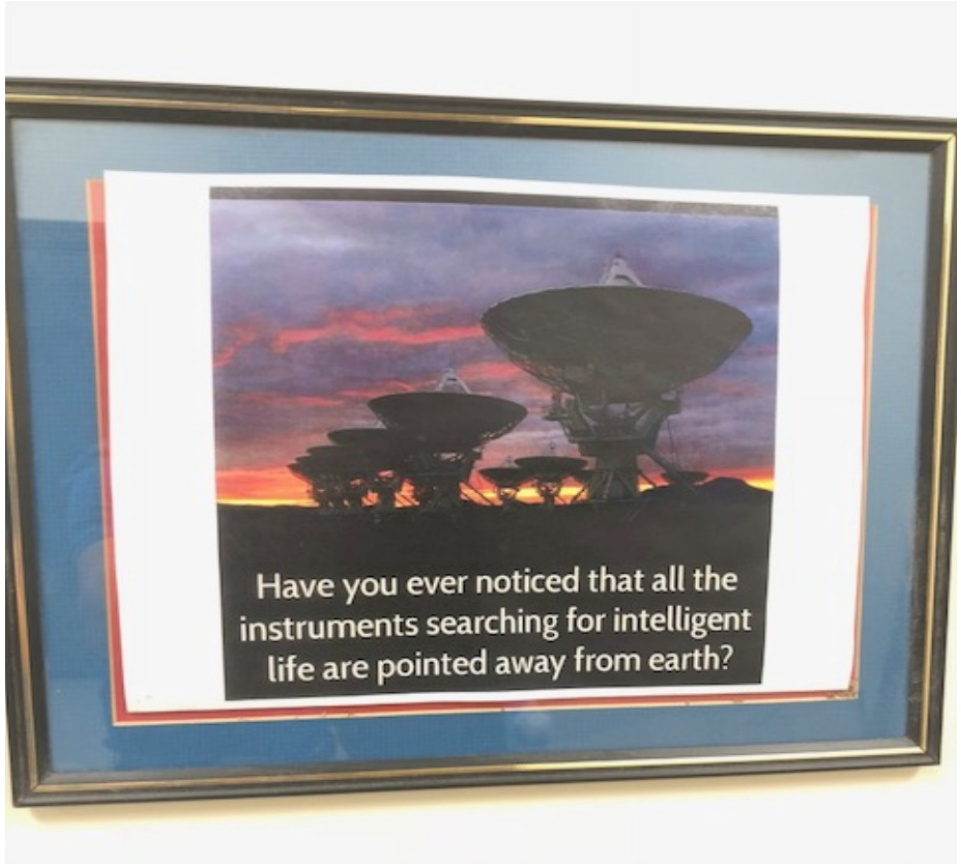
## 2030?: Square Kilometer Array (SKA)

A multi-frequency (~0.1 - 3 GHz?) imaging array with a collecting area of 1 square kilometer.

www.skatelescope.org

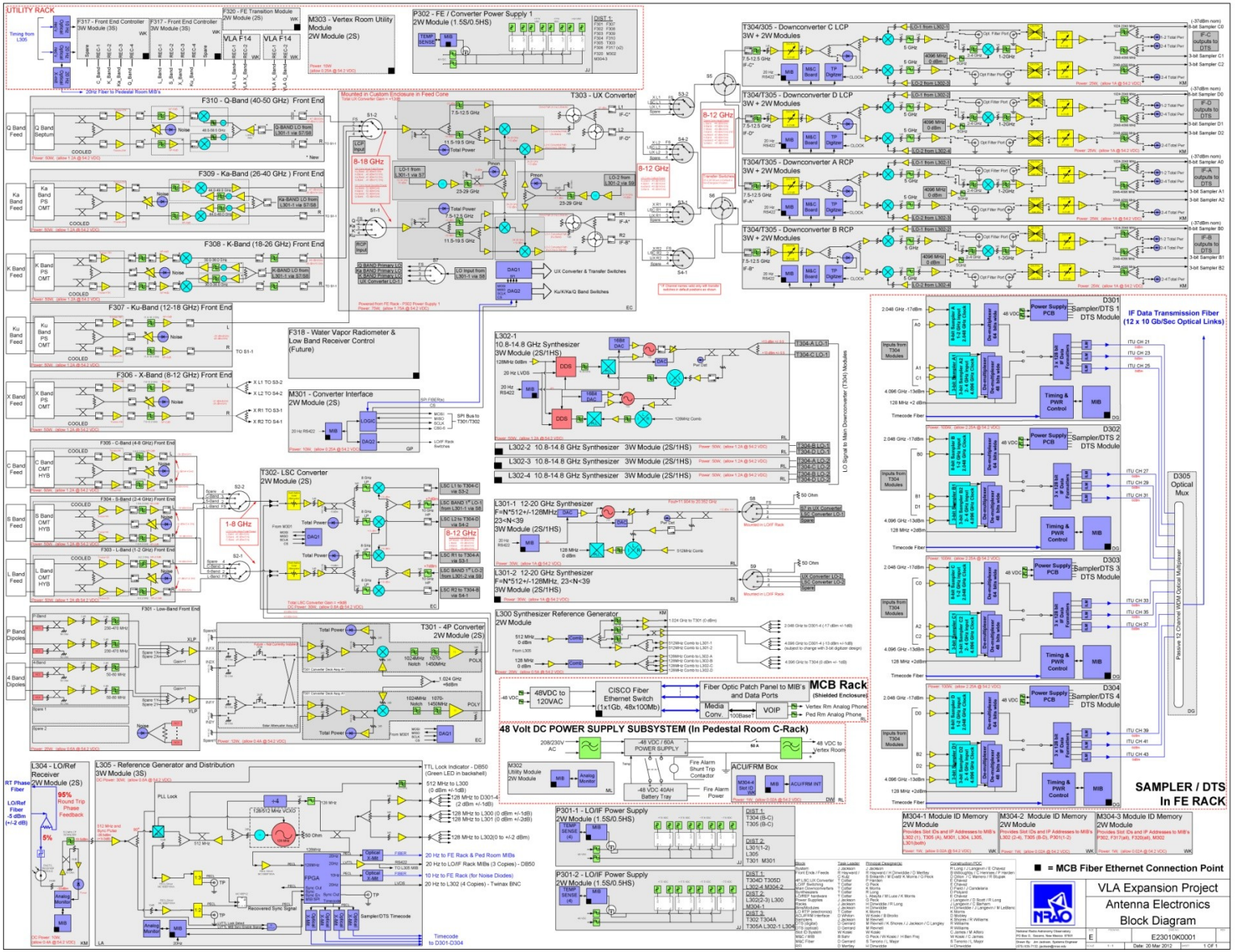
# Conclusions

- Radio astronomical imaging is a relatively young, but rapidly advancing field which will explode in the next decade
- You don’t have to have a well-funded P.R. machine to churn out fascinating science



# Questions?

# EVLA Antenna Block Diagram



# EVLA Control building diagram