Performance Assessment of Space-Based Radio Arrays & Applications to the Lunar Surface

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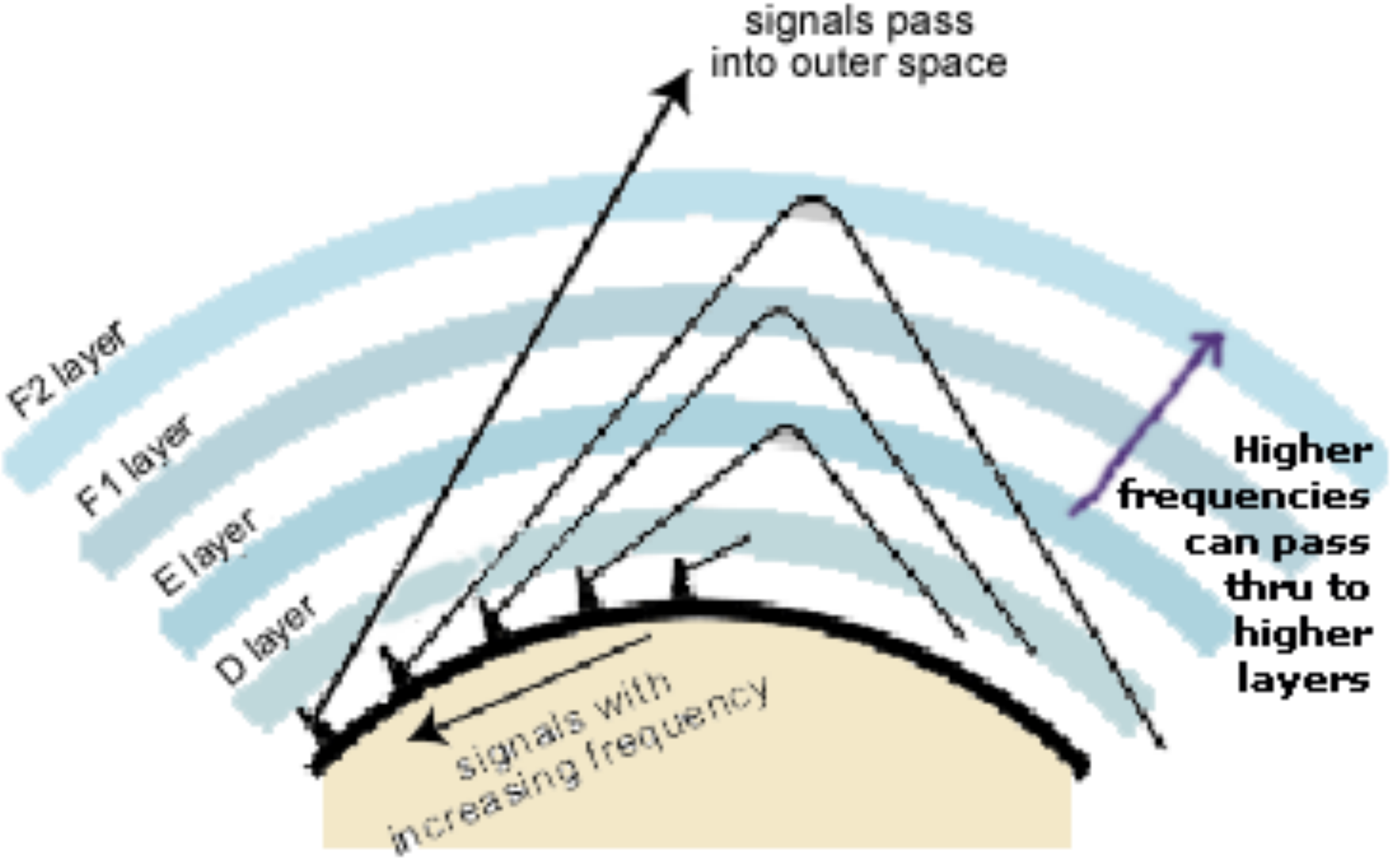
5/25/17

Why Space? Ionospheric Cutoff



How the ionospheric layers refract different frequencies

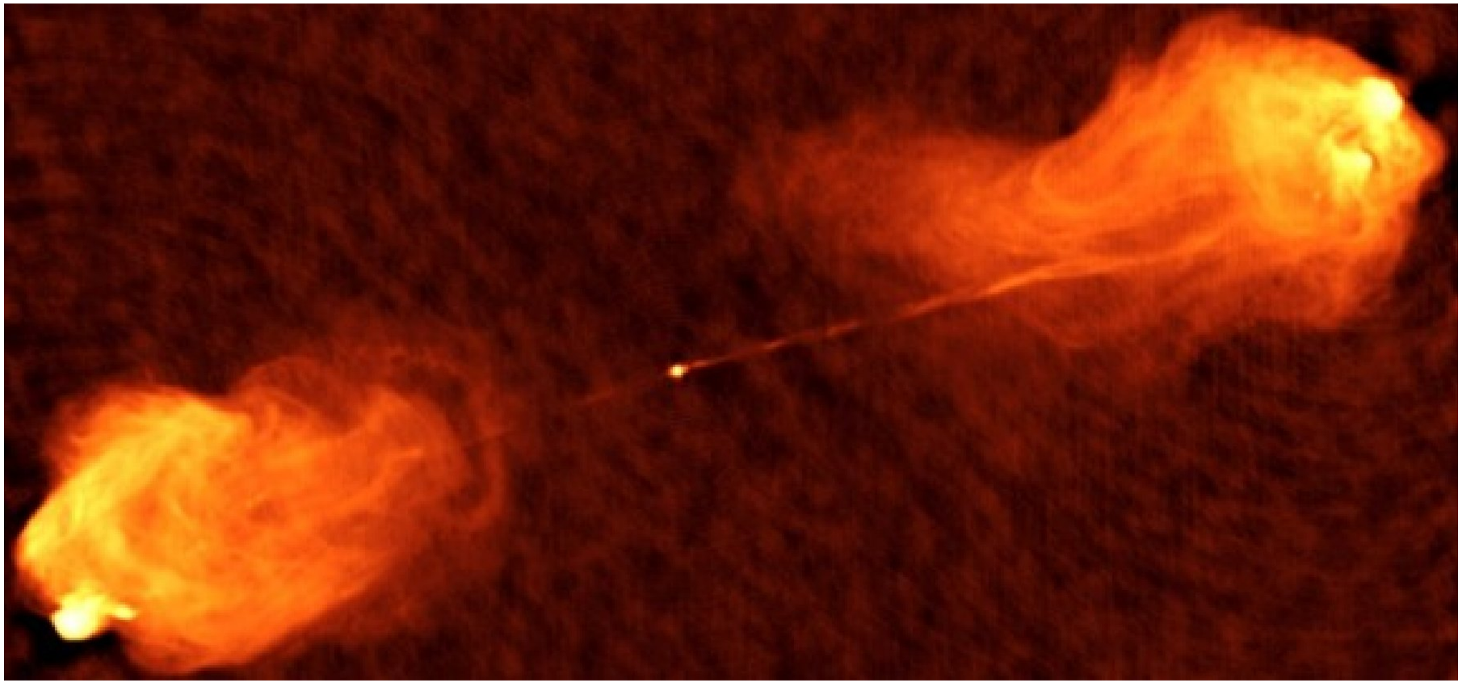
Image from http://www.engineeringwall.com/blogs/entry/1-what-is-ionospheric-bending/

Science Target: DRAGNs

Relic Array Concept

30+ spacecraft
Orbit around the moon
Image DRAGNs at low frequencies
(Double Radio-Source Associated with Galactic Nucleus)

But how do we deal with the motion of the antennas?



Radio Galaxy Cygnus A, photo by NRAO

Positional Projection

Must project antenna positions to the plane that's at right angle from source direction

No Radio Astronomy software is equipped to do this for orbiting spacecraft

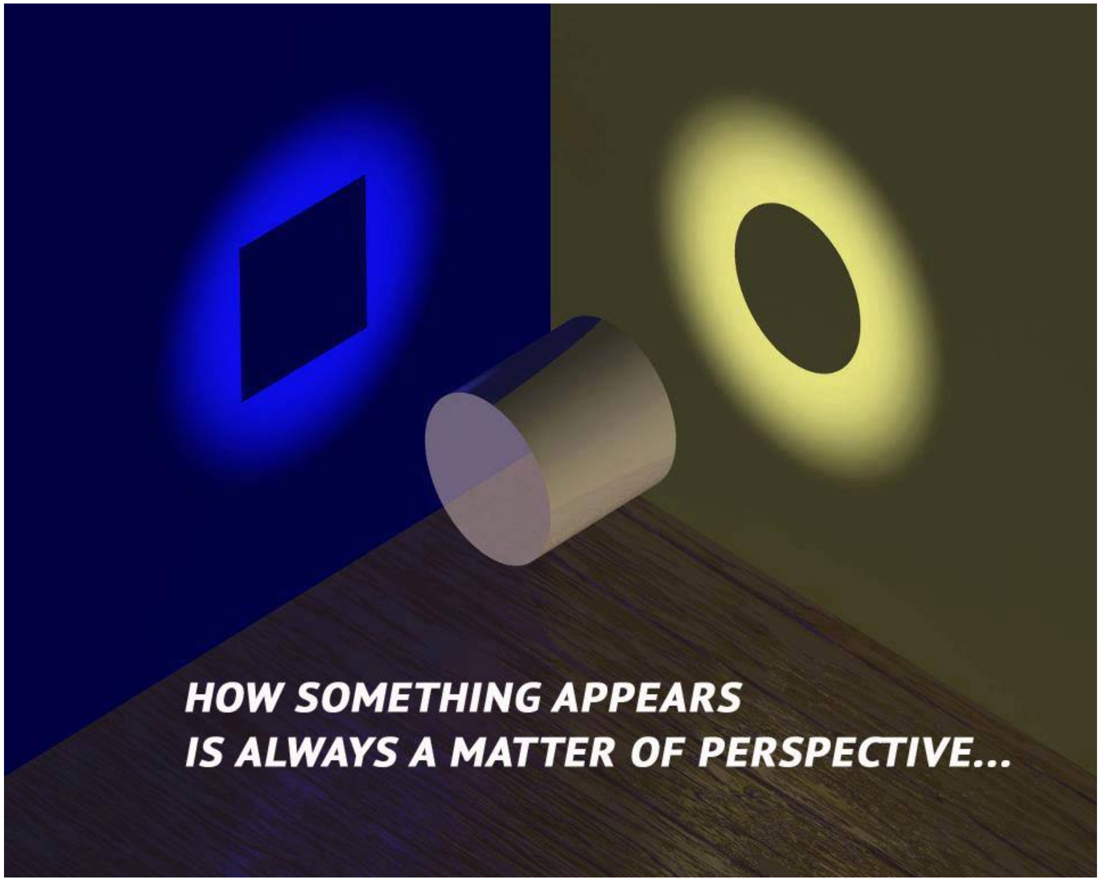
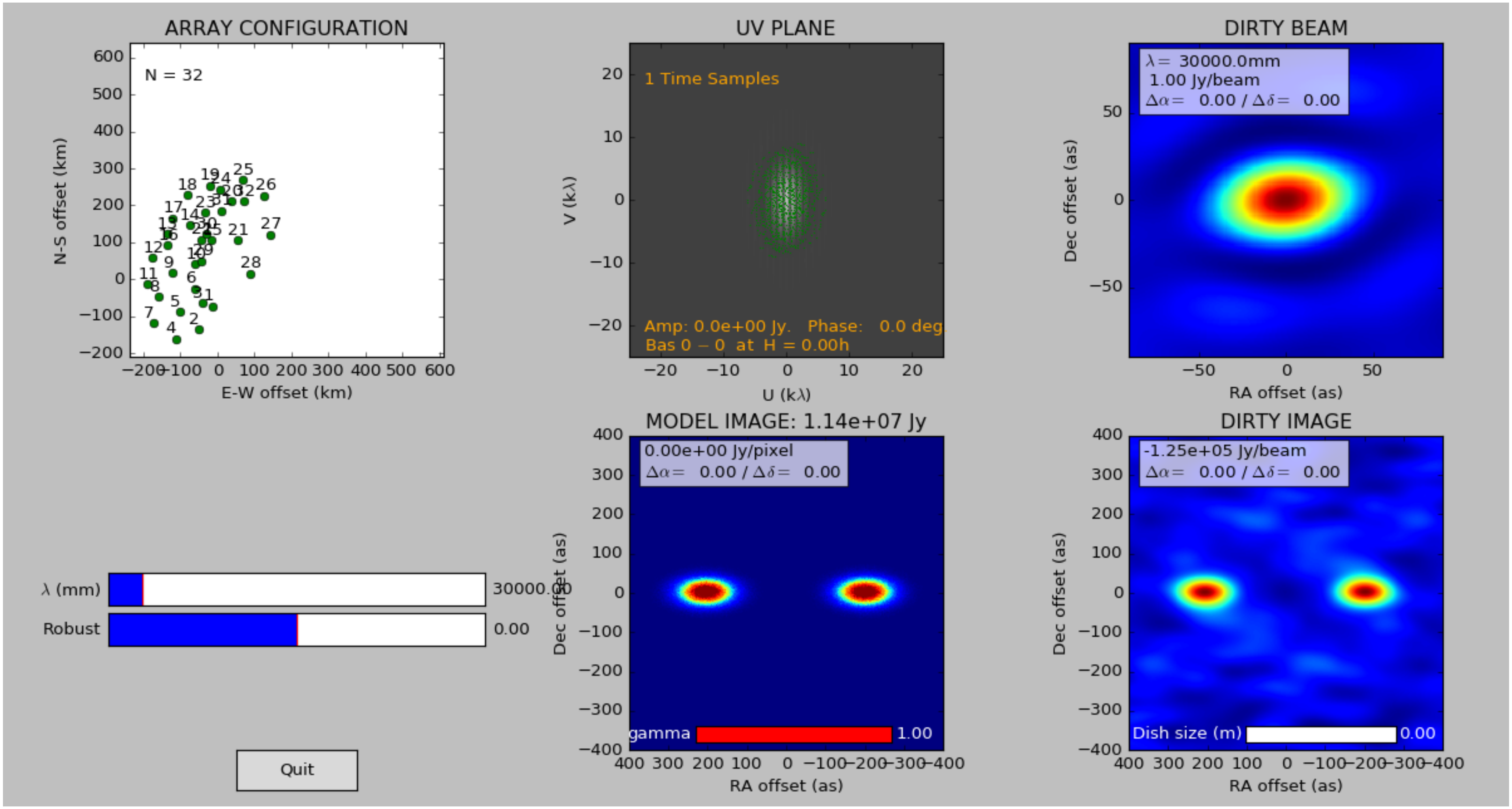


Image from http://www.compassforcreatives.com/wp-content/uploads/2014/03/1070085_232446043613328_1572139113_n.jpg

Meet APSYNSIM



1 Time Samples

Amp: 0.0e+00 Jy. Phase: 0.0 deg
Bas 0 − 0 at H = 0.00h

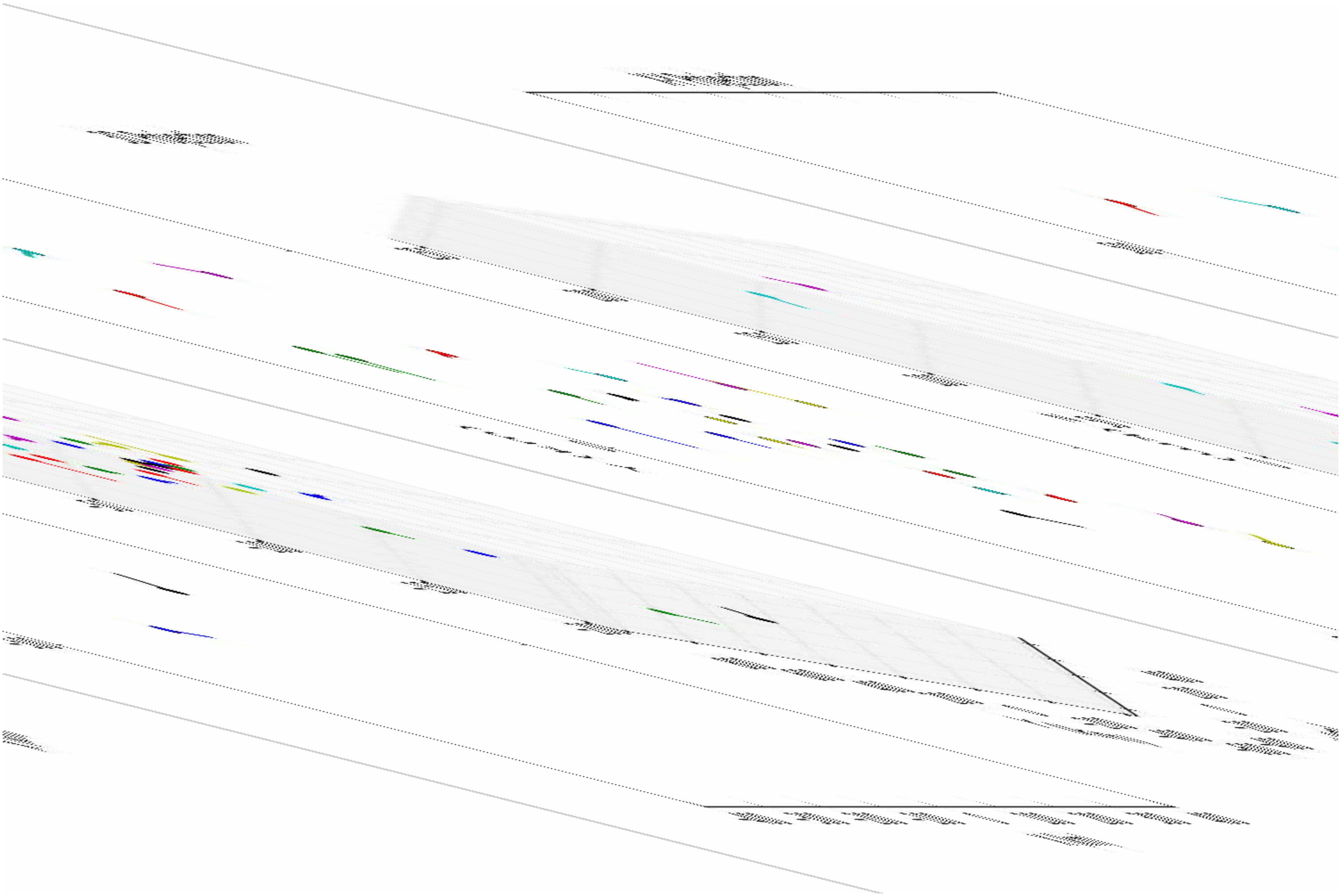
$\lambda =$ 30000.0mm
1.00 Jy/beam
$\Delta\alpha =$ 0.00 / $\Delta\delta =$ 0.00

0.00e+00 Jy/pixel
$\Delta\alpha =$ 0.00 / $\Delta\delta =$ 0.00

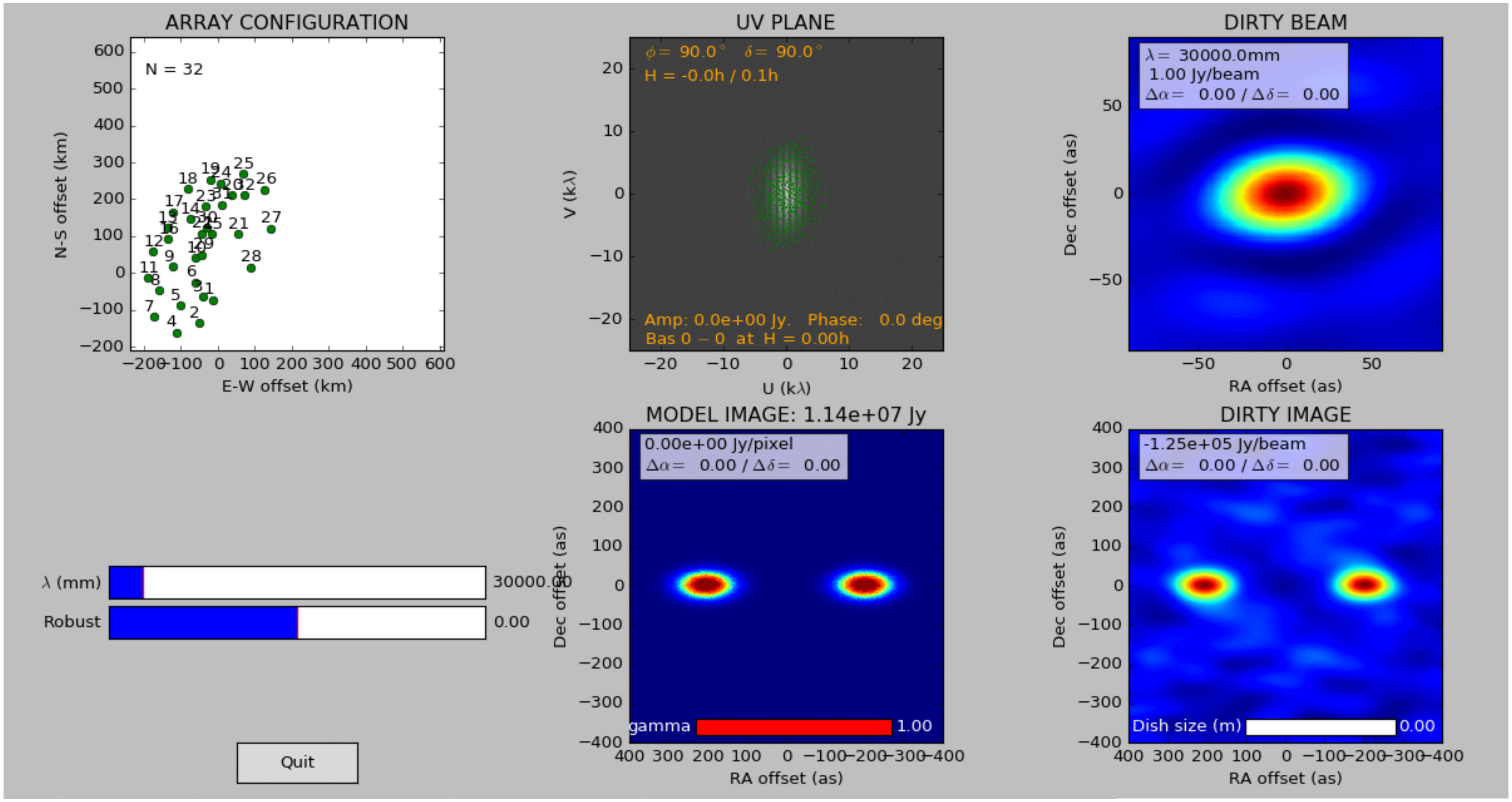
-1.25e+05 Jy/beam
$\Delta\alpha =$ 0.00 / $\Delta\delta =$ 0.00

λ (mm) 30000.00
Robust 0.00
gamma 1.00
Dish size (m) 0.00

Original software by Ivan Marti-Vidal, used under GNU GPL



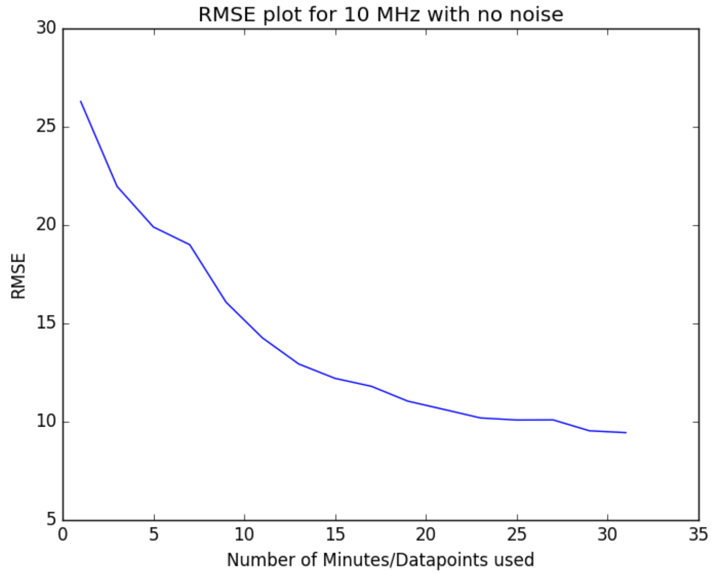
Simulated Orbit by Sonia Hernandez



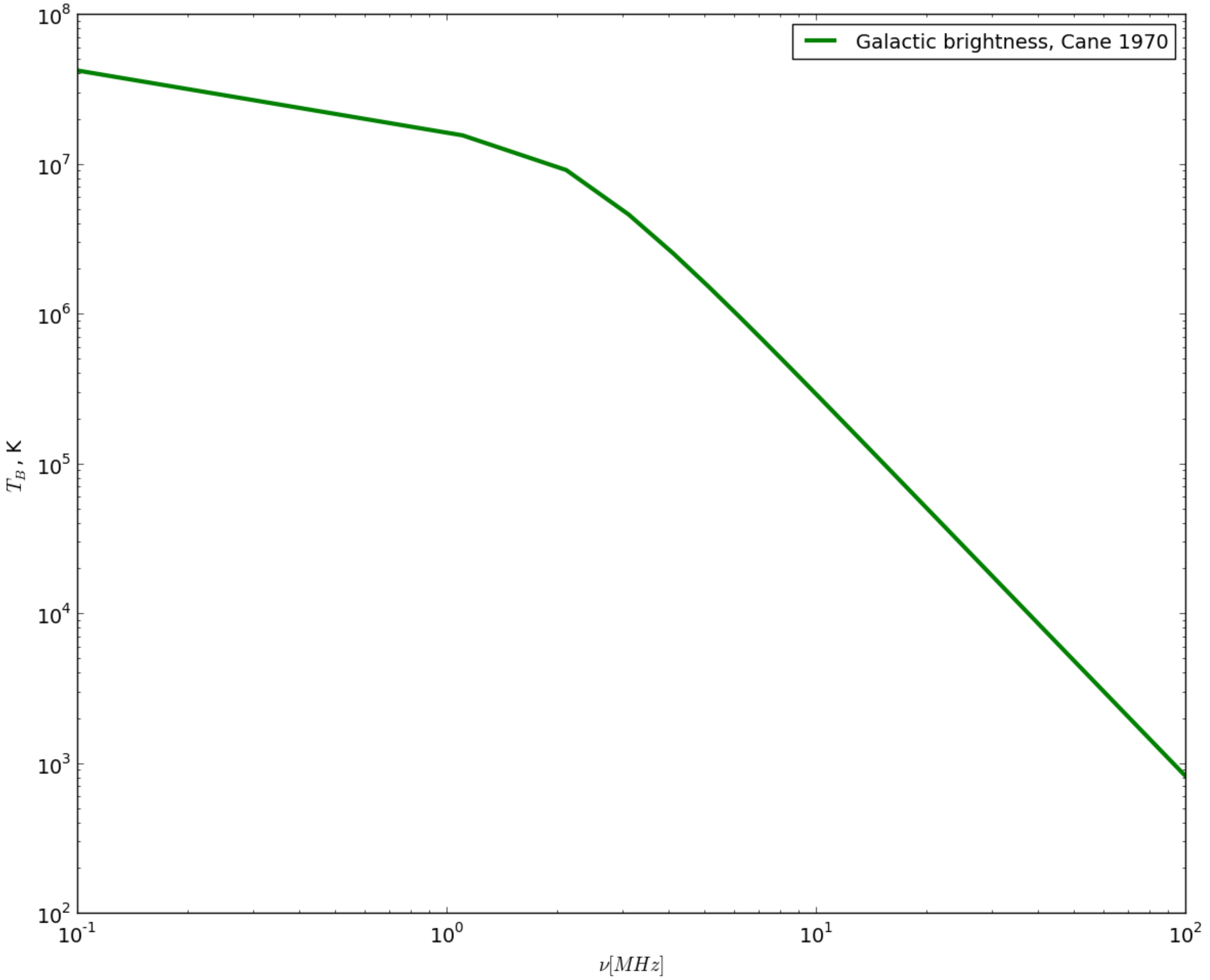
λ (mm) 30000.00

Robust 0.00

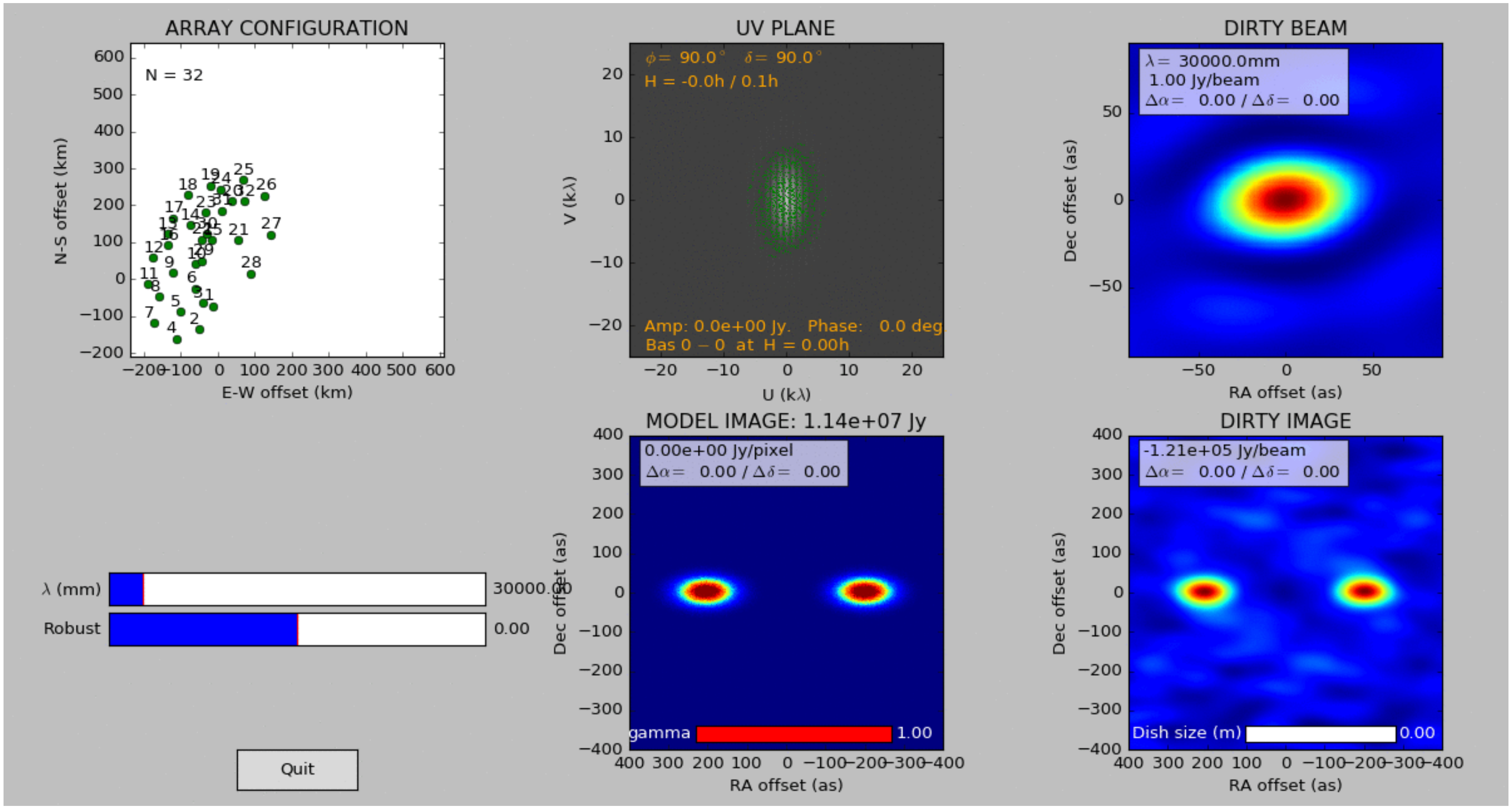
Aperture Synthesis with projected positions from orbiting Relic Array, no noise



Adding Thermal Noise



$$\sigma = \frac{2\,k_B\,T_{sys}}{\eta_s\,A_{eff}\,\sqrt{N(N-1)(N_{IF}\,\Delta T\,\Delta\nu)}}$$

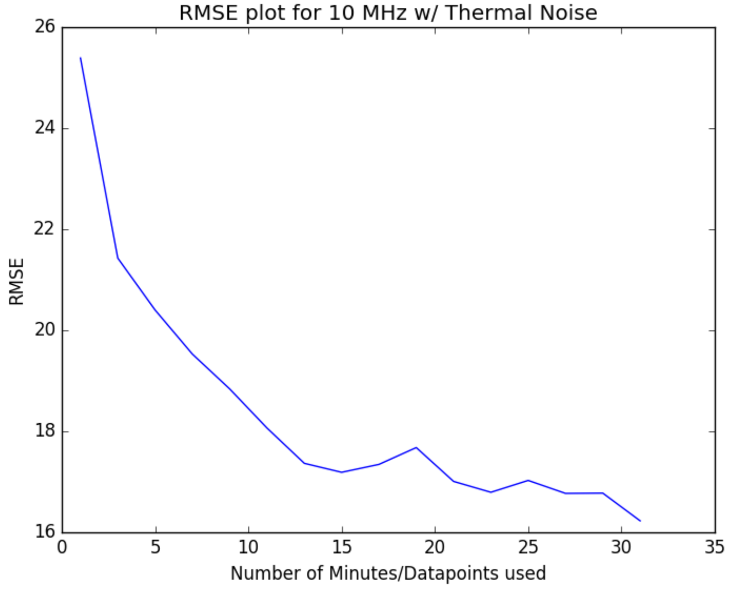


λ (mm) 30000.00

Robust 0.00

With Galactic Thermal Noise

σ = 60 Jy



Adding Phase Noise from Spacecraft Positional Uncertainty

Due to GPS limitations, can only know positions to within some tolerance

Phase error is 2πντ for uncertainty τ seconds

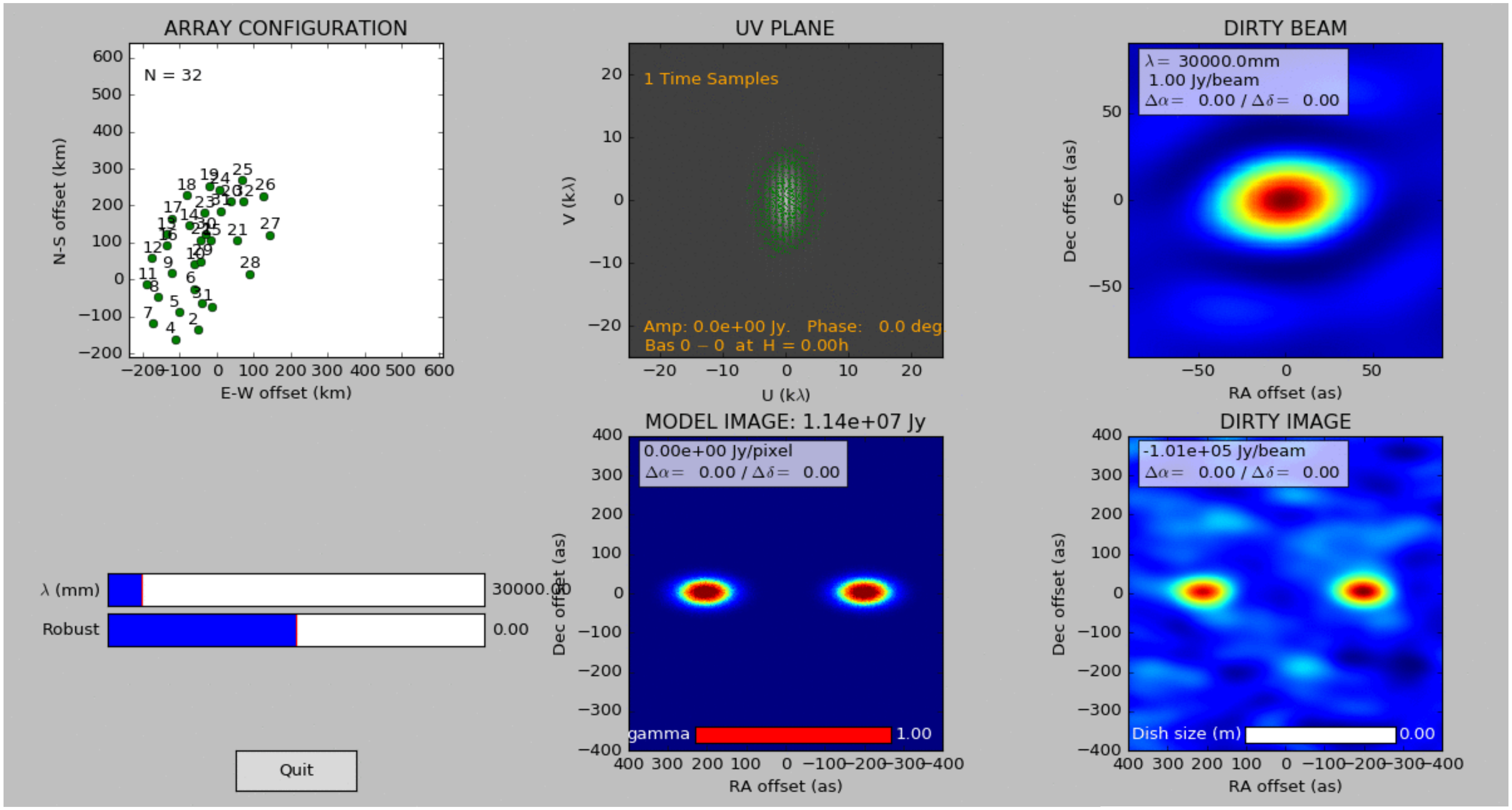
$$V_\nu(u,v,w) = \iint I_\nu(l,m) e^{-2i\pi[ul+vm+w(\sqrt{1-l^2-m^2}-1)]} dl dm$$

Uncertainty = positional uncertainty + clock uncertainty

$$\tau\nu = du * l + dv * m + dw\sqrt{1 - l^2 - m^2} + dt * \nu$$

$$\tau = \frac{dx*l+dy*m+dz\sqrt{1 - l^2 - m^2}}{c} + dt$$

$$l, m \ll 1 \Rightarrow \tau = \frac{dz}{c} + dt$$



Amp: 0.0e+00 Jy. Phase: 0.0 deg
Bas 0 − 0 at H = 0.00h

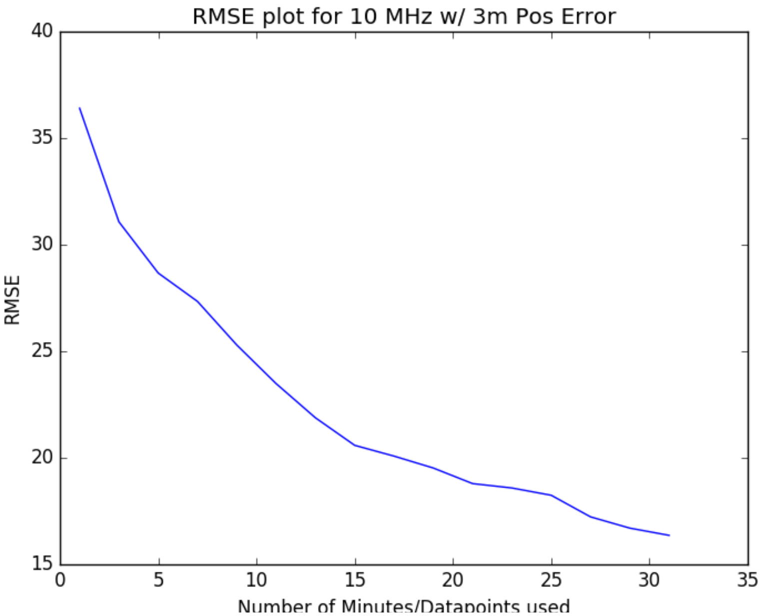
λ= 30000.0mm
1.00 Jy/beam
Δα= 0.00 / Δδ= 0.00

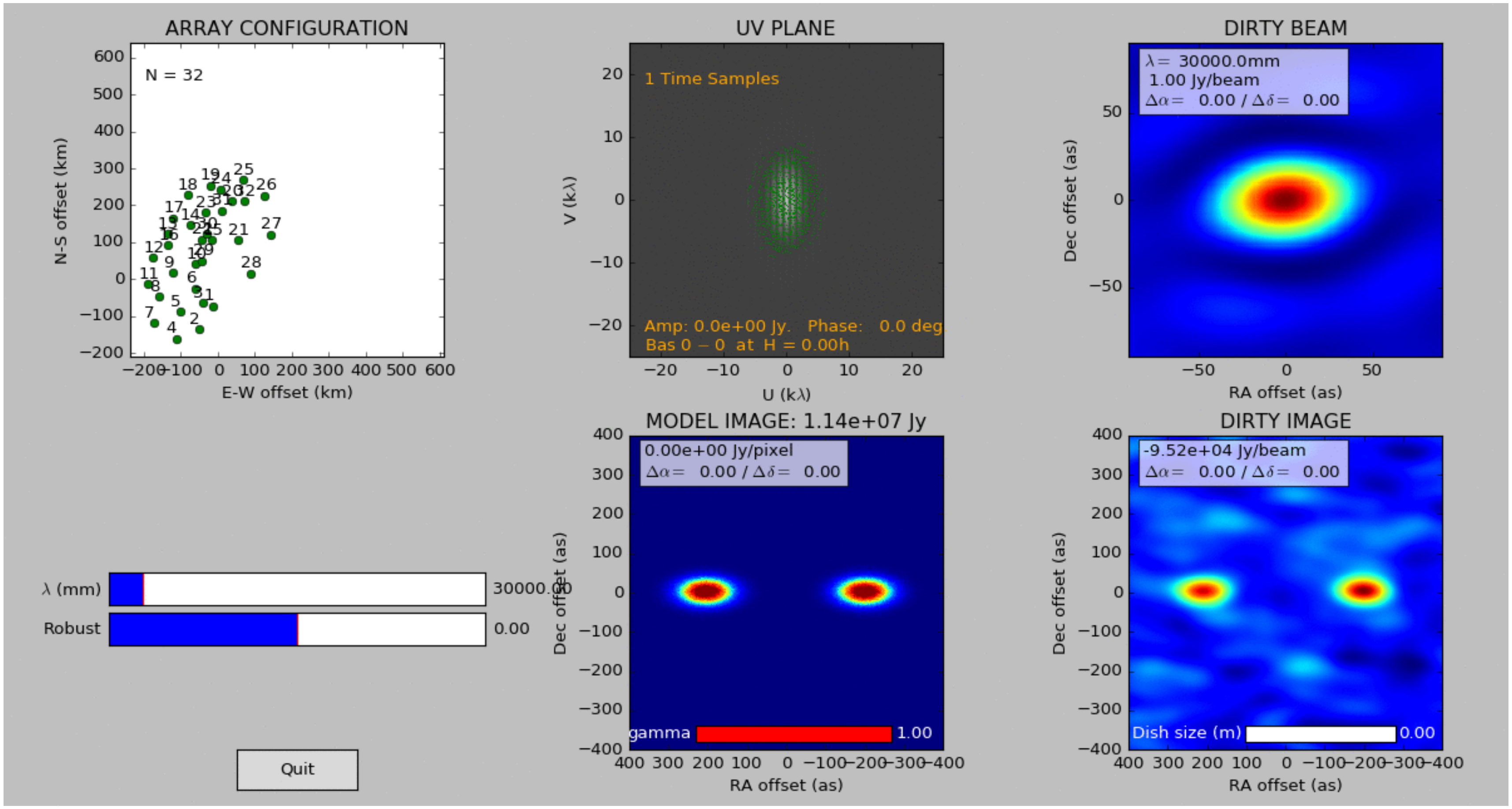
0.00e+00 Jy/pixel
Δα= 0.00 / Δδ= 0.00

-1.01e+05 Jy/beam
Δα= 0.00 / Δδ= 0.00

λ (mm) 30000.00
Robust 0.00
gamma 1.00
Dish size (m) 0.00

3m == 10 ns Position Error

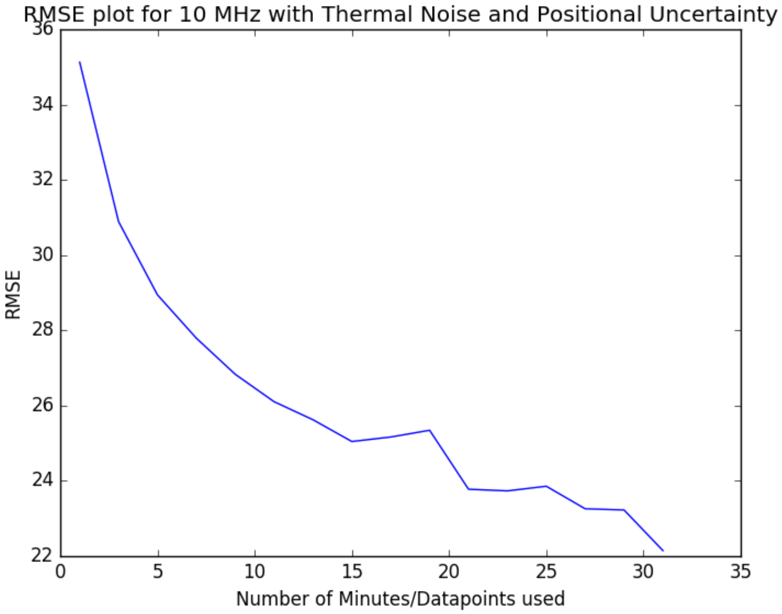


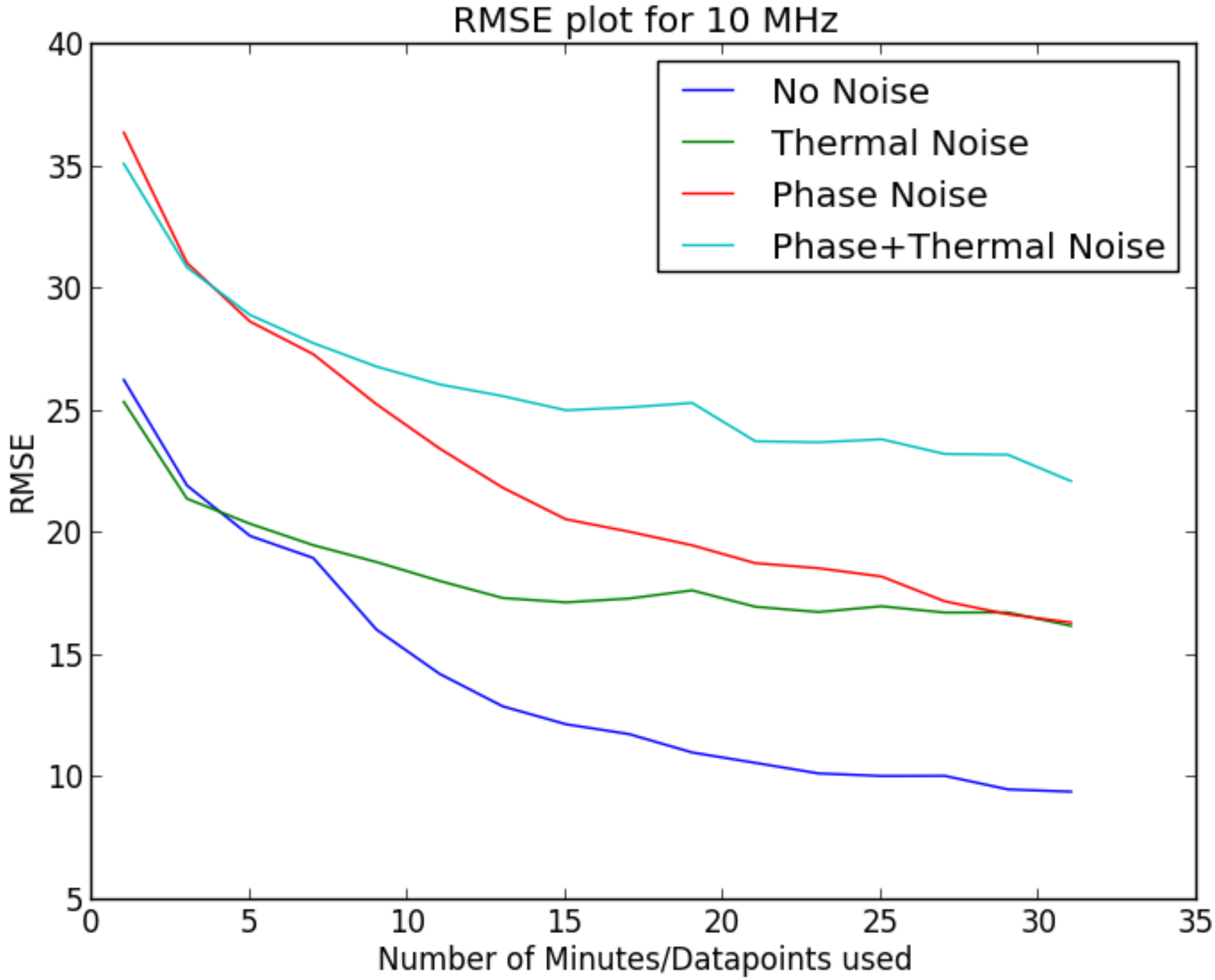


λ (mm) 30000.00

Robust 0.00

Phase and Thermal Noise


RMSE plot for 10 MHz with Thermal Noise and Positional Uncertainty


RMSE plot for 10 MHz
RMSE
Number of Minutes/Datapoints used
No Noise
Thermal Noise
Phase Noise
Phase+Thermal Noise
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35

Orbital-APSYNSIM: Easy & Flexible Parameter Changing

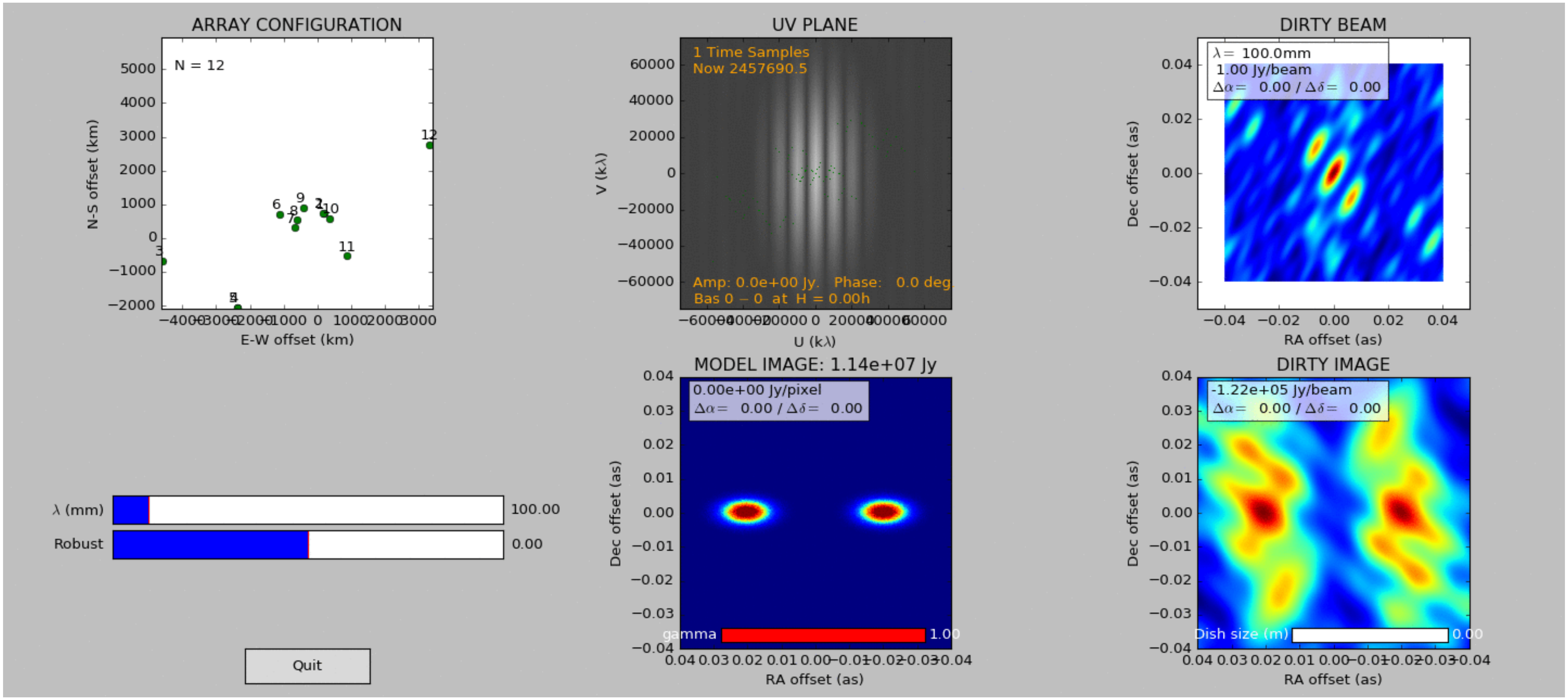
Including:

- Path to .png Image for Ground Truth Source
- How large in arcsec width of image is
- RA, Dec of source
- Scale brightness of image’s brightest pixel
- Observing wavelength, bandwidth, integration time
- Diameters of individual antenna
- Pixel resolution of Dirty Image (power of 2 fastest bc FFT)

- Non-contiguous time periods over which to integrate (e.g. 10:00 – 10:30 & 11:00-11:30)

- Path to file describing spacecraft orbits (EME2000)
- All Noise modes

VLBA Applications



λ (mm) 100.00

Robust 0.00

Image made with 10 VLBA antenna and 2 GEO satellites at 3GHz

Overview of Current Capabilities of Orbital-APSYNSIM

- Orbital-APSYNSIM can realistically simulate the response of a Space Based Interferometer with a particular orbit on a given science target

- It is useful for fine tuning orbits and scheduling system operations

- Can identify **point of diminishing returns for integration time**, e.g. for Relic observing a 500 Jy DRAGN it is about **10-15 minutes**

- Combine Earth based and Space based receivers

More Science Targets for Space Based Arrays

- Other science targets are transient and evolve quickly, e.g. CMEs
- Array of few spacecraft couldn't do detailed imaging but could at least localize the emission
- Want to show that snapshot images can point to the radio hotspot with accuracy
- No orbit integration so can use industry standard CASA

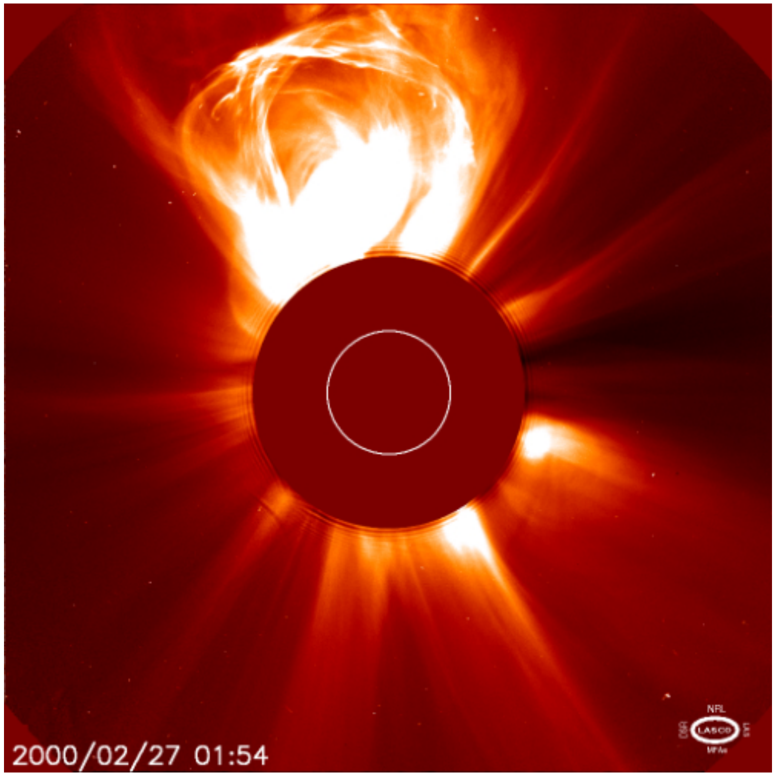


Image taken by SOHO spacecraft

SunRISE Mission

- 6 spacecraft
- Orbit around Earth
- Goal: localize emission on CMEs to within 1/3 its width
- Help clarify the basic physics of CMEs

Evaluating SunRISE’s Performance

- Create truth images of idealized CMEs Gaussians
- Create simulated array, choose frequency, etc.
- Observe with simulated array, creates .ms file
- Image and clean
- Fit Gaussian to image, compare to truth position

Using Electron Density Models to Inform CME Position

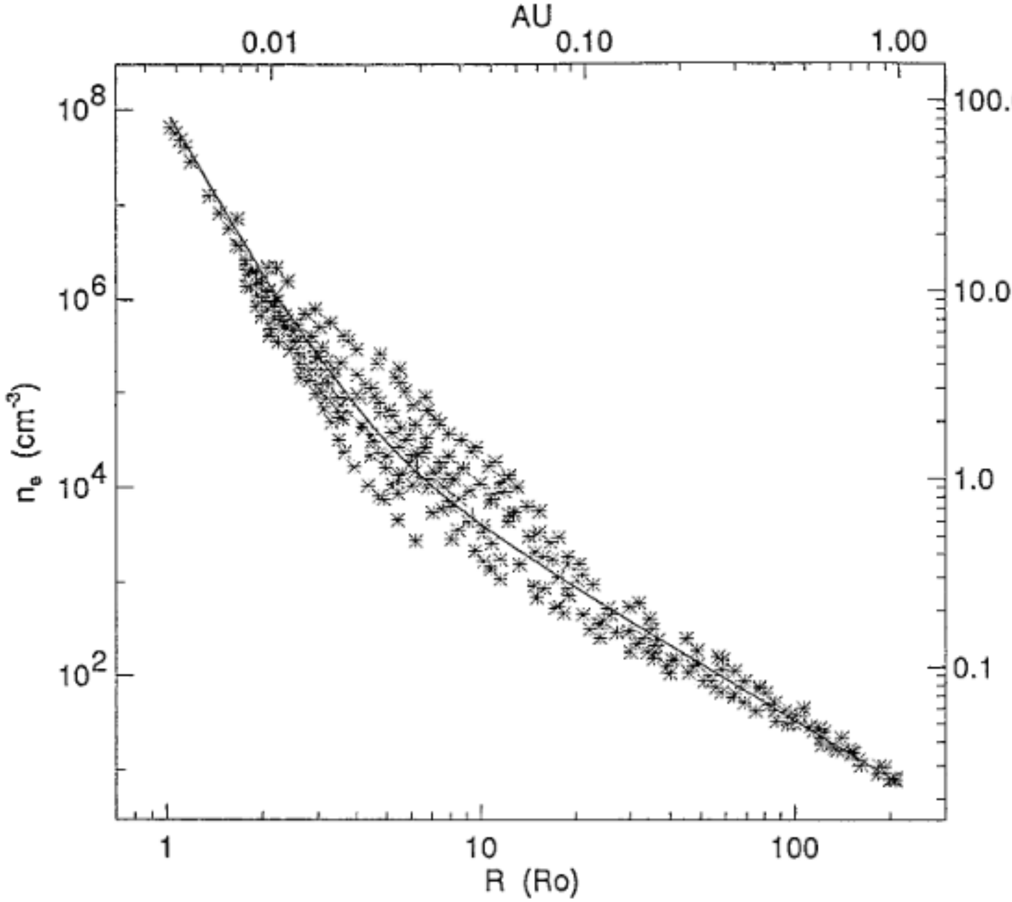
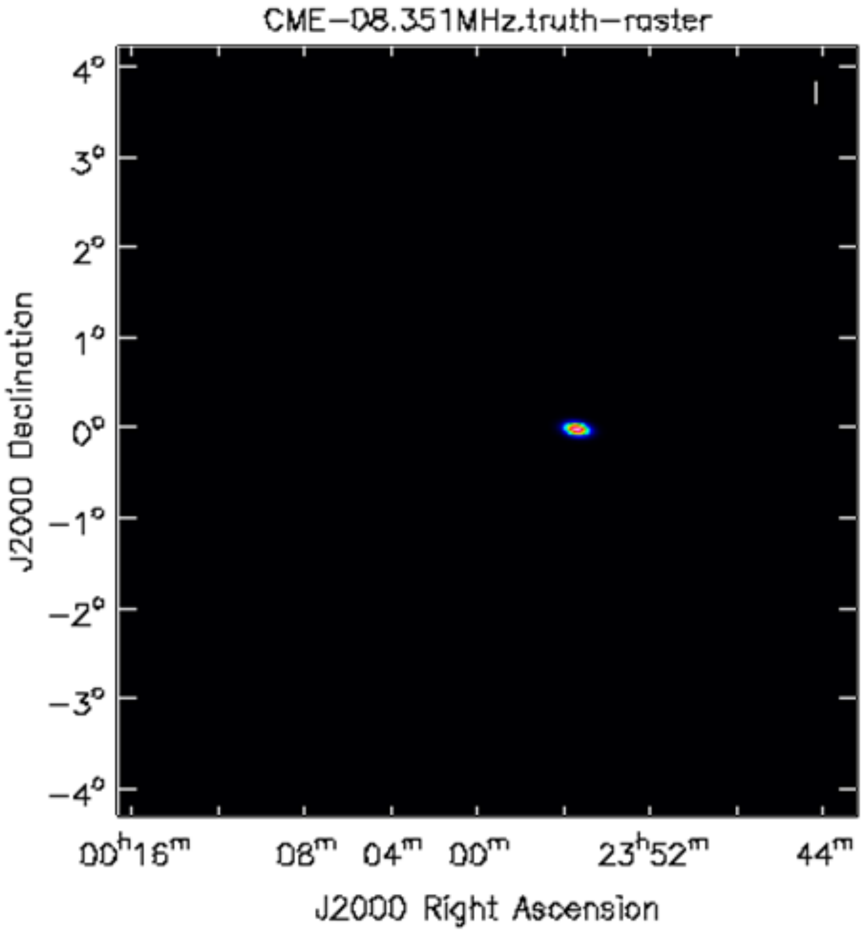
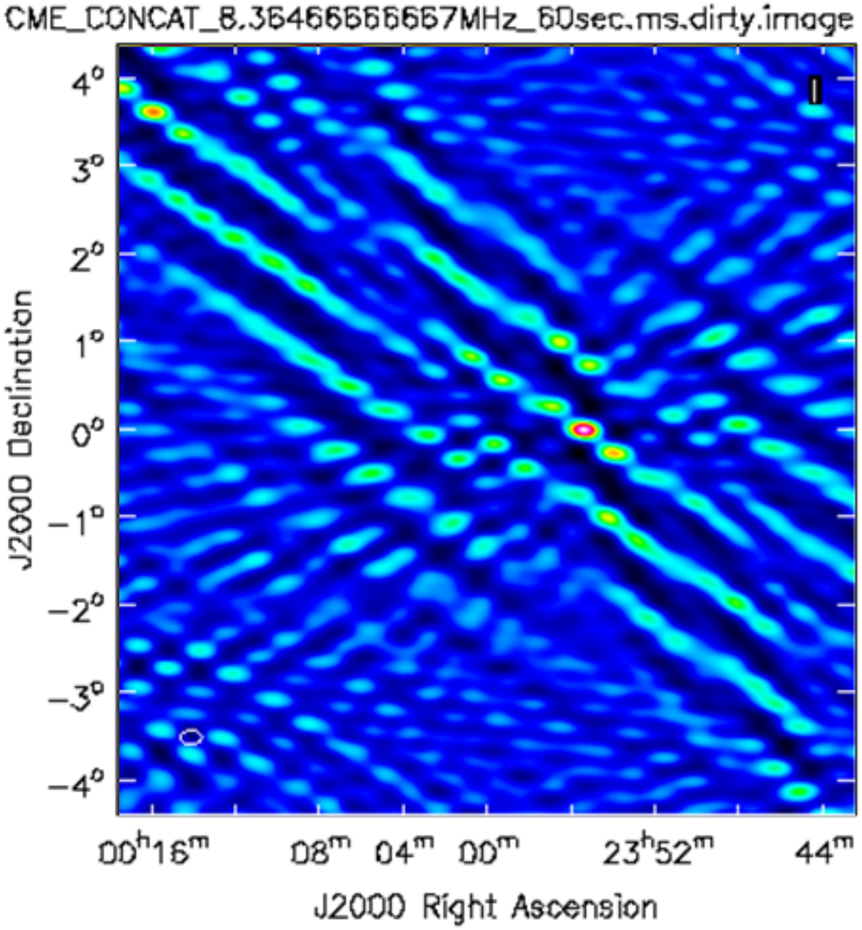


Figure 5. Electron density model vs radial distance derived from all 11 events, where the density at 1 AU has been normalized to 7.2 cm^{-3} ($f_p = 24$ kHz). The solid line is the best fit whose equation is given in the text. The small cluster of points in the upper left comes from 25–75 MHz observations of Nançay for one event.

Figure by Leblanc et al. 1998 *Solar Physics*



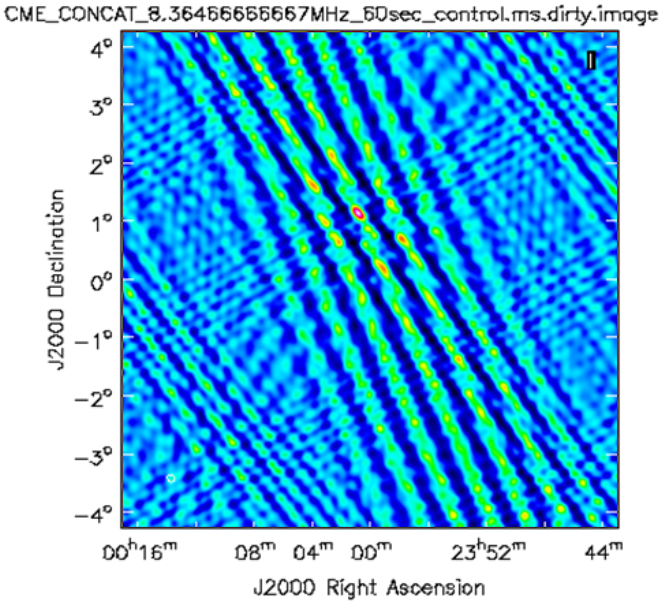
Truth Image to be recreated by simulated array

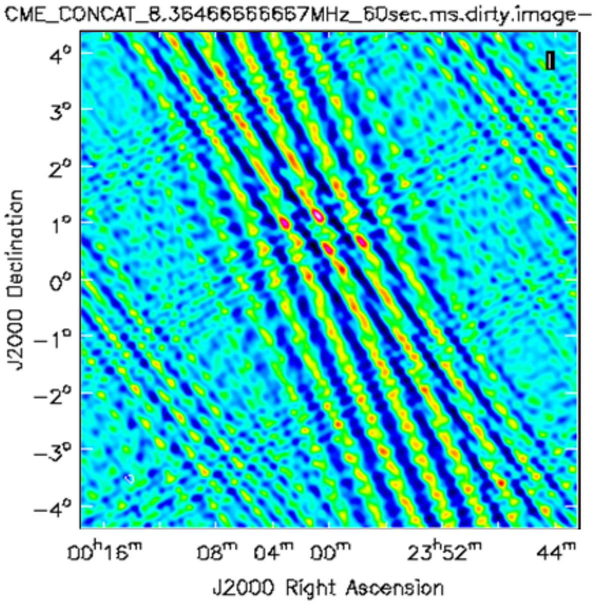


SunRISE simulated dirty image from 3 concatenated frequency subbands

Effect of Positional/Phase Error on CASA SunRISE Images

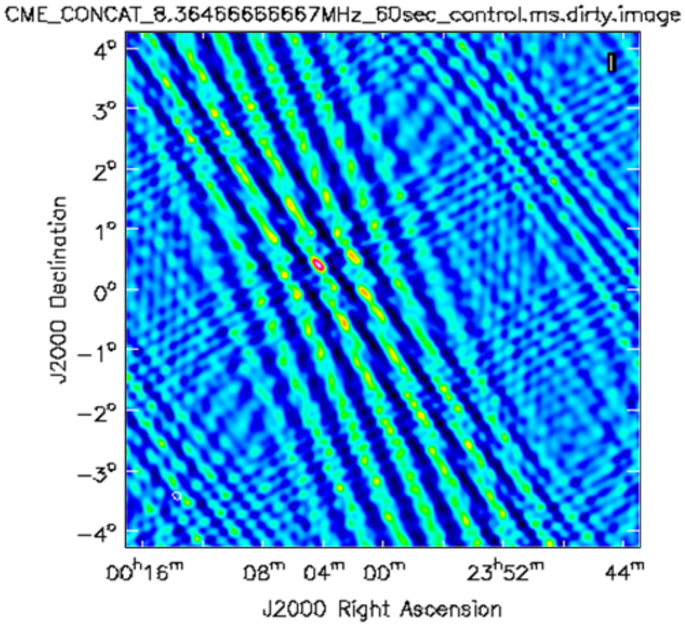
No Error

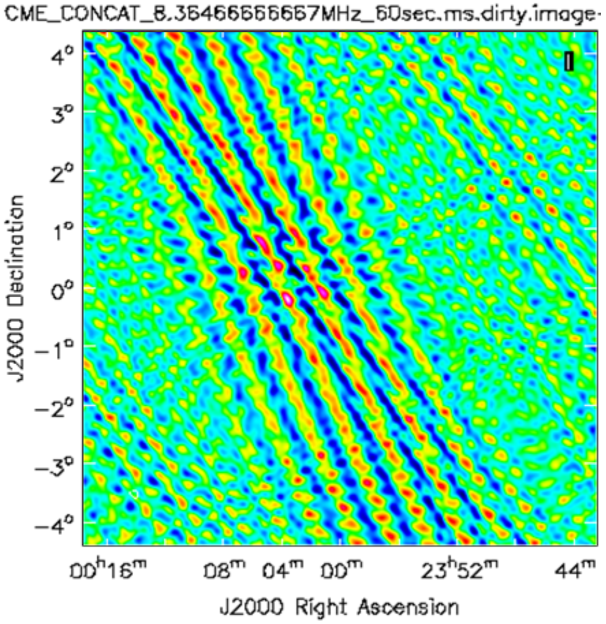




20 degrees
τ =6.5 ns

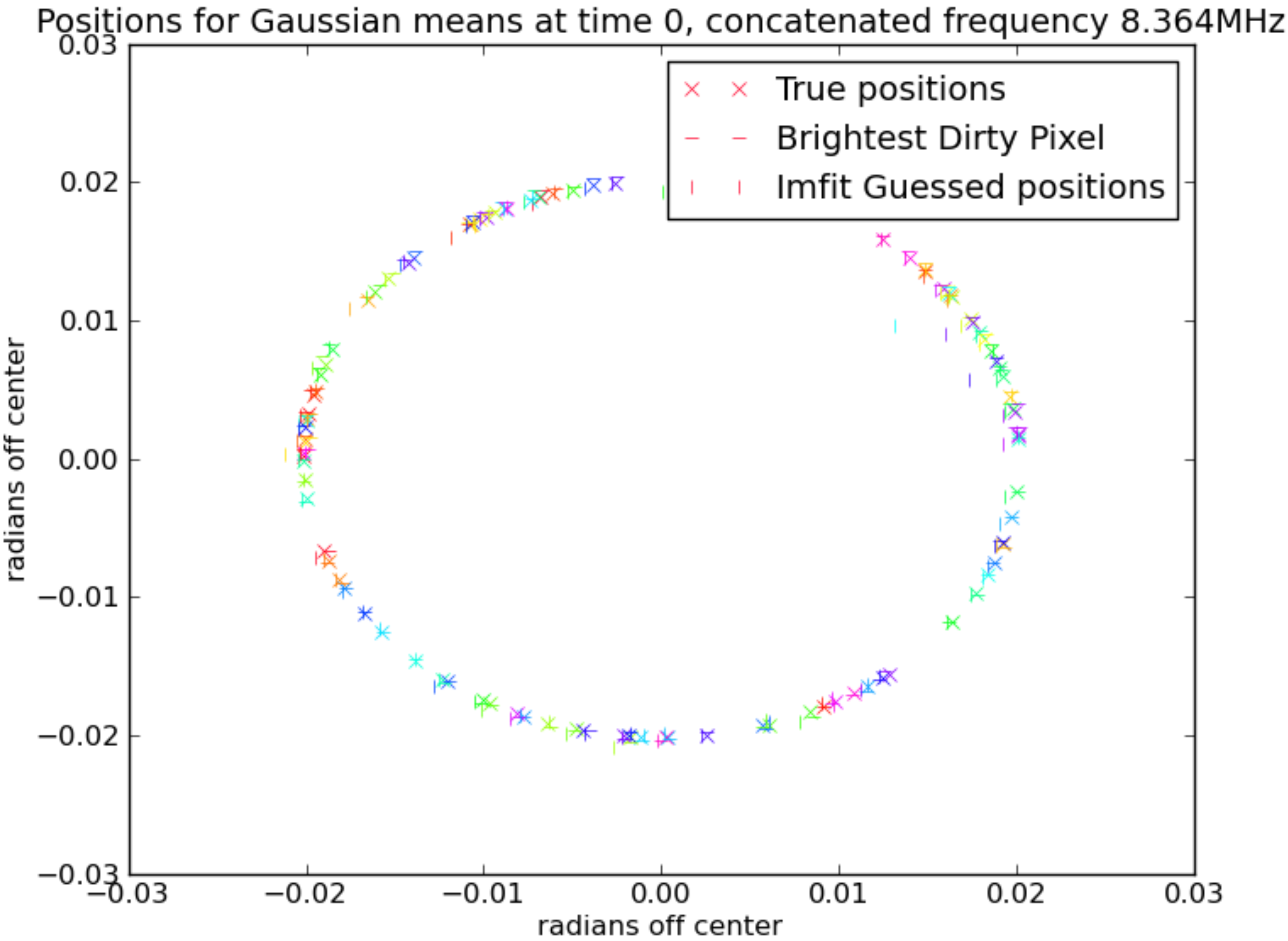
No Error



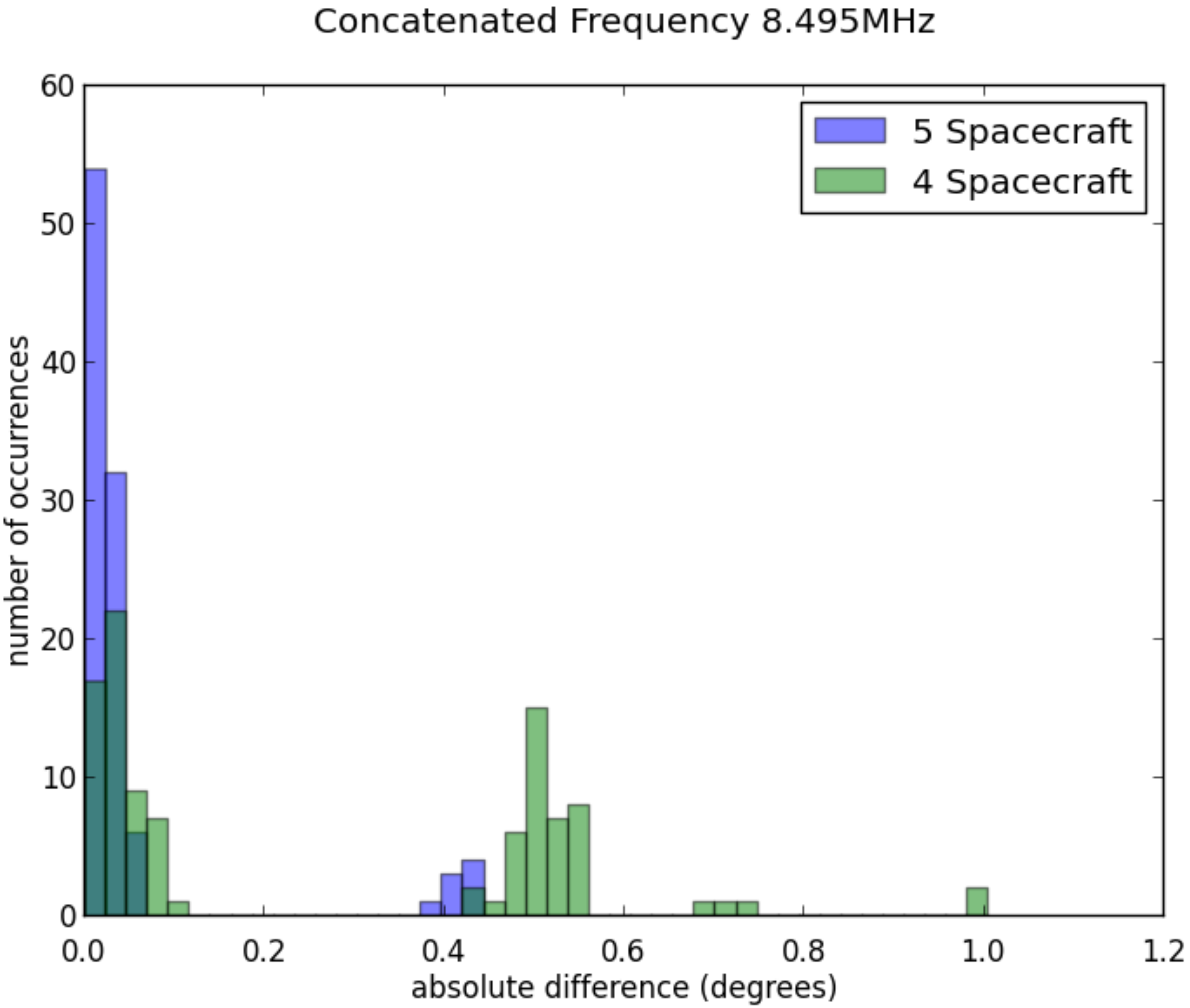


40 degrees
τ =13 ns

Recreating Positions



With Galactic Noise, 5 ns clock bias, 5 ns positional uncertainty



98% are within goal of .5 degrees, showing that SunRISE is feasible

Future Work

Additional steps for Lunar Surface Array

- Add ephemerides of moon and sun to baseline computation, also Lunar rotation
- Add in digital elevation models from LOLA to increase realism
- Use LOLA data of elevation slope and roughness to filter out bad areas & use Boone (2001) to optimize placement of antenna
- Output computed visibilities into CASA for analysis

Understanding Trade Space

- Key Figures: Complexity vs Science Value & Cost vs Science Value
- Come up with metrics
- **Complexity:**
  - Options: Isotropic vs High gain antennas, observing ranges
  - snapshots of transients vs long integration of static targets

- **Cost:**
  - Get an idea on the cost curve for putting up x spacecraft
  - Fuel costs, hardware costs, labor costs, etc.
  - Mission lifetime versus time needed for data transmissions for science targets

- **Science Value:**
  - For long integration science targets, value is a function of resolving power, sensitivity, number of spacecraft, observing frequency range, and total integration time on targets.
  - For transient snapshot capabilities, it depends on the sort of regression problem you define, which in turn depends on all those other variables.

Questions?