Modeling the interferometer response to Satellite RFI

Urvashi Rau , 11 Feb 2022 , ARDG Discussion Forum, NRAO

– Context

– Modeling the interferometer response

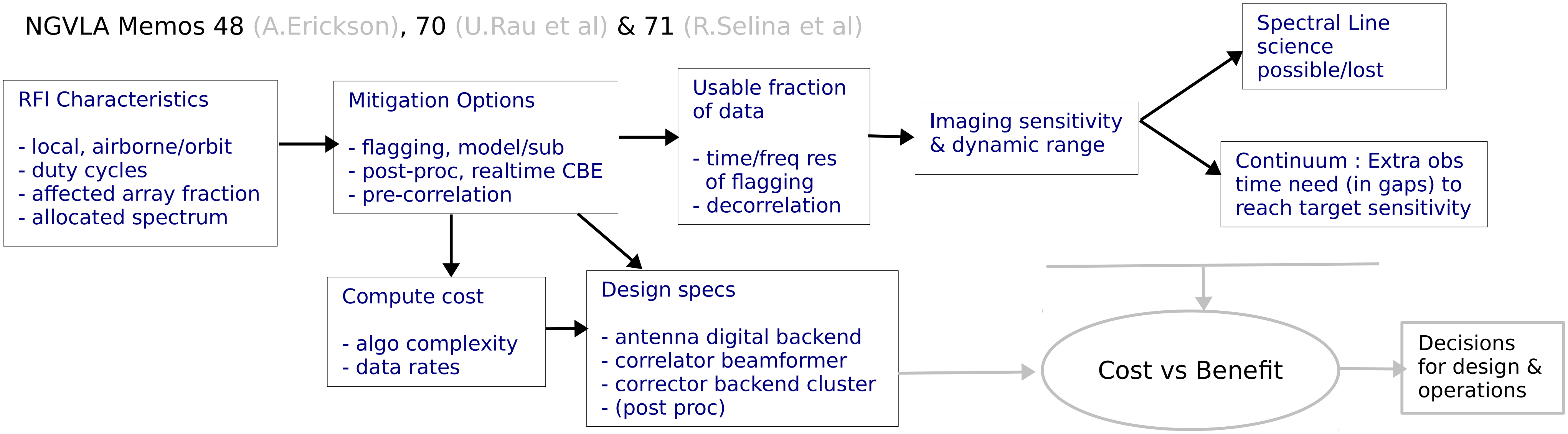
  – Power measured at each antenna
  – Attenuation due to the interferometer response
  – Effect on imaging

– Tests and Results

  – User Terminals
  – Satellite illumination of the VLA
  – Monitoring program

Context – ngVLA System Design

NGVLA Memos 48 (A.Erickson), 70 (U.Rau et al) & 71 (R.Selina et al)



Context – ngVLA System Design

RFI Impact Simulator for the Next Generation VLA

RFI Characteristics

Type of RFI	Array Visibility	Time Fraction	Sig Len (s)	Sig Gap (s)	Chan Width (kHz)	
People	['outlier', 'core']	[0.9, 0.4]	0.001	0.01	20000.0	
UWB	['outlier', 'core']	[0.9, 0.2]	1e-09	1e-07	900000.0	
UWBcar	['outlier', 'core']	[0.2, 0.03]	1e-09	1e-07	8000000.0	
Cell 5G	['outlier', 'core', 'full']	[1.0, 0.2, 0.2]	0.0001	0.0	200.0	
LEO Sat	['full']	[0.9]	0.0001	0.0	200.0	[[1.61, 1.63], [2.2, 2.33], [10.7, 12.
Aircraft Comm	['core', 'outlier']	[0.5, 0.9]	2e-05	5e-05	100.0	[[1.24, 1.37
Sat Comm	['full']	[0.4]	2e-05	0.0001	100.0	

RFI mitigation options

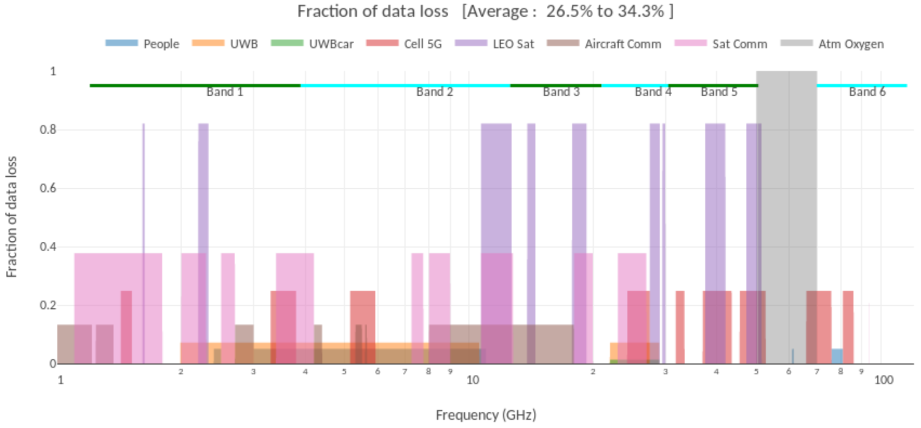
- [x] Post-Processing Flagging
- [ ] Antenna-based Real Time Flagging
- [ ] Baseline-based High time resolution Flagging (in-correlator)
- [ ] RFI modeling and subtraction at high time resolution

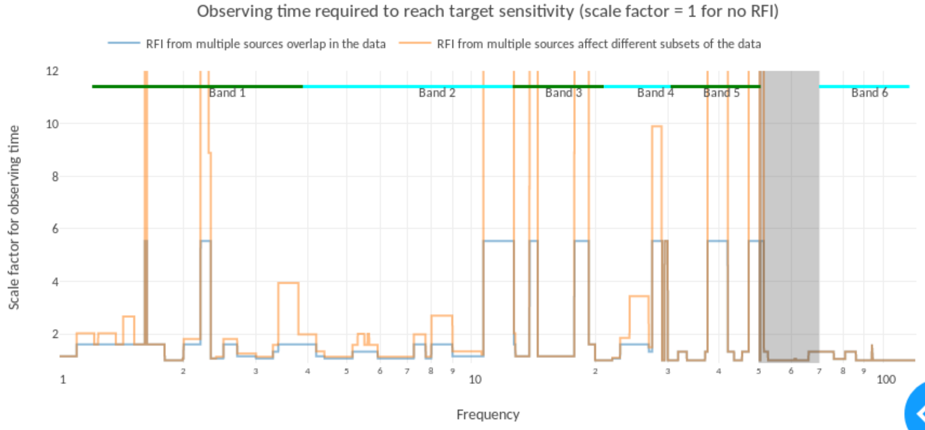
RFI Decorrelation

- ○ None (ignore from calculations)
- ◉ RFI at 20deg from phase-center (practical estimate)
- ○ RFI at 90deg from phase-center (maximal decorrelation)

Attenuation threshold

○ 20 dB ◉ 40 dB ○ 60 dB





https://github.com/urvashirau/ngVLA-RFI-impact-simulator/tree/master/RFI_Impact_Calculator

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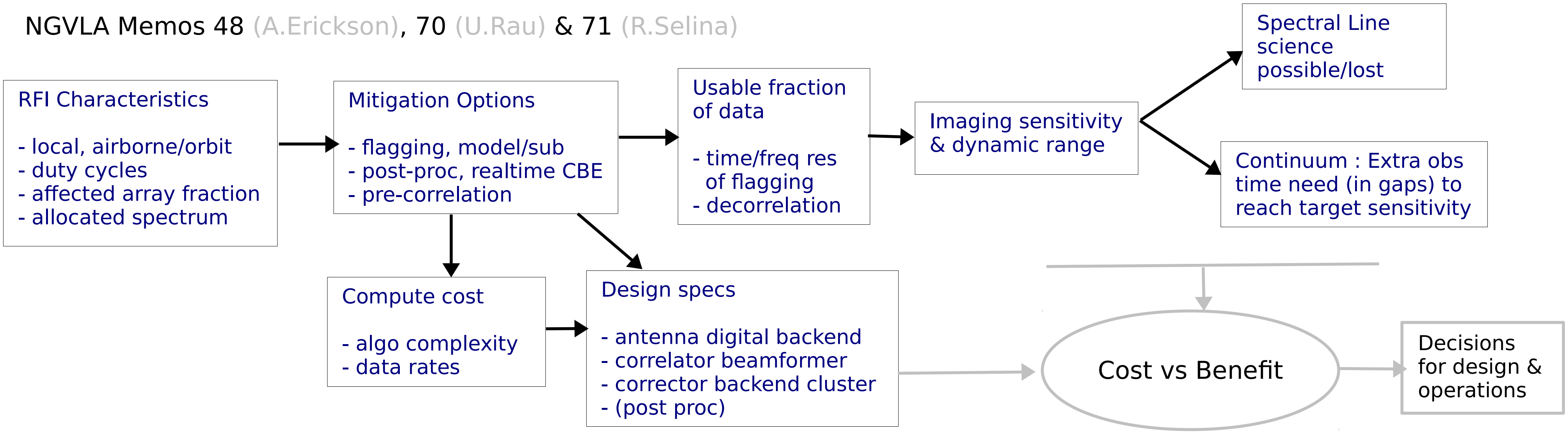

Many assumptions and approximations !!

– Entire allocated bands are filled with RFI
– Duty cycles of some comm transmissions show usable gaps at milli-sec to micro-sec time resolution
– Accuracy of autoflag or modeling/subtraction algorithms
– Relative compute cost of algorithms
– Effect of decorrelation per antenna group (core/main,etc..) and not individual baselines.
– Possibility of building an RFI database and using it to tune post-processing autoflag...

=> Several follow-up studies to answer questions and test assumptions (not funded => science time)

Context – LEO satellite transmissions

(1) Model RFI decorrelation and verify with VLA-SiriusXM data (U.Rau, R.Selina, S.Yadav) → Built modeling tool

(2) Analysis of incident power levels (R.Selina : ngVLA Electronics Memo – draft)

Transmitter : LEO satellite (MainLobe + SideLobe)
Receiver : ngVLA Antenna (MainLobe + Sidelobe) → Received PSD < ngVLA noise level (per antenna)

Ambient signal from N satellites + Comparisons with system noise
(SpaceX + OneWeb)

(3) National Radio Dynamic Zone (C.DePree & T.Beasley)

- Needed to know how the VLA / ngVLA would see LEO satellite transmissions.
- Coordination with SpaceX (and maybe OneWeb later) to test NRDZ ideas of time/freq sharing (Commercial / RadioAstro)
- NRAO buying SpaceX User-Terminals for the Alamo Reservation (J.Robnett) → Need to know impact on the VLA

Current Project : (C.DePree, U.Rau, B.Svoboda)

=> Modeling of VLA received power from SpaceX SAT/UT + effects of decorrelation + impact on imaging sensitivity
=> Verify using VLA-SpaceX coordinated tests

Modeling the interferometer response to Satellite RFI

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Power measured at each antenna

Quantity to calculate : Measured Spectral Power Flux Density : W/(m2 Hz)
(Ref:https://bwinkel.github.io/pycraf/conversions/index.html#using-pycraf-conversions)

Parameters : – Transmitted power, transmitter gain (mainlobe/sidelobe), distance : PFD incident at the receiver
– Receiver gain (mainlobe/sidelobe), chan BW : Measured PFD and SPFD

Mainlobe or Sidelobe ?

SAT : PFD at the Earth's surface (from SpaceX) : -146 W/m2/4kHz
Satellite forward gain : 38.3 dB (relative to 0dB sidelobe gain)

SAT beam footprint = 22km diameter

=> If the UT is within 22km of a VLA dish, we will see the SAT mainlobe. Otherwise, sidelobe.

UT : Transmitted power (EIRP from SpaceX) : 3.2 W

Assumption : Always a sidelobe : UT gain : 0 dB

VLA : Mainlobe gain $10 \times \log_{10} k \left(\frac{\pi D}{\lambda}\right)^2$ dB , Sidelobe gain : 0 dB (Ref : https://www.everythingrf.com/rf-calculators/parabolic-reflector-antenna-gain)

VLA HPBW = λ / D => If the SAT is within 2 x HPBW, we will see it in the VLA mainlobe. Otherwise, sidelobe.

[VLA sidelobe gain as a constant 0 dB, vs using the actual voltage pattern (and angular separation) ?]

Power measured at each antenna

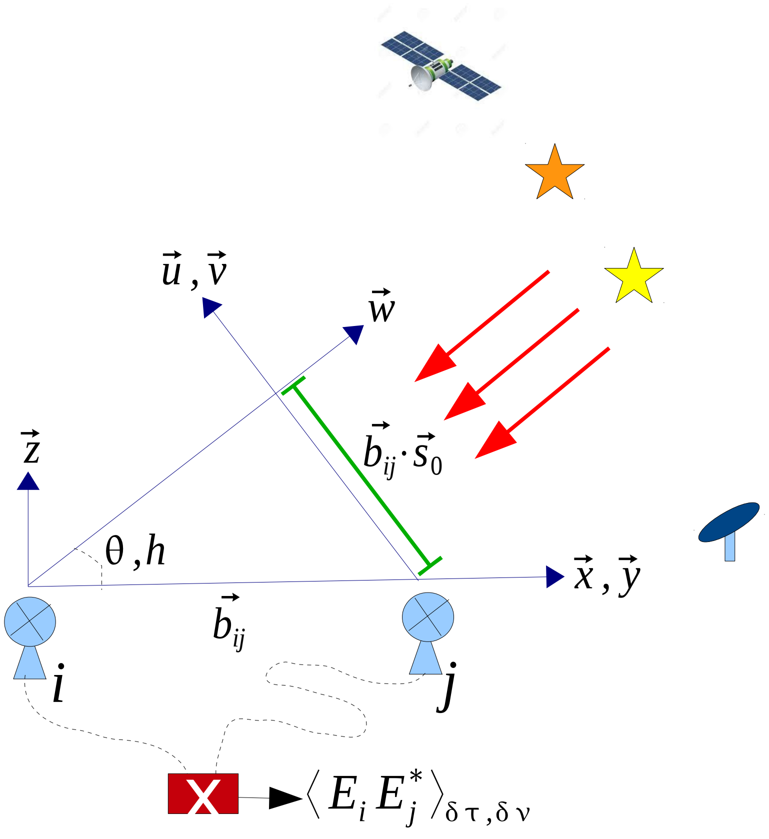
Measured SPFD (calc) W / (m2 Hz)	SAT Mainlobe	SAT Sidelobe	UT sidelobe
VLA Mainlobe	-182 dB 6e+7 Jy	-220 dB 9e+3 Jy	X
VLA Sidelobe	-250 dB 9 Jy (VLA SAT-illumination test)	-288 dB 1e-3 Jy (most common case)	-247 dB 16 Jy @50km -241 dB 67 Jy @25km -193 dB 4e+6 Jy @0.1km

ITU regulations : Power Spectral Density (Mainlobe) : -176 dB (2e+8 Jy)
Equivalent Power Spectral Density (SL,many) : -206 dB (2e+5 Jy)
Detrimental ITU RFI threshold : -240 dB (100 Jy)

Ref : ITU info from Table 4, JASON Report (Jan2021) : The Impacts of Large Constellations of Satellites

[Background behind these ITU thresholds ? Relevance to Tsys per antenna ? For a point src, this is visibility amp.]

Attenuation and decorrelation of RFI signals



Assumption :

$\vec{b}_{ij} \cdot \vec{s}$ is constant across $\delta\tau, \delta\nu$

For any finite channel bandwidth,

$\vec{b}_{ij} \cdot \vec{s}$ varies across channel for any offset location 

or any moving source 

=> $\langle E_i E_j^* \rangle_{\delta\tau, \delta\nu}$ is an average over multiple Fourier components

=> Decorrelation and Attenuation

=> Vis correlation matrix has >1 eigen values

(Ref : JWSteeb PhD thesis + our VLA experiments with BYU RFI group)

Attenuation/Decorrelation & Eigen-Value analysis : Same thing ?
Power is distributed vs attenuated ?

Attenuation and decorrelation of RFI signals

Ref:“ The response of a radio synthesis array to interfering signals” : Thompson1982: https://ieeexplore.ieee.org/abstract/document/1142799

Averaging Effect : $F_1 = \frac{\sin(\pi f \tau)}{\pi f \tau}$ where $f = \omega_o u \cos\delta$ and τ is integration (or uv-cell crossing) time.
(Eqn 3)

Bandwidth Decorrelation : $F_2 = \frac{\sin(\pi \beta \tau_D)}{\pi \beta \tau_D}$ where $\tau_D = b(\cos\delta_{pc} - \cos\delta_{rfi})/c$ and β is channel bandwidth
(Part of Eqn 19)

Combined Attenuation : $F_1 \cdot F_2$
(Part of Eqn 19)

=> Calculate attenuation per baseline and timestep (per position of moving source)

=> Multiply by received power level => Prediction in Jy (per visibility)

- For F1, use Phasecenter direction or the RFI direction (for u, delta) ? Moving source : Wo = relative velocity (ps--rfi) ?
- Near-field vs Far-field : phase-only effect => ignore ? (Sats are near-field D_far = B^2/lam = 5e+6 km, D_sat = 570 km)
- Same effect (and model?) for baseline-based averaging – across time and frequency, within a UV cell ?

Effect of an RFI signal on the image

For a point source,

Image amplitude = Source SPFD = $\left\| \langle E_i E_j^* \rangle \right\|$

Received Spectral Power Flux Density
- attenuation/decorrelation.....

Noise per measurement = $\sigma_{vis}^{obs} \propto \frac{T_{sys}}{\eta_a \delta \tau \delta \nu}$

(Assumption : Gaussian random)

Ambient signal can raise T_{sys}
(e.g. 100s of satellites at low power)

Image noise floor : $\frac{\sigma_{vis}^{obs}}{\sqrt{\frac{N(N-1)}{2} x N_{time} x N_{chan} x N_{pol}}}$

(sensitivity limit)

RFI may not behave like sky sources

=> cannot calibrate (with std cal)

=> noise floor goes up
(w/wo imaging artifacts)

=> dynamic range limit, etc...

Quantifying the effect of partially decorrelated RFI signal on an image ?

- RFI : weaker than the (uncalibrated) visibility amplitude, but stronger than image noise level
→ It will not just ‘average out’ beyond the “uv cell” ==> dynamic range limit due to baseline-based errors

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User Terminal Tests

September 2021 (C.DePree, J.Robnett, D.Schafer, SpaceX-Engg)

Locations : VLA (Hwy 60), Between VLA-Mag, Mag, Socorro,
Alamo Reservation, Datil, PieTown

Experiment : UT turned ON/OFF, and running benchmarks with SAT

VLA phased up to the North Pole : RFI-Sweep setup
(not for calibration/imaging)

→ from Chris's phone...

What did we detect ?

UT : 14.0 – 14.5 GHz : Some detections at VLA, VLA-Mag, Alamo reservation

SAT : 10-12 GHz : Nothing obvious, even when the UT was at the VLA site.

User Terminal Tests

Bandwidth :

4MHz transmissions

- Expectation : wider?

Antennas :

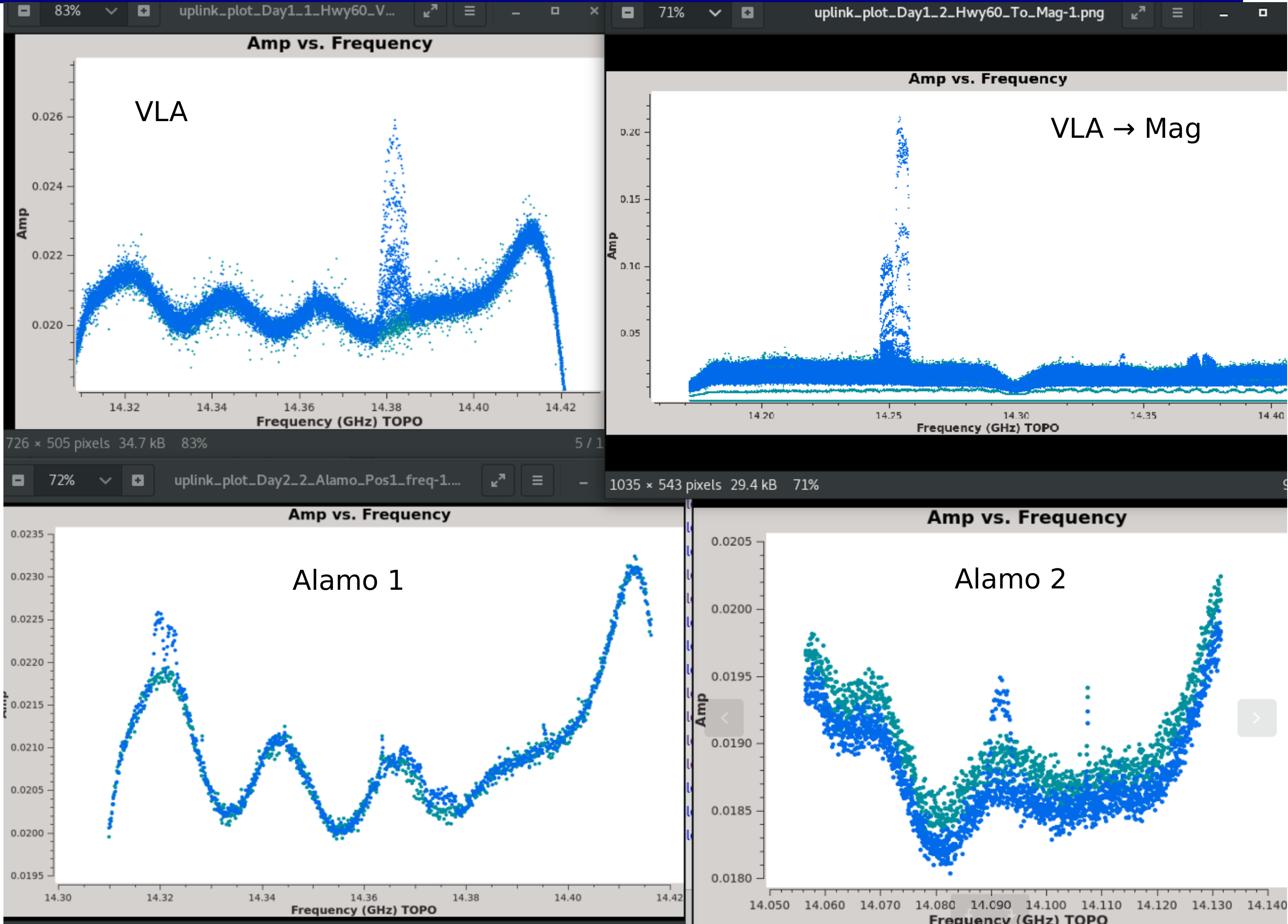
VLA and VLA-Mag
- Center and East arm

Alamo
- Center and North arm

Amplitude : Unknown.

- Expected (from calc) :
  - ~ 16 Jy @ 50km
  - ~ 60 Jy @ 25km
  - ~ 4e+6 Jy @ VLA site

=> Need observations
where we can calibrate....



SAT illuminating the VLA directly

SpaceX illuminated a cell over the VLA (B-config) + turned on transmissions during out test observation

- Obtained “SAT on” and “SAT off” scans on 3C295

- Calibration solutions from “SAT off” scans, applied to “SAT on”

- Plots + Imaging to compare “SAT off” and “SAT on”

Questions :

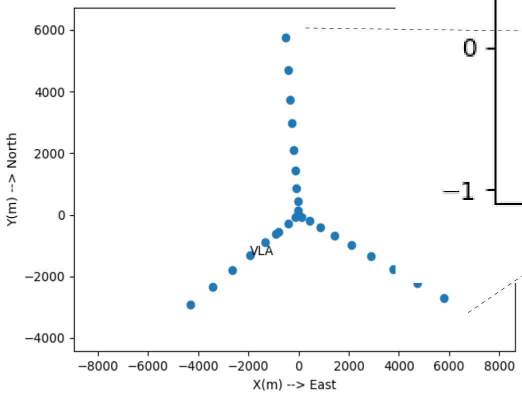
- Do we see the SAT RFI ?
- At expected power levels per baseline ?
- Effect on imaging quality (compare on/off) ?

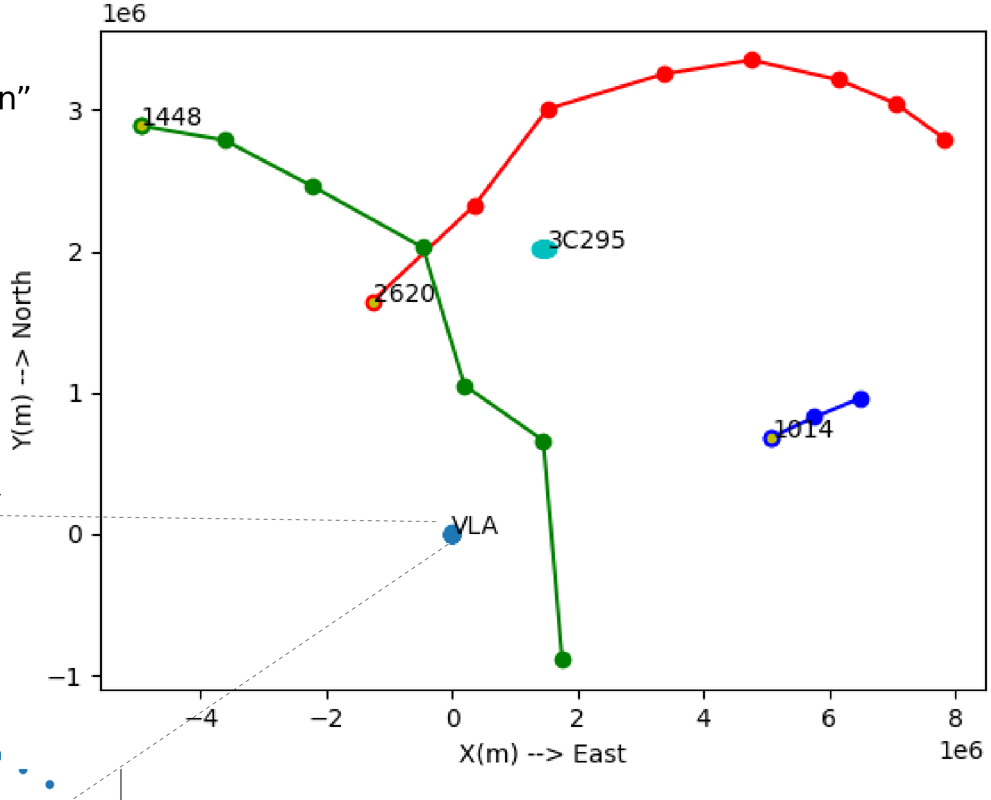
Satellite Positions (& VLA, 3C295)

Scan 10 : 5 minutes

3 satellites were transmitting (and moving)

Apparent speed : 0.75 deg/sec

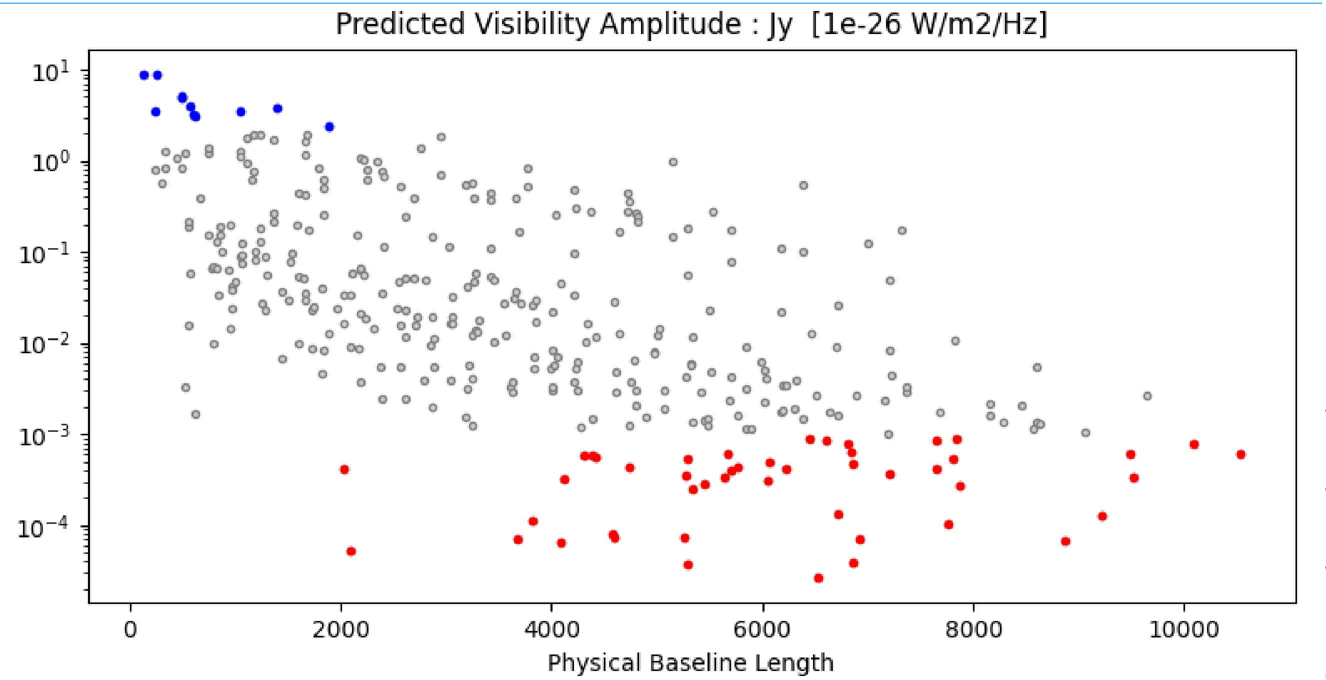


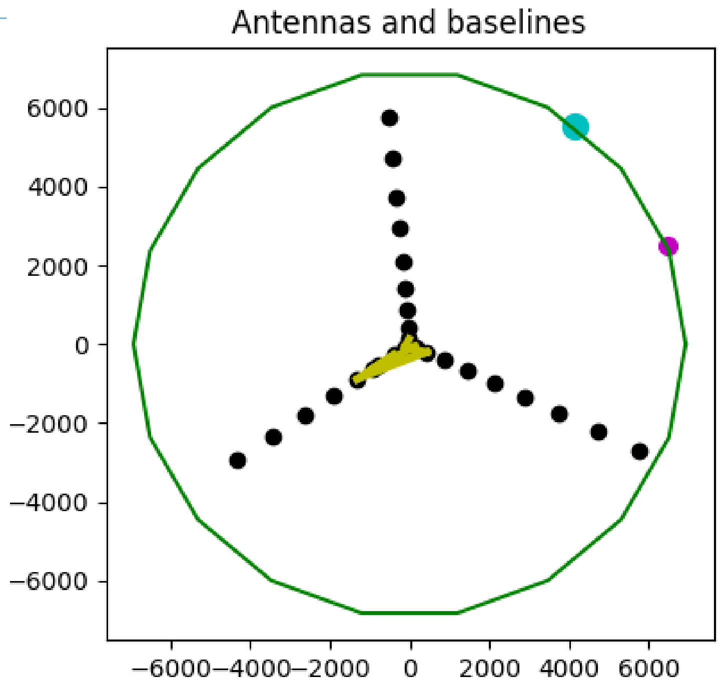


SAT IDs and positions provided by SpaceX

Attenuation due to interferometer response : Predictions

Example prediction, for one satellite location (East – NorthEast)



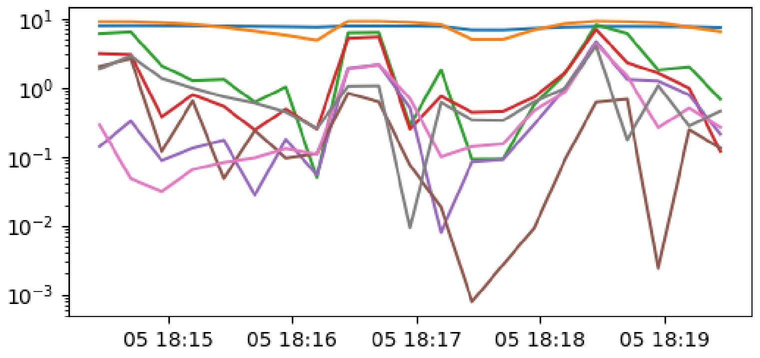


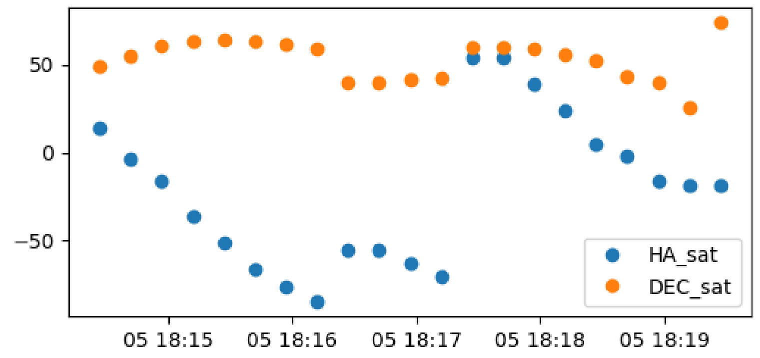
Handful of shortest baselines (as seen in projection by the satellite) will show the strongest signals.

Blue (above target brightness level of 2.3Jy). **Red** (below image noise level)

Gray : Everything invisible in these raw data, but above the image noise level.

Attenuation due to interferometer response : Predictions





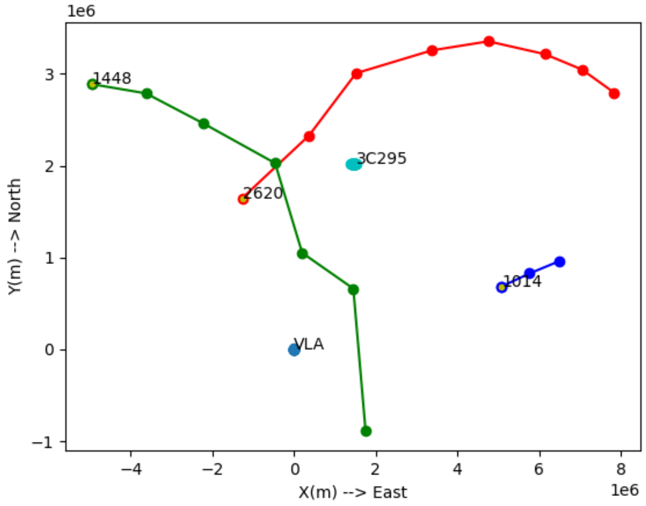
For a 5-minute scan….

Predicted amplitude for all baselines that went above 2.33 Jy at any time in scan #10.

X-axis : Time (one scan)

Satellite locations :

Hour-Angle
Declination



Some baselines should measure > 2.33 Jy only for short time periods (< 1min)

Two shortest baselines should see continuous transmissions (for all satellite locations).

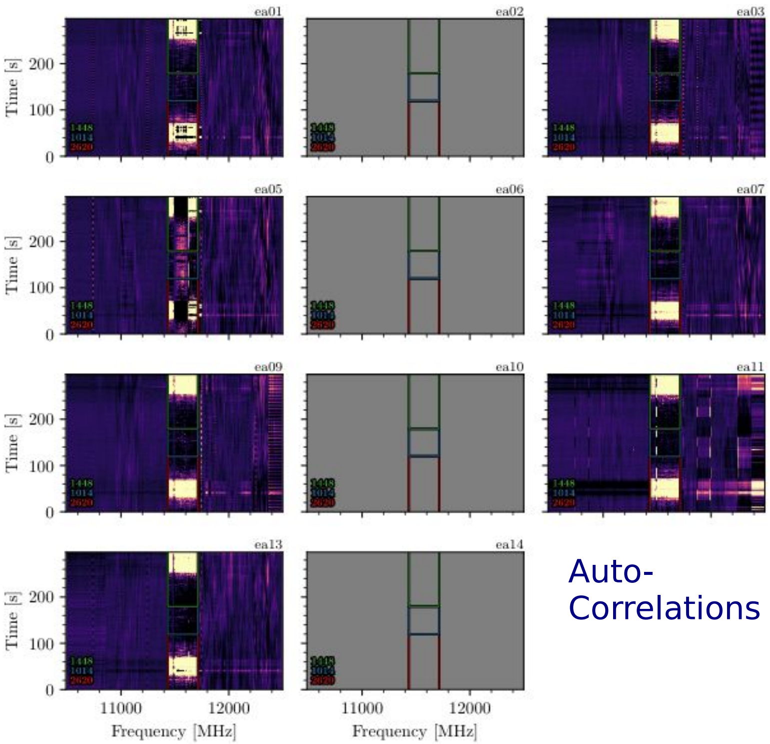
Different satellite locations => different ‘shortest’ baselines ? Maybe…

Waterfall plots (from B.Svoboda)

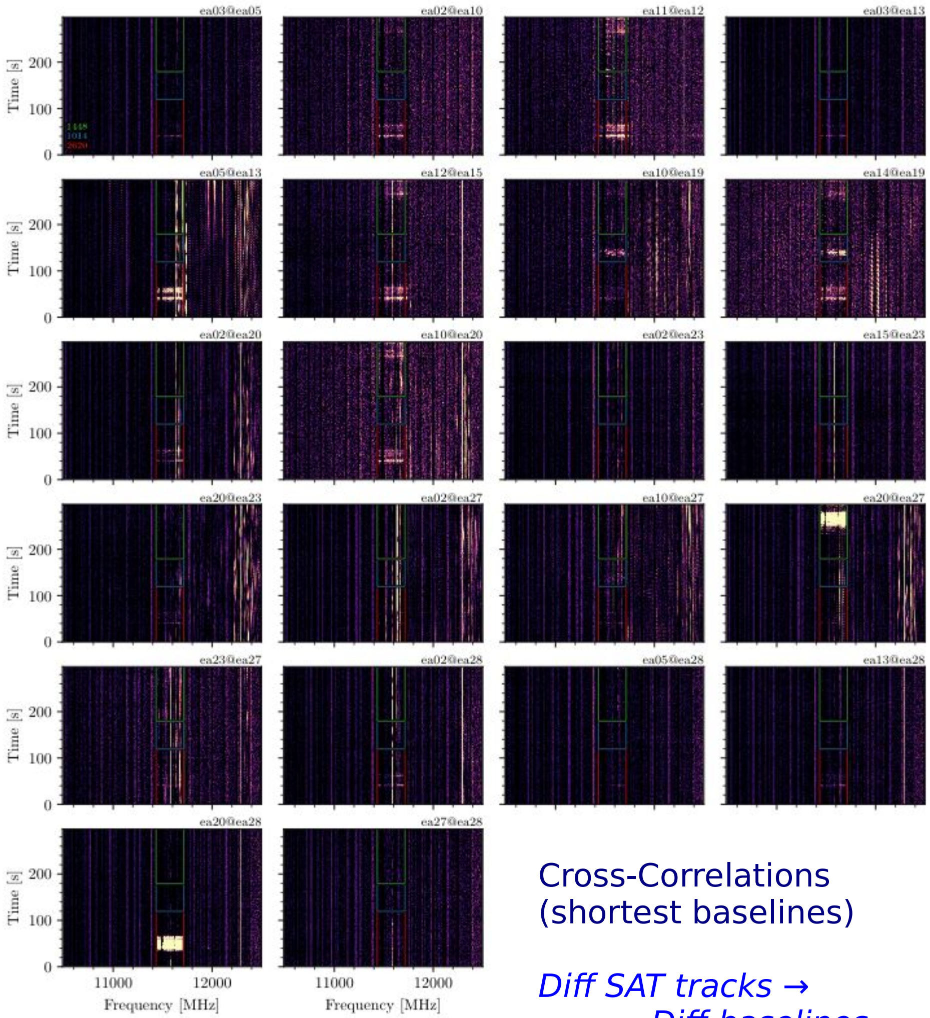
Plots of Visibility Amplitude (+ Enhanced Contrast)
For the same 5-minute scan, 10.5 – 12.5 GHz

~250 MHz transmissions

Signal seen (above 2.3Jy) for ~40sec stretches



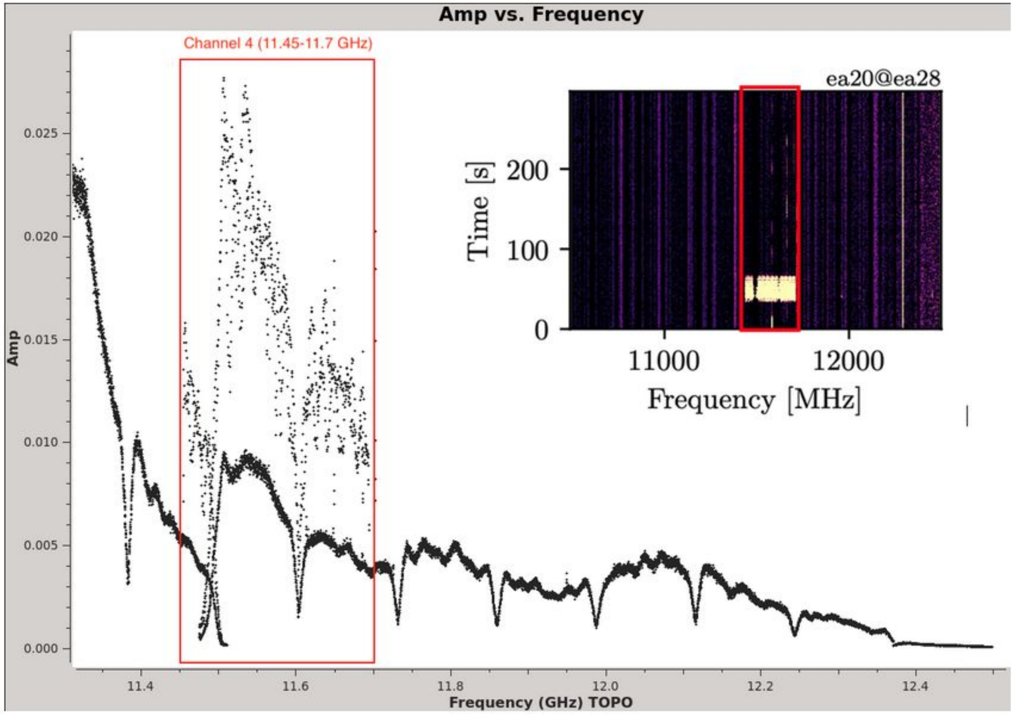
Auto-
Correlations

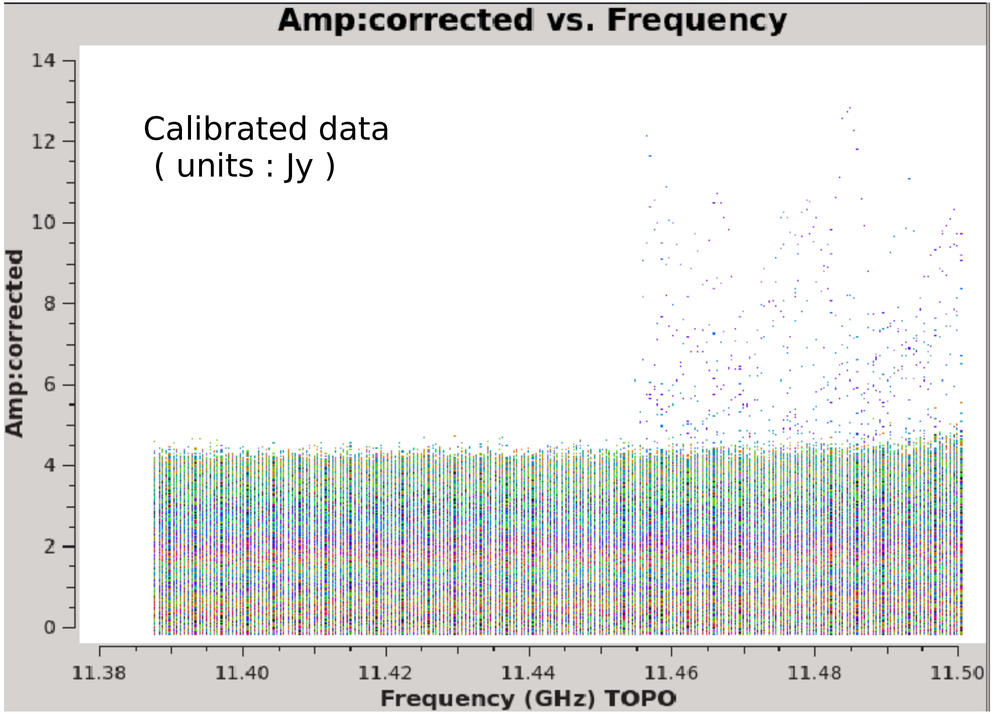


Cross-Correlations
(shortest baselines)

Diff SAT tracks →
Diff baselines…

Measured signal amplitude – matches predictions (close...)





Raw data (arbitrary flux units)

- RFI seen only in a few of the shortest baselines.

  - Baseline IDs did not exactly match model (offset in angle)

  - Geometry error ?

  - VLA sidelobe gains (not just 0dB...) ?

Predicted : ~ 9 Jy

Observed : Between 7 and 11 Jy on the brightest few baselines

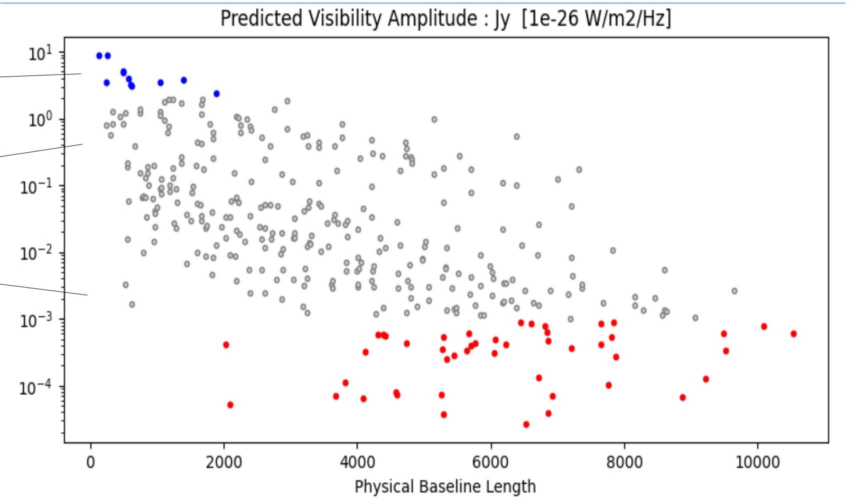
→ A reasonable match....

Sky source : average of 2.3 Jy

Imaging Results - Inconclusive

Seen in data plots

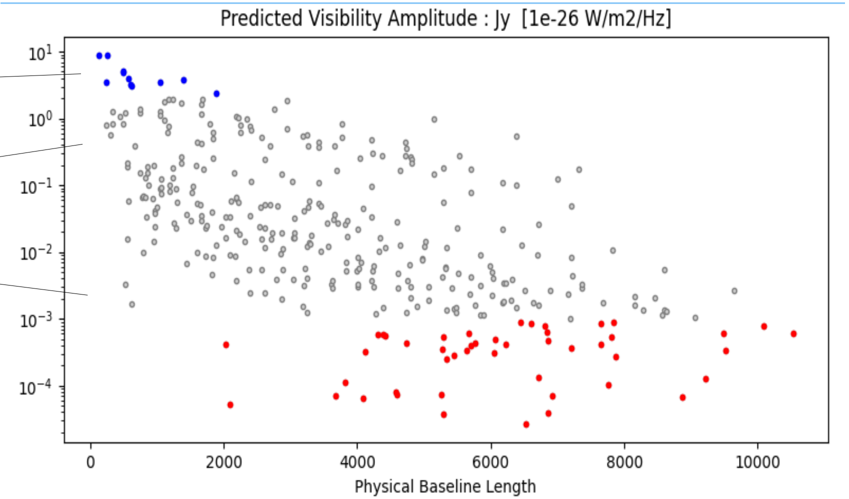
If present, the effect should be seen in the image as a sensitivity limit (or artifacts)



Need to make images of 3C295
+ Compare with expected 'ideal' noise levels.

SAT OFF scans : We should see theoretical noise levels
SAT ON scans : Should see a limit….. or not….

Imaging Results - Inconclusive



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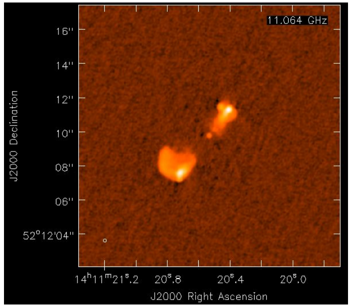
Problem : Our tests were affected VLA 'gain compression'

Non-linear quantization errors (per baseline)
Similar effect as per-baseline attenuation (!)

=> Unable to reach theoretical noise level even for SAT OFF scans
(or outside SAT freq-bands).

=> Need to change our obs setup to avoid this problem, and do a re-test with SAT OFF and ON

Dec/Jan 2021 : testing observing setup that avoids such instrumental issues



3C295 Cal Model

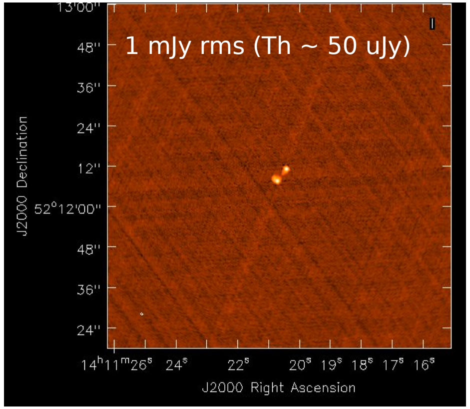


Image in SAT **OFF** scan....

Future Tests + Plans

A repeatable test observation setup for monitoring and imaging

– Avoid gain compression => Observe extra setup scan on the calibrator

– Pick an empty field (not 3C295) => Try to see the weaker RFI directly in the calibrated visibilities

– Add calibrator scans before and after 'empty field' scans (3C286 or 3C48)

– Add a 'weak source' field that one can self-cal on ?

Monitoring : Cover 10-12 GHz with 512 kHz channels + 13.8 – 14.5 GHz with 125 kHz channels
Look for evidence of RFI from the Alamo Reservation (60 UTs to be installed next month)

Imaging : Need to easily reach thermal noise on empty sky (with SAT off and UT off)
(Dec 2021 test : Can reach thermal noise of 30uJy in 10min, 128MHz with a bandpass cal and imaging.)

– Look for evidence of partially attenuated signal + refine the model to identify baselines better

Coordinated tests with SpaceX :

– Use this setup to coordinate SAT "ON" and SAT "OFF" VLA illumination tests again.

– Test frequency sharing ideas for NRDZ (there are 8 256MHz SpaceX channels between 10 and 12 GHz).

NgVLA : Connect this back to the Cost-Benefit analysis for ngVLA system design + Address other open questions