A Prototype Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) for Atmospheric Temperature Sounding

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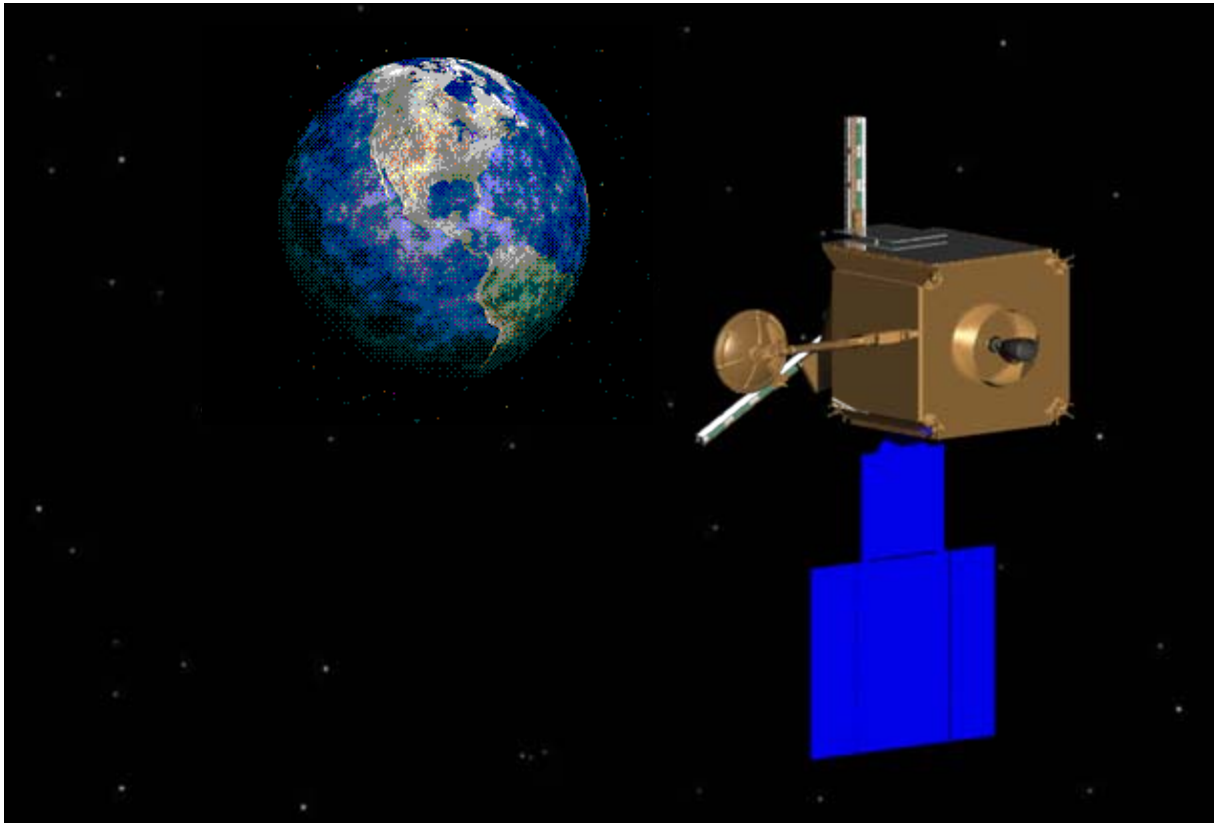


Outline:

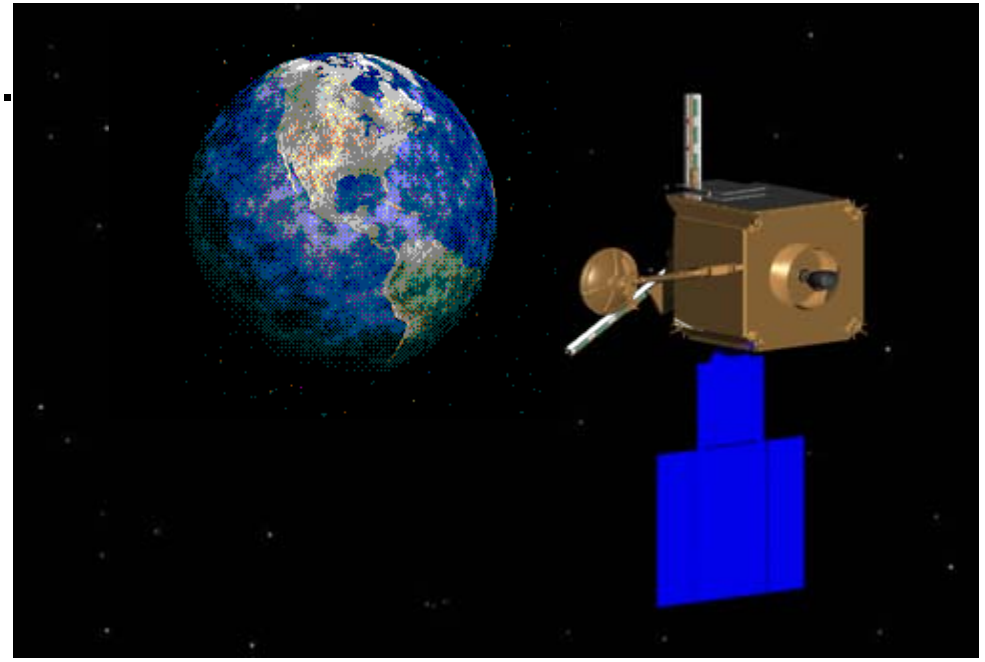
1. Overview
2. Requirements & error allocations
3. Design
4. Problems, and how we solved them
5. Results

Overview

- GeoSTAR is a concept to deploy a microwave radiometer in Geostationary Earth Orbit.

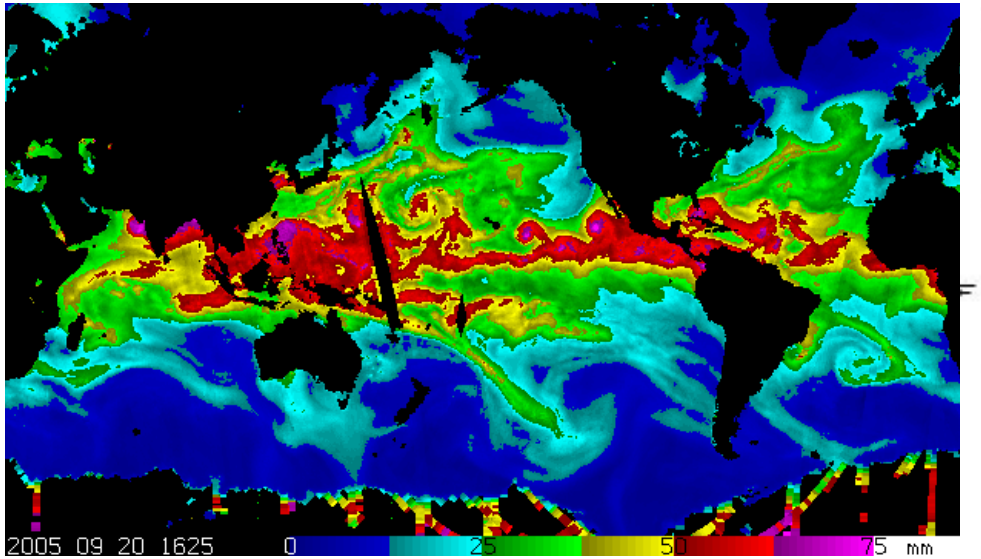
- Aperture Synthesis used to achieve high spatial resolution from thinned array with no moving parts.

- 25 - 50 km spatial resolution in bands from 50 to 180 GHz, 1 K NEDT.

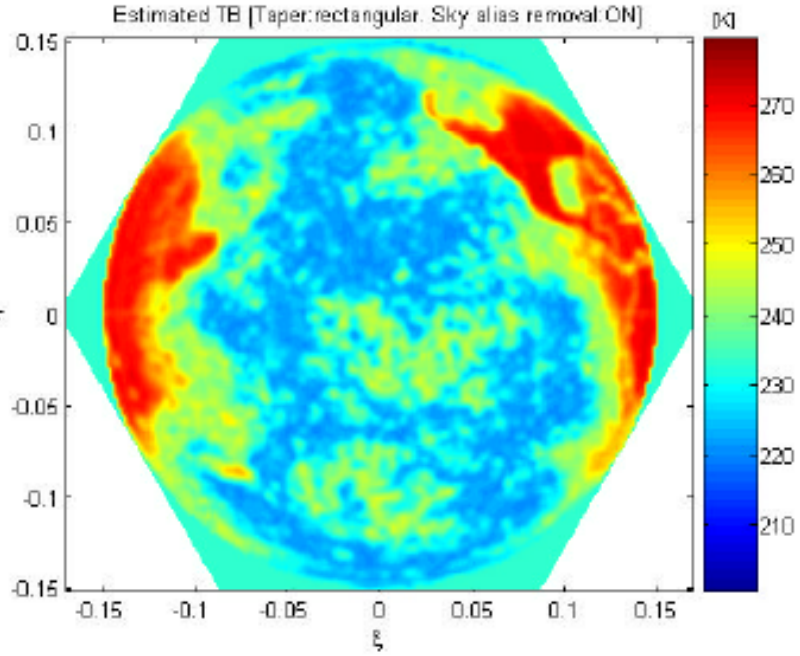


Science Driver

Provide short-term full disk data on atmospheric temperature and humidity, to improve weather forecasting on rapidly evolving, cloud covered weather systems (eg tropical storms).

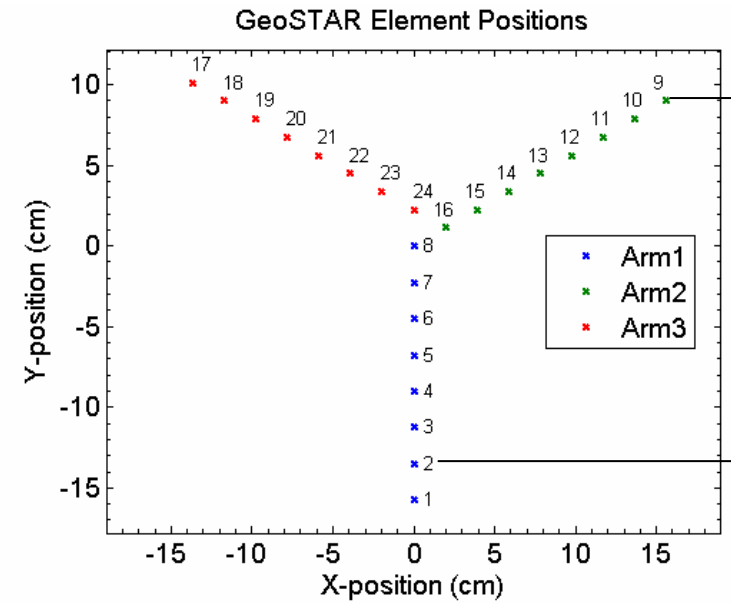


AMSU/SSMI/S 6 hour global water vapor image



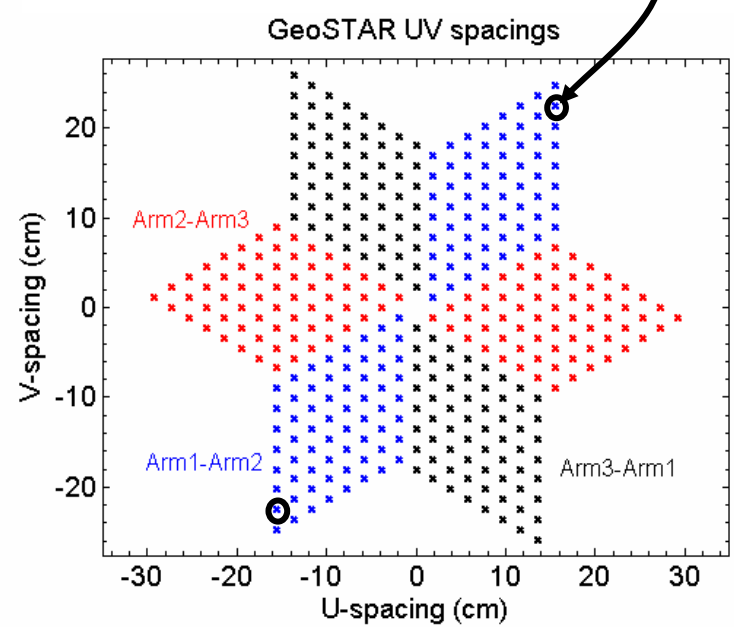
Simulated GeoSTAR 15 min retrieval.

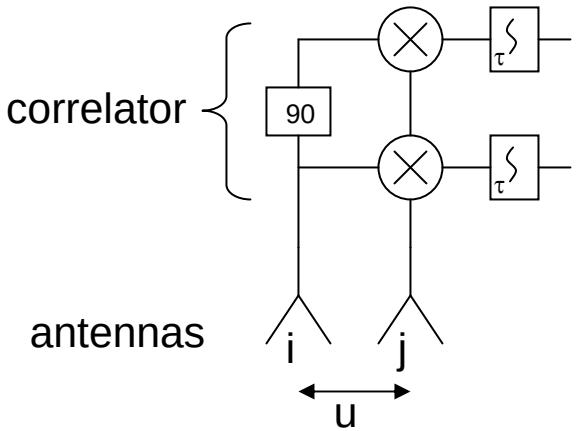
GeSTAR is an array of correlation interferometers:



one cross-correlation
= <u>one</u> sample of 'visibility'

Correlations of <u>all</u> antenna pairs fills synthetic aperture in "U-V" space





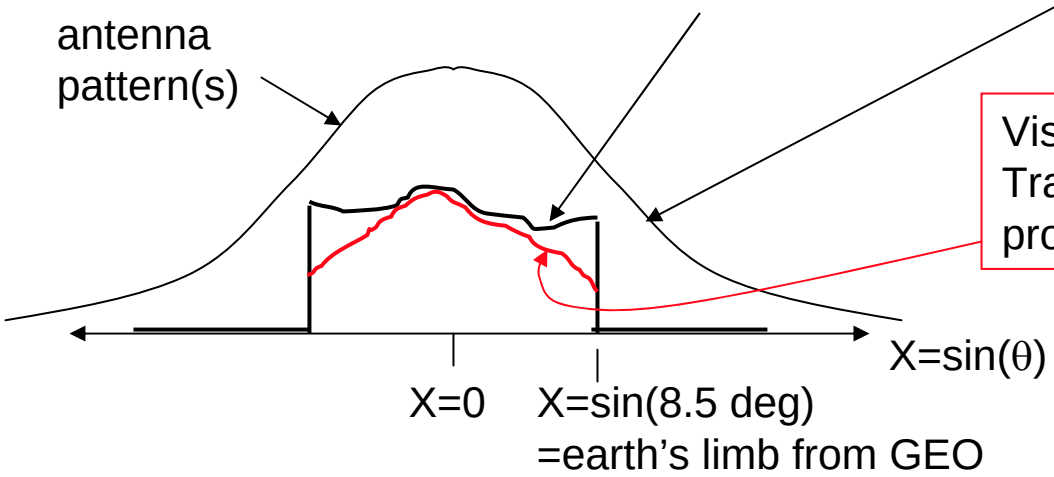
visibility

$$V_Q(u) = \int_x T_B(x) f_i(x) f_j(x) \sin\left(2\pi x \frac{u}{\lambda}\right) dx$$

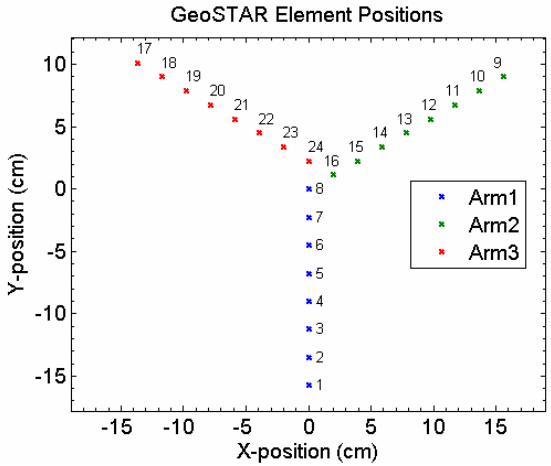
$$V_I(u) = \int_x T_B(x) f_i(x) f_j(x) \cos\left(2\pi x \frac{u}{\lambda}\right) dx$$

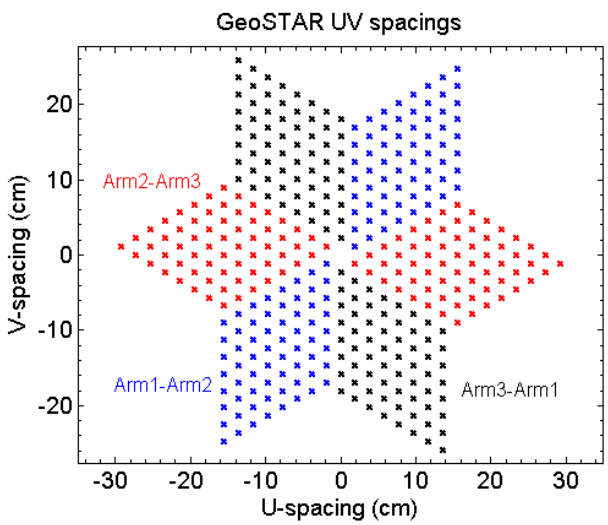
brightness temperature $=T_B(x)$

antenna pattern product $=f_i(x)f_j(x)$



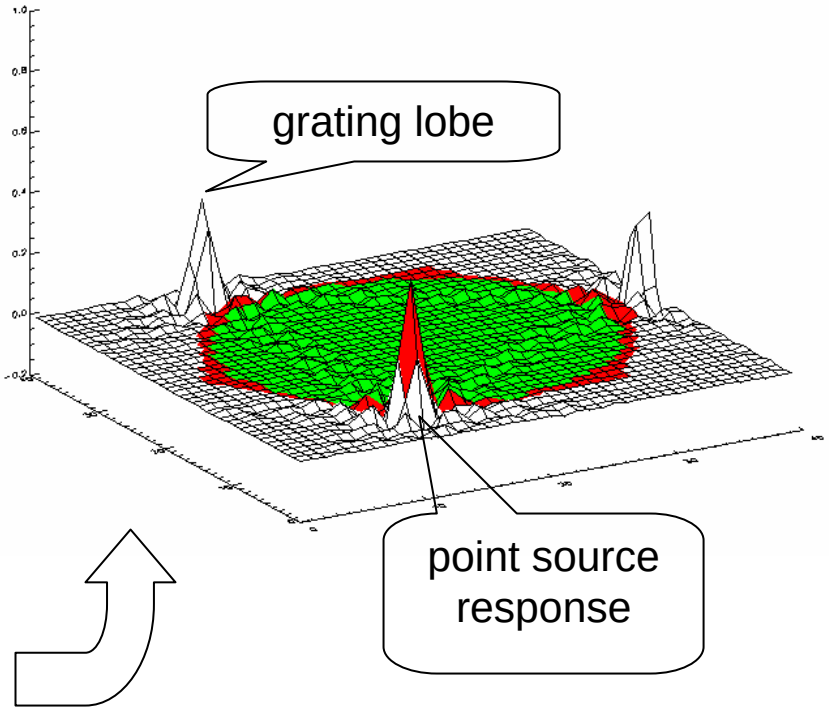
Visibility is the Fourier Transform of the product: $T_B(x)f_i(x)f_j(x)$





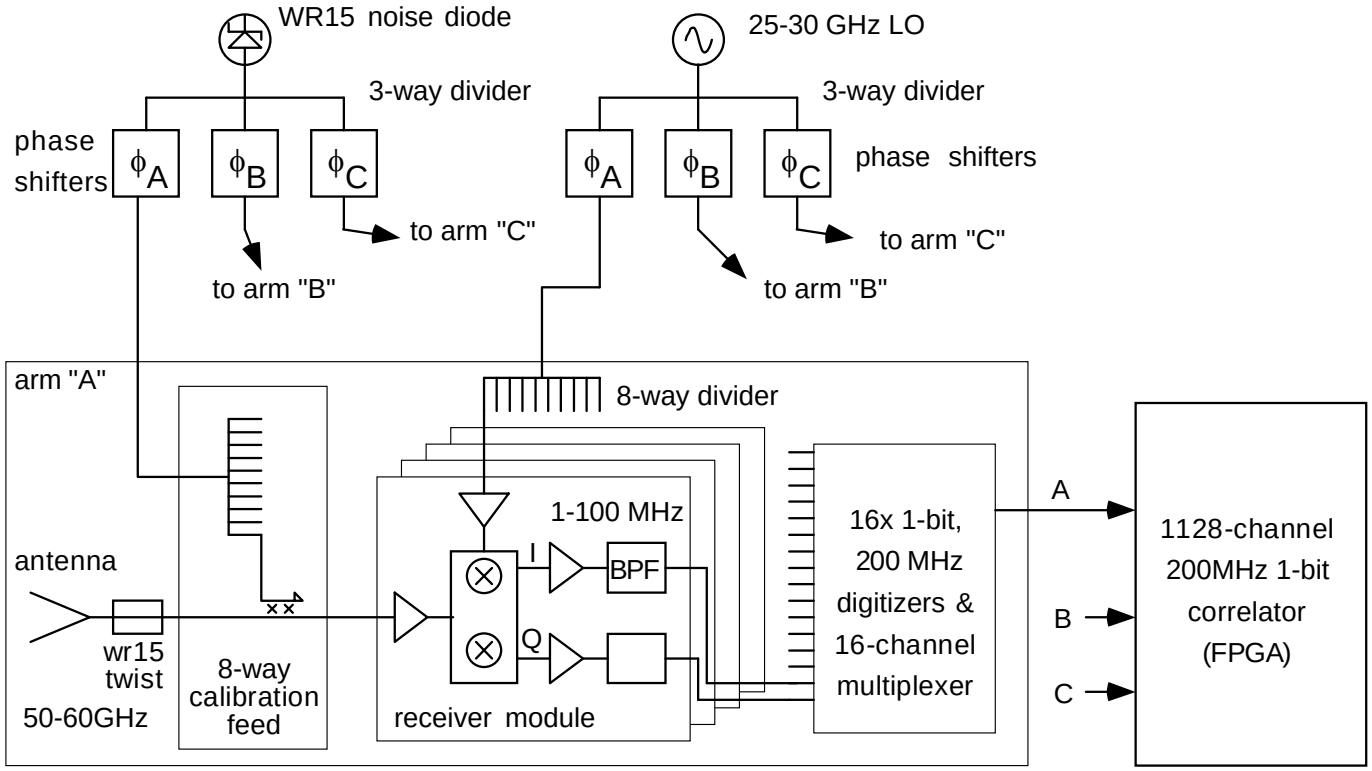
hexagonally gridded UV samples

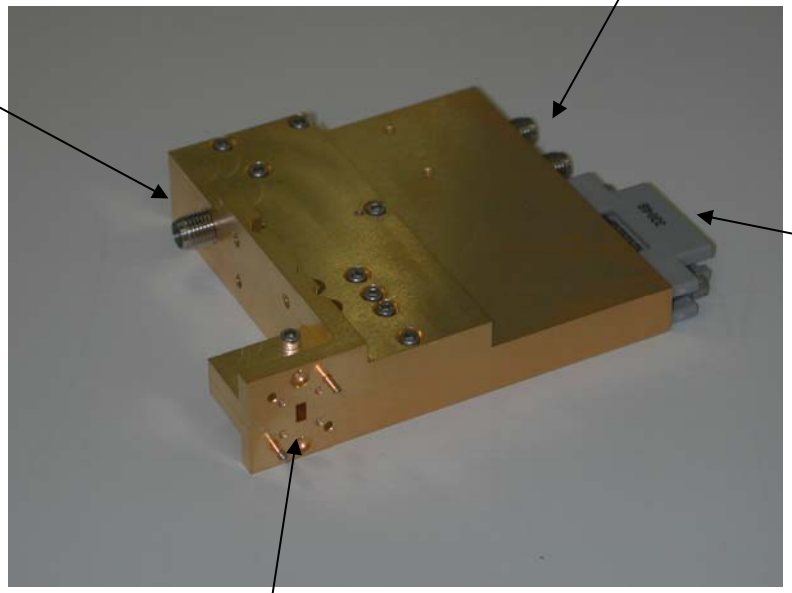
hexagonal unambiguous field of view



GeoSTAR Prototype:

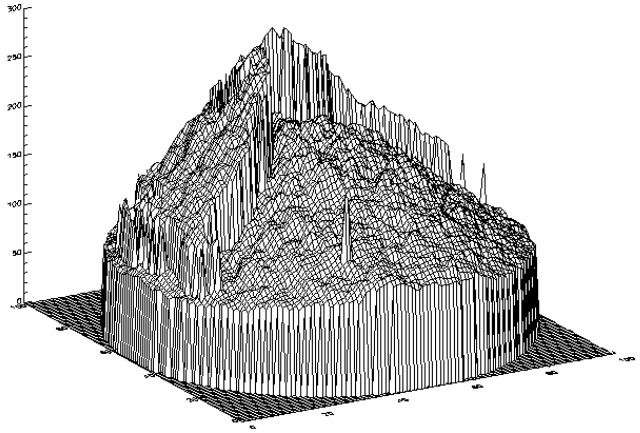
- Ground based “proof of concept” synthesis array radiometer
- 50 - 55 GHz (temperature sounding)
- 24-element Y-array (vs ~ 300 elements for space)
- 0.6 degree spatial resolution
- 17 degree FOV (= earth diameter in GEO)


WR15 noise diode
25-30 GHz LO
3-way divider
3-way divider
phase shifters
ϕ_A
ϕ_B
ϕ_C
ϕ_A
ϕ_B
ϕ_C
phase shifters
to arm "C"
to arm "B"
to arm "C"
to arm "B"
arm "A"
8-way divider
1-100 MHz
antenna
I
BPF
Q
wr15 twist
50-60GHz
8-way calibration feed
receiver module
16x 1-bit, 200 MHz digitizers & 16-channel multiplexer
A
B
C
1128-channel 200MHz 1-bit correlator (FPGA)


IF Output(I+Q)
LO
Input
Power
&
control
WR15 Antenna Input

Requirements & error allocations

- Based on numerical simulations
- Derived for spaceborne system

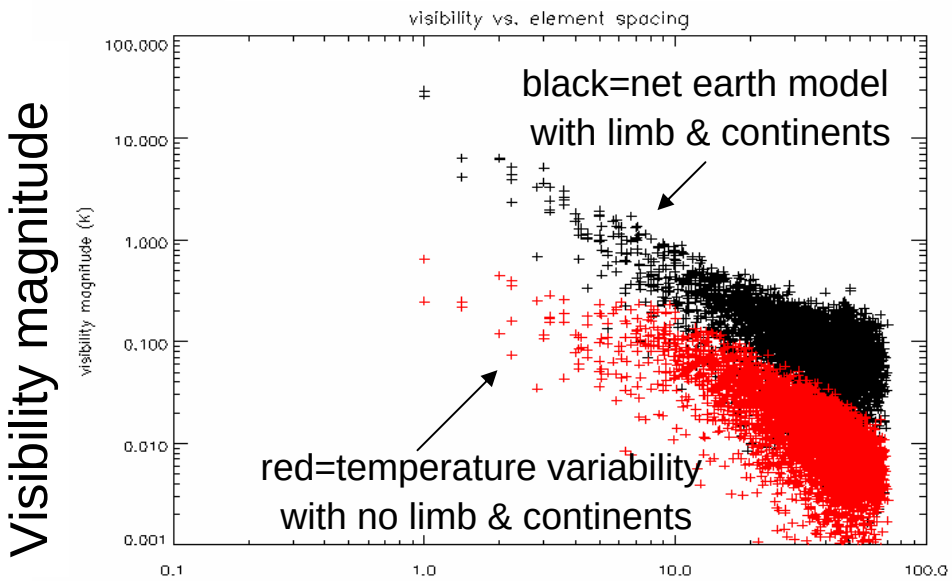


earth model, weighted
by antenna pattern

Calibration Error Budget

- Simulations reveal how visibility spectra falls off with larger spacings

Modeled visibility spectra



Visibility magnitude

UV element spacings

⇒ gain and phase requirements relaxed at larger UV spacings

⇒ helpful for large arrays

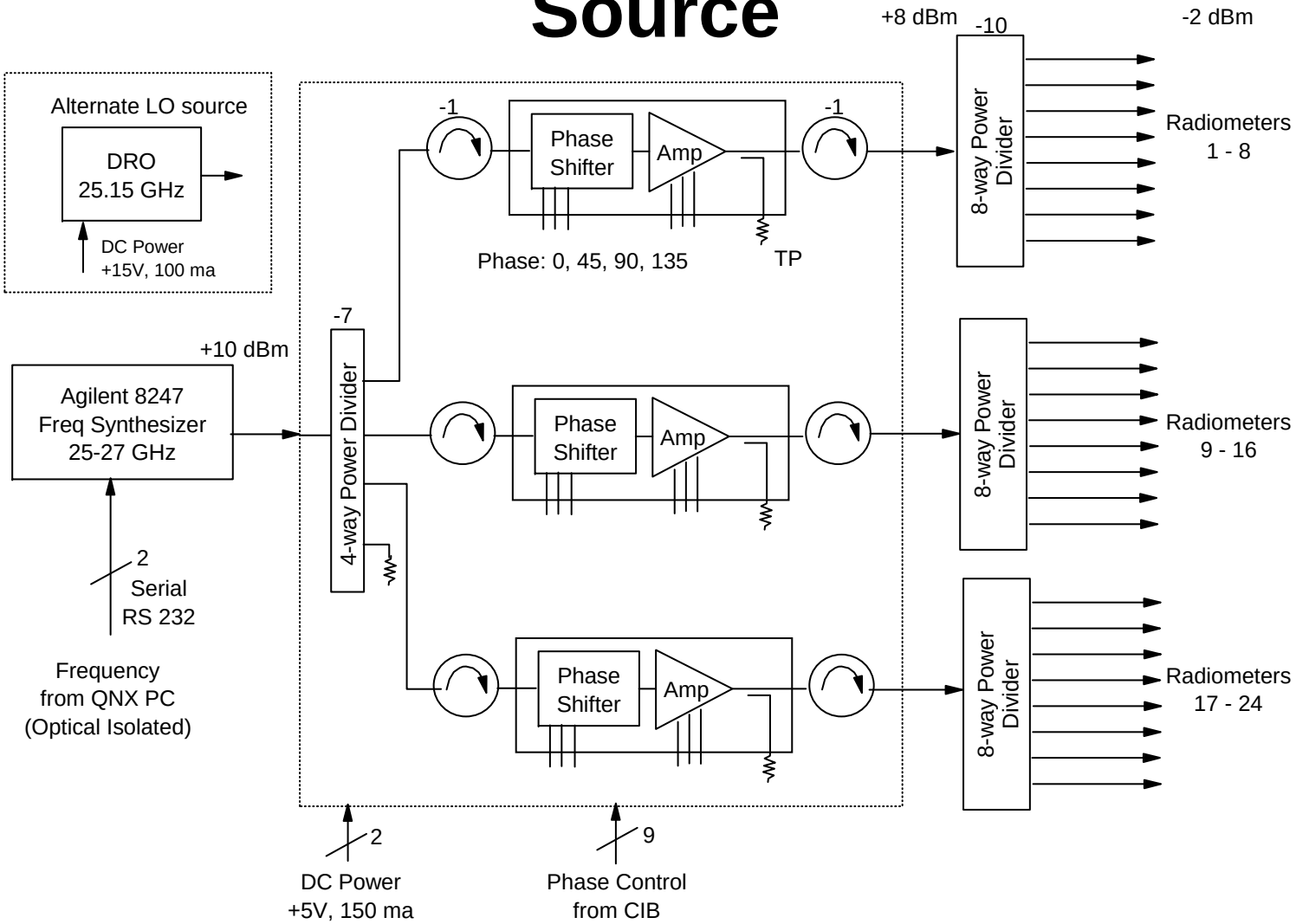
⇒ visibility dominated by earth's limb and continental contrasts

Calibration Error Budget

image size (pixels)	additive noise = biases and delta-V $T_{sys}/\sqrt{2B\tau}$ (Kelvin)	delta-G =gain error in each correlator (%)	delta-P =phase error at each correlator (degrees)	phase error scaled by spacing. (degrees at max spacing)	antenna pattern error (%)	net image delta-T (Kelvin)
50x50	0.0076	0.32	0.19	1.7	0.17	1.0
200x200	0.0019	0.32	0.19	3.5	0.17	1.0

Each contributes 1/root(5) K to net T_B error → 1K net T_B error

GeoSTAR Local Oscillator Source

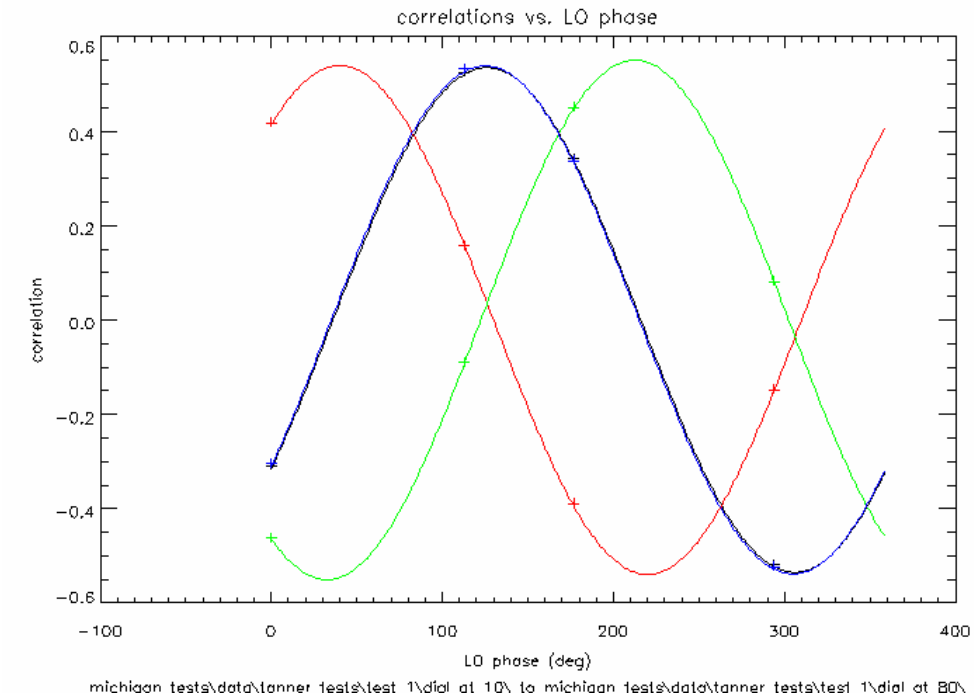


Evaluation Board Test Results from July & August

The ‘four-phase’ LO turns out to be very helpful- if not essential!

- Every correlator has 16 associated measurements: four LO phases each in the four correlators I1*I2 Q1*Q2 Q1*I2 and I1*Q2

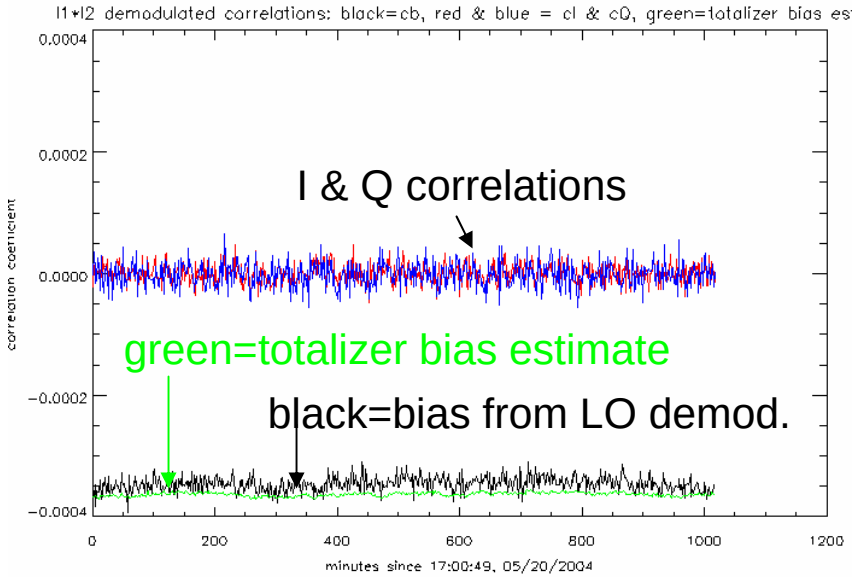
- The example to the right shows how it is possible to resolve the exact phase separation between in-phase (black and blue) and quadrature phase (green and red) correlations. The “+” marks are the measurements.



Evaluation Board Test Results from July & August

Back-end correlator biases were tested with incoherent LOs

- Test results show no correlator bias due to coherent IF or digital noise!
- Only bias is from digitizer null-offsets, which are precisely characterized with totalizer data.
- Tests also show that sample noise decreases precisely as expected out to 10,000 seconds!



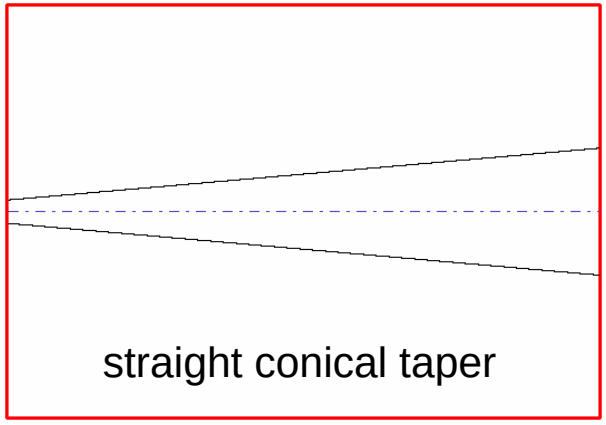
Integration time (s)	RMS noise I	Q	theory
1	0.0000903	0.0000907	0.0000828
10	0.0000286	0.0000284	0.0000262
100	0.0000090	0.0000091	0.0000083
1000	0.0000030	0.0000027	0.0000026
10000	0.0000009	0.0000010	0.0000008

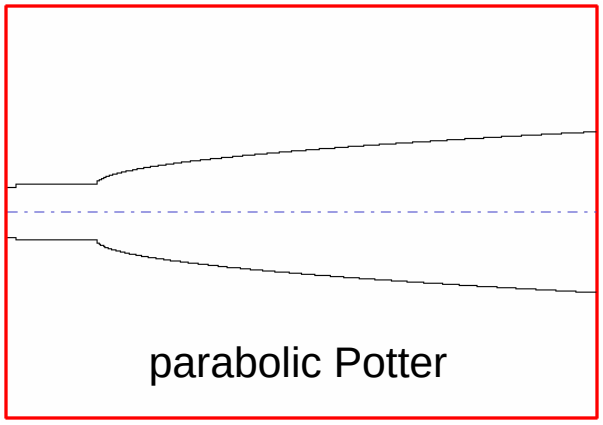
Antenna requirements

- Error budget from simulation allows only 0.17% uncertainty in antenna gain.

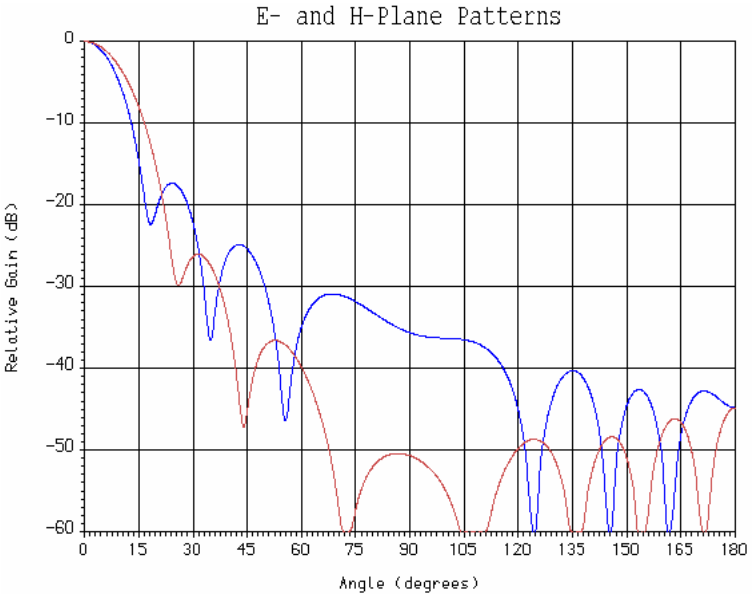
- Simulations indicate need for maximum gain. The earth-disk beam efficiency from GEO is 50% at best. The tight array spacing rules out corrugated horns.

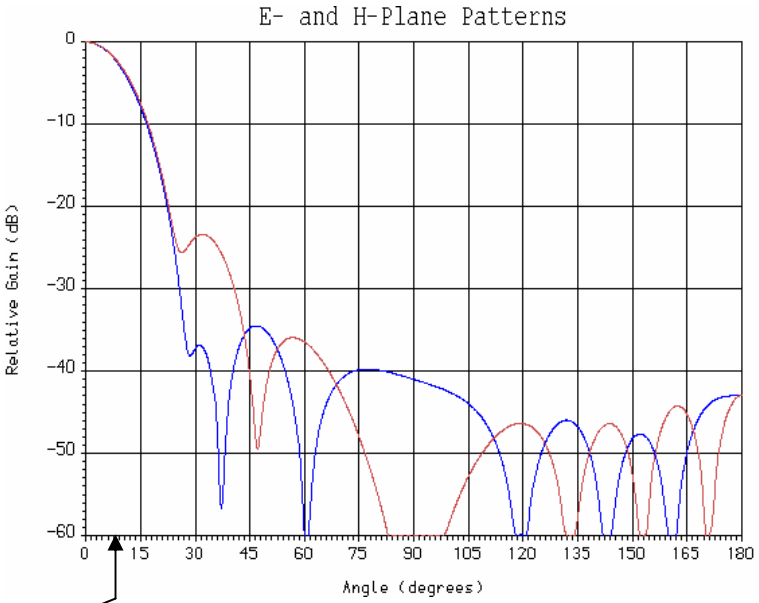
- Two designs were prototyped: straight taper, and parabolic Potter horns.





Antenna pattern comparison





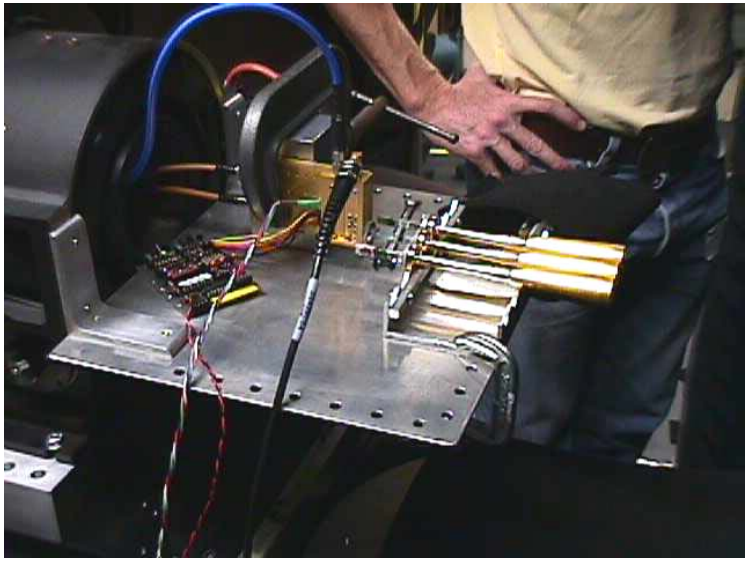
limb

straight taper

- poor symmetry and SLL, but highest earth efficiency of ~46%

parabolic potter

- best symmetry and SLL, but lower earth efficiency of ~40%



Initial antenna tests revealed that:

Straight taper horn pattern changed by ~5% when embedded in array

Parabolic Potter changed by < 0.5%

Parabolic Potter was the clear choice!

Evaluation Board Test Results from July & August, 2004

The most significant problem: RF cross-talk between antenna ports

- Coherent noise emitted from LNA input can create VERY high correlations of >0.5 when receiver inputs are directly connected to one another
- Correlations only decrease as square root of power attenuation
- Data indicate need for as much as 100 dB isolation between receivers!
- 100 dB possible for elements with wide spacing- but not neighbors

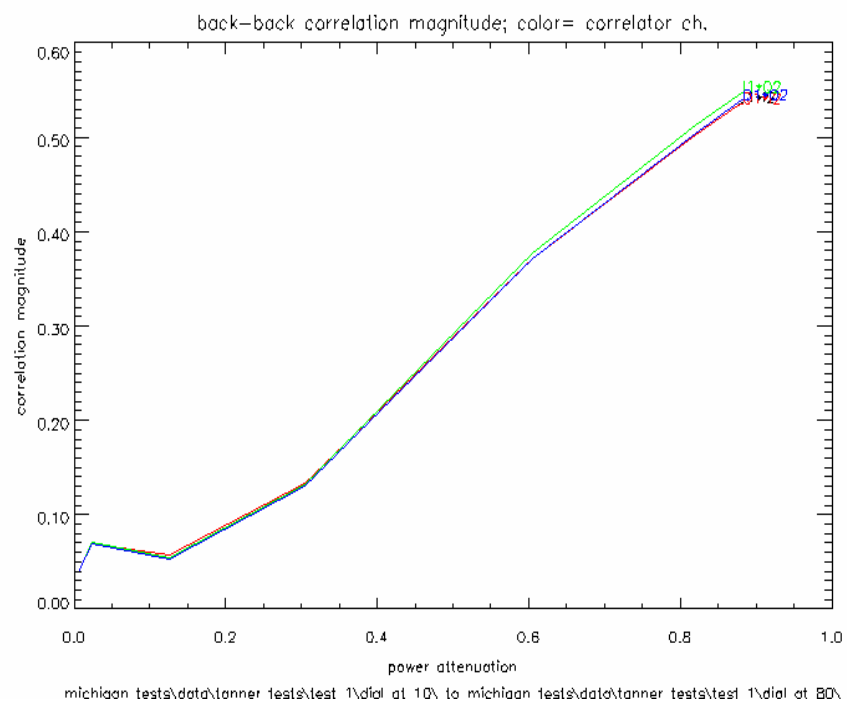
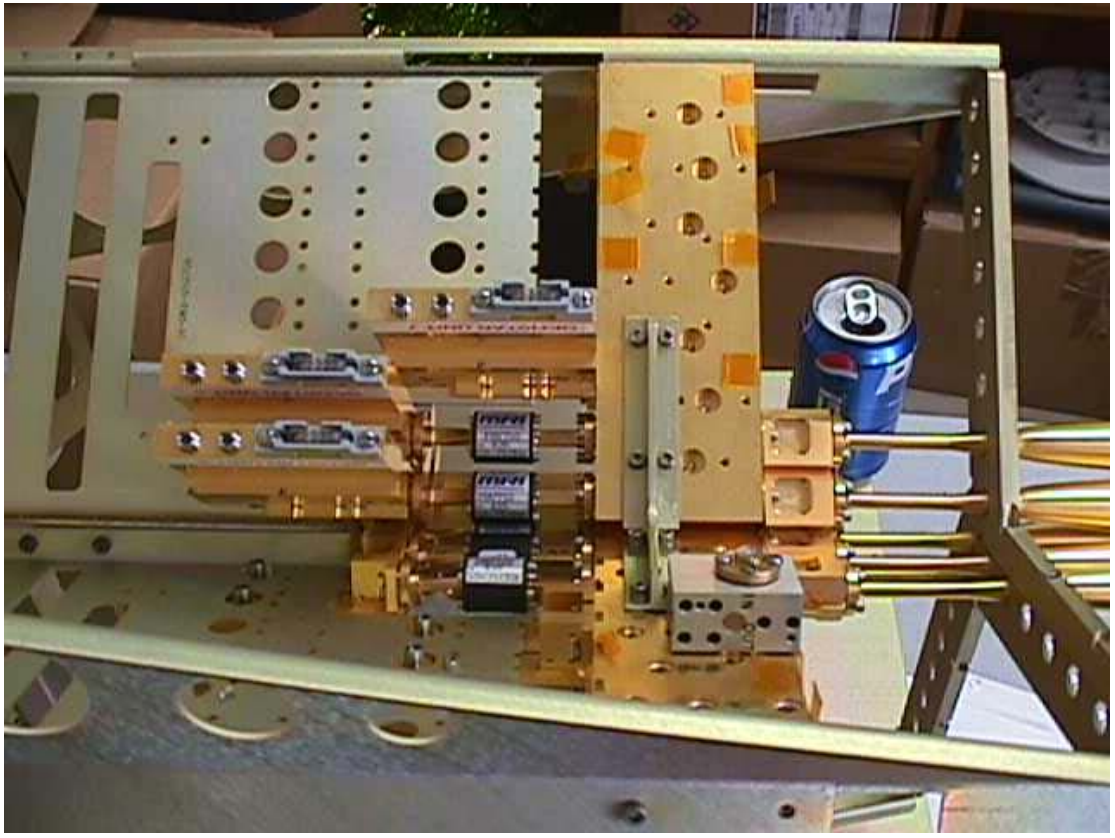
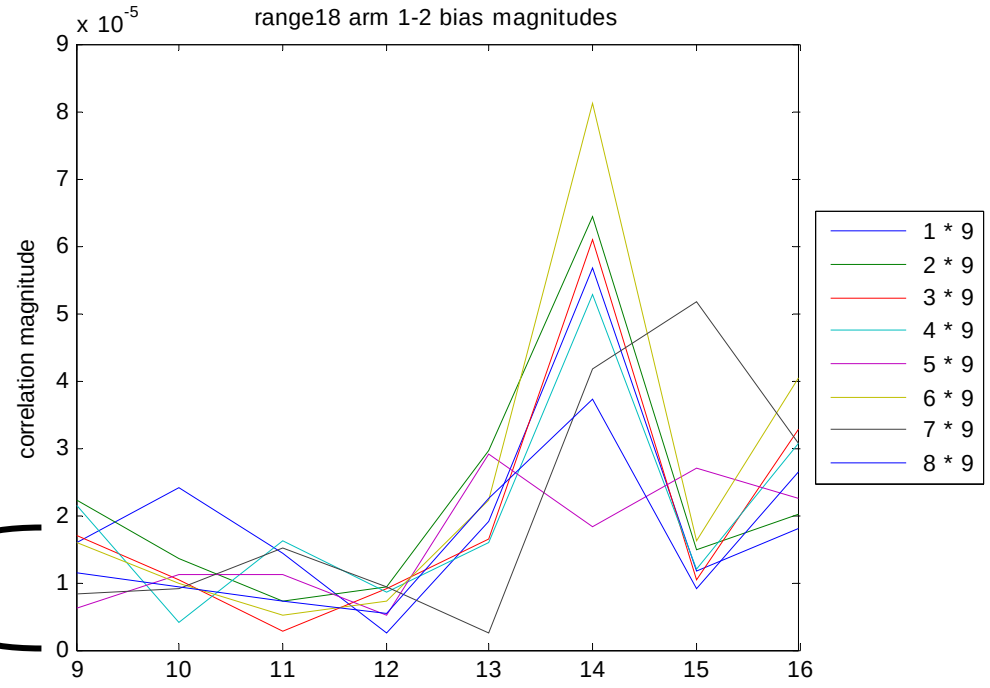


Figure 10: Correlation magnitudes versus attenuation between receivers in back-to-back tests. Different colors represent correlator channels: black=I1*I2, red=Q1*I2, green=Q2*I1, blue=Q2*Q1.

Solution to coupling problem:
Isolate only those receivers close to the center



Final correlator biases observed in anechoic chamber



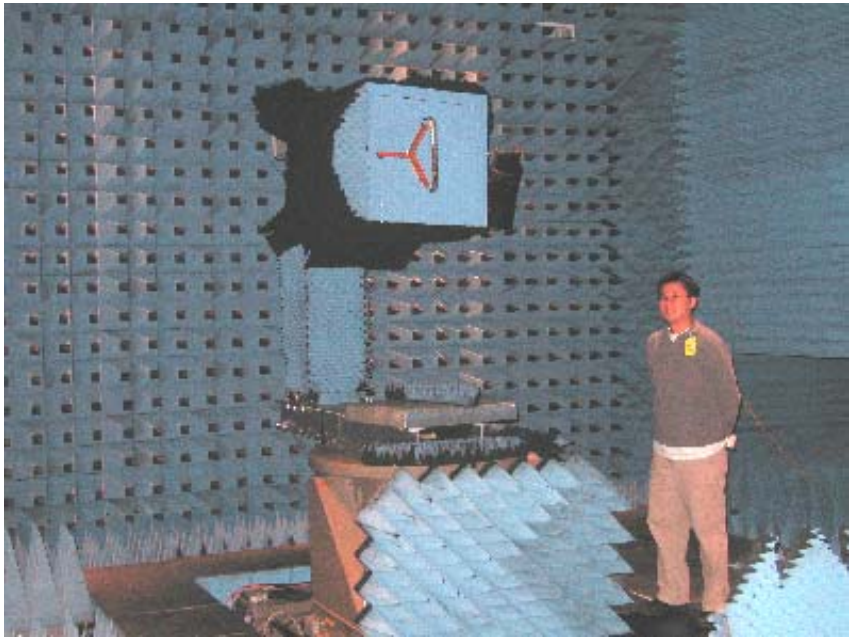
~ 10 mK
visibility bias

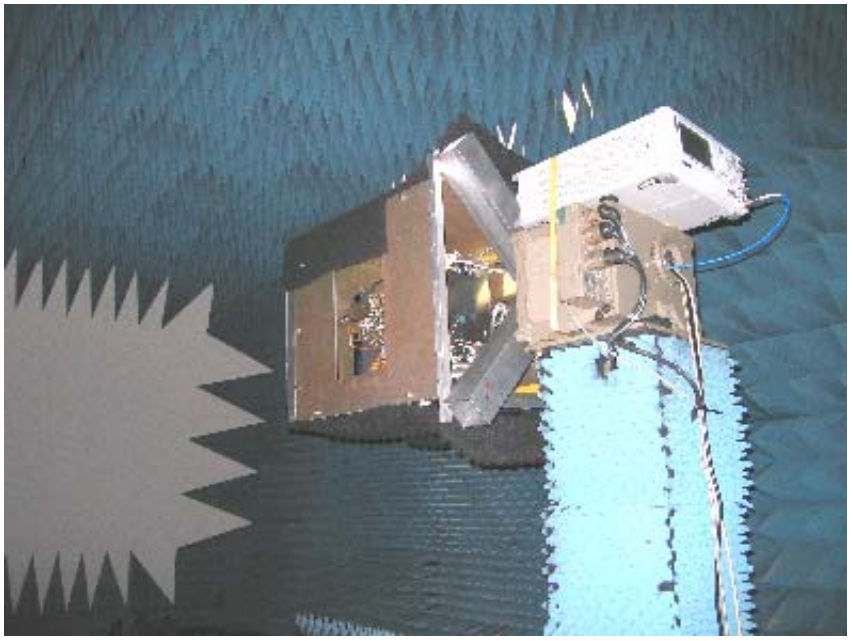
elements away from
array center, no isolators

near array center,
with isolators

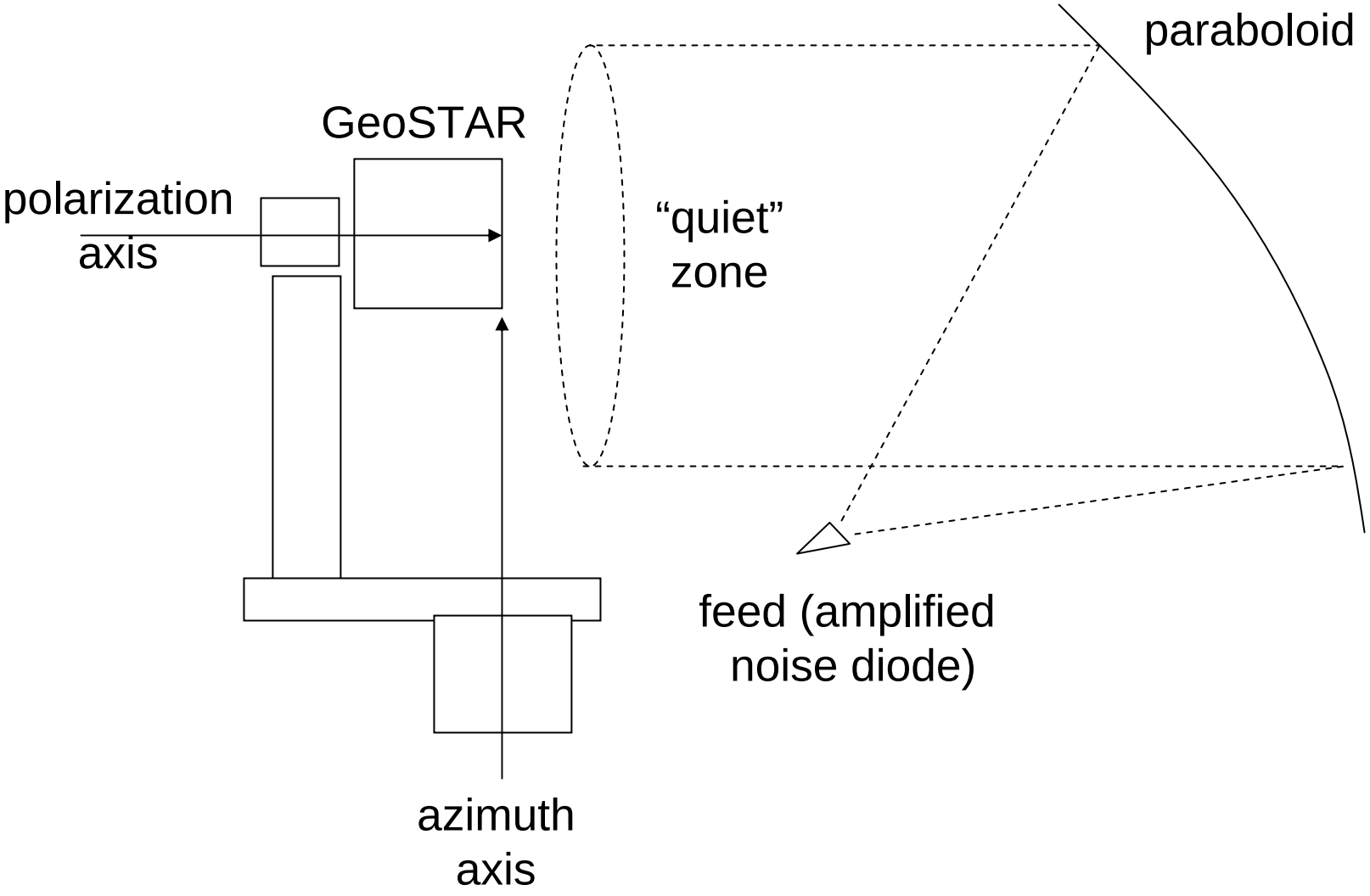
Antenna Range Tests

Goddard Space Flight Center, September 24-30, 2005

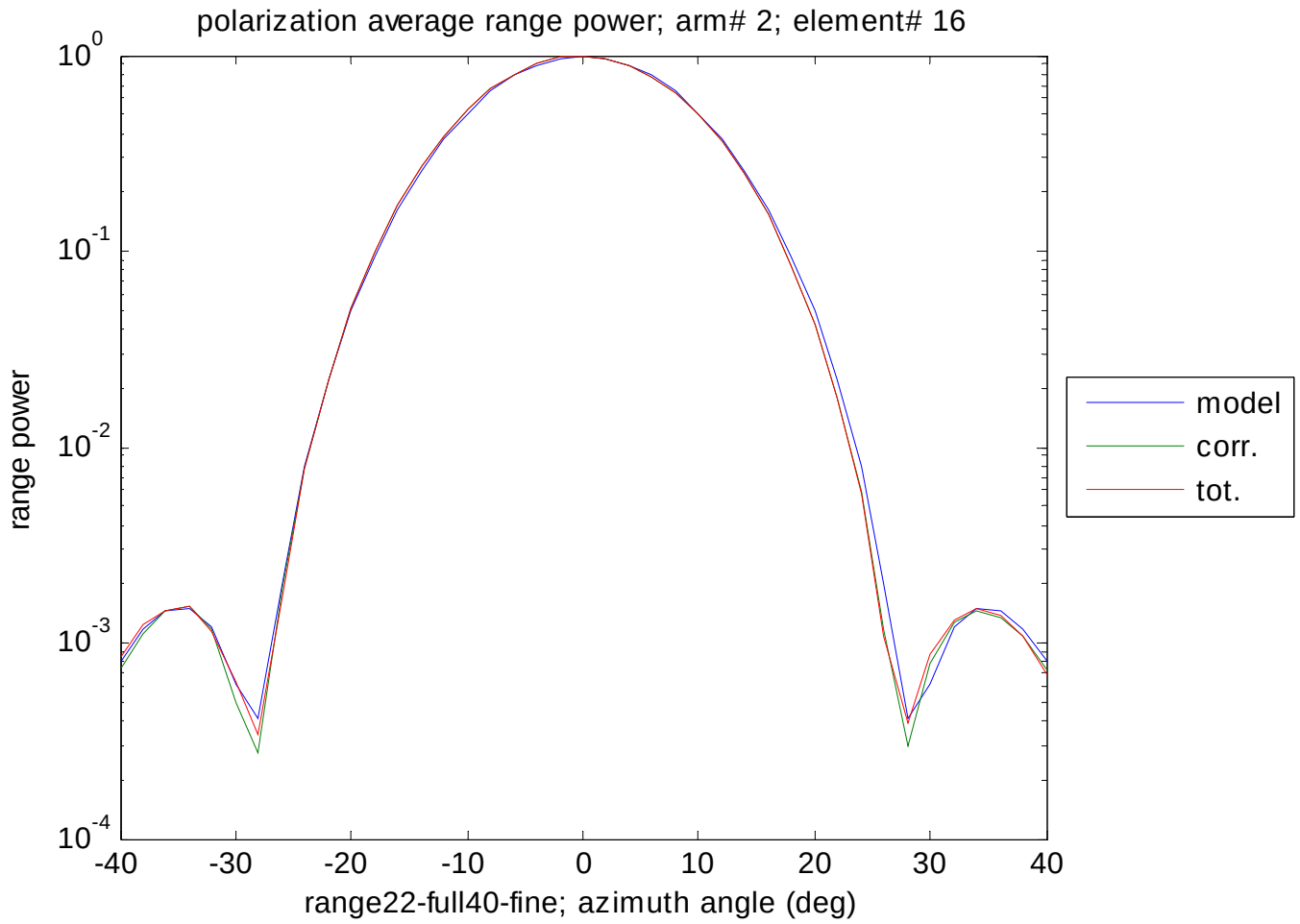




GSFC Compact Range Geometry

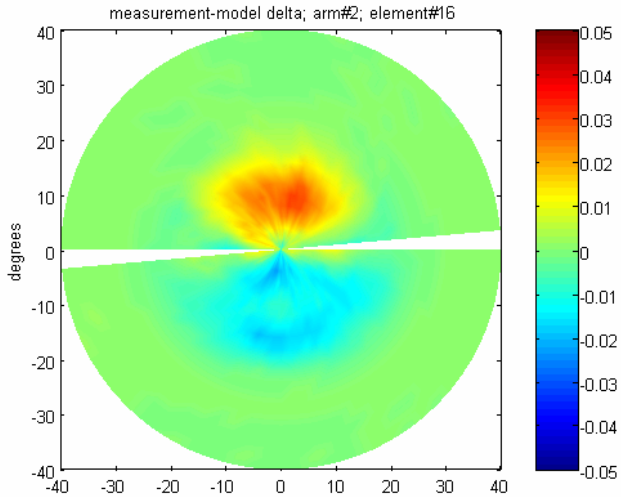


Measured and modeled patterns

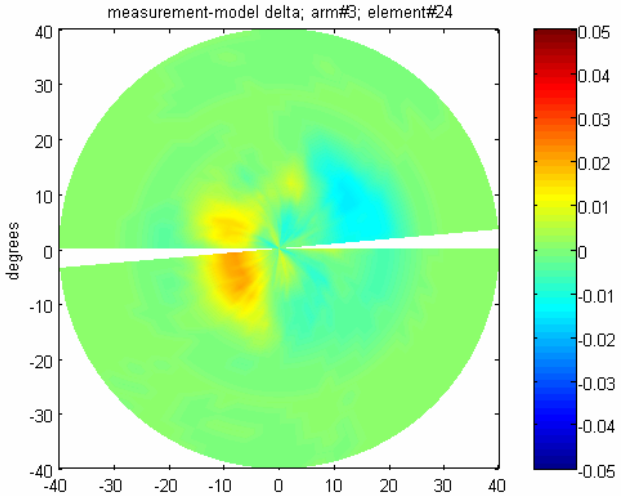


Antenna Pattern Errors from comprehensive set measured at all polarizations for inner-most three elements:

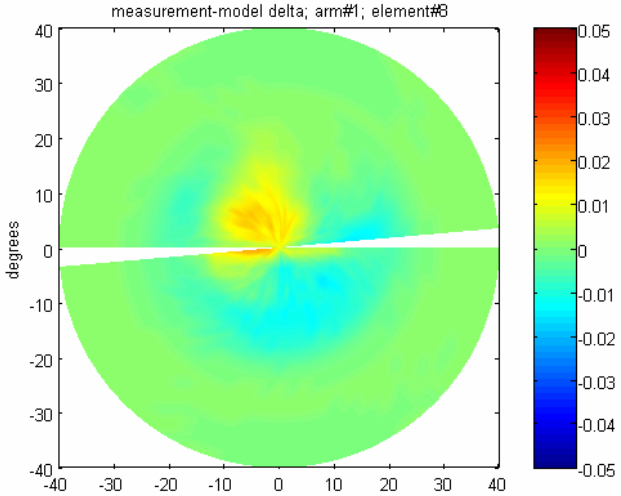
#16



#24

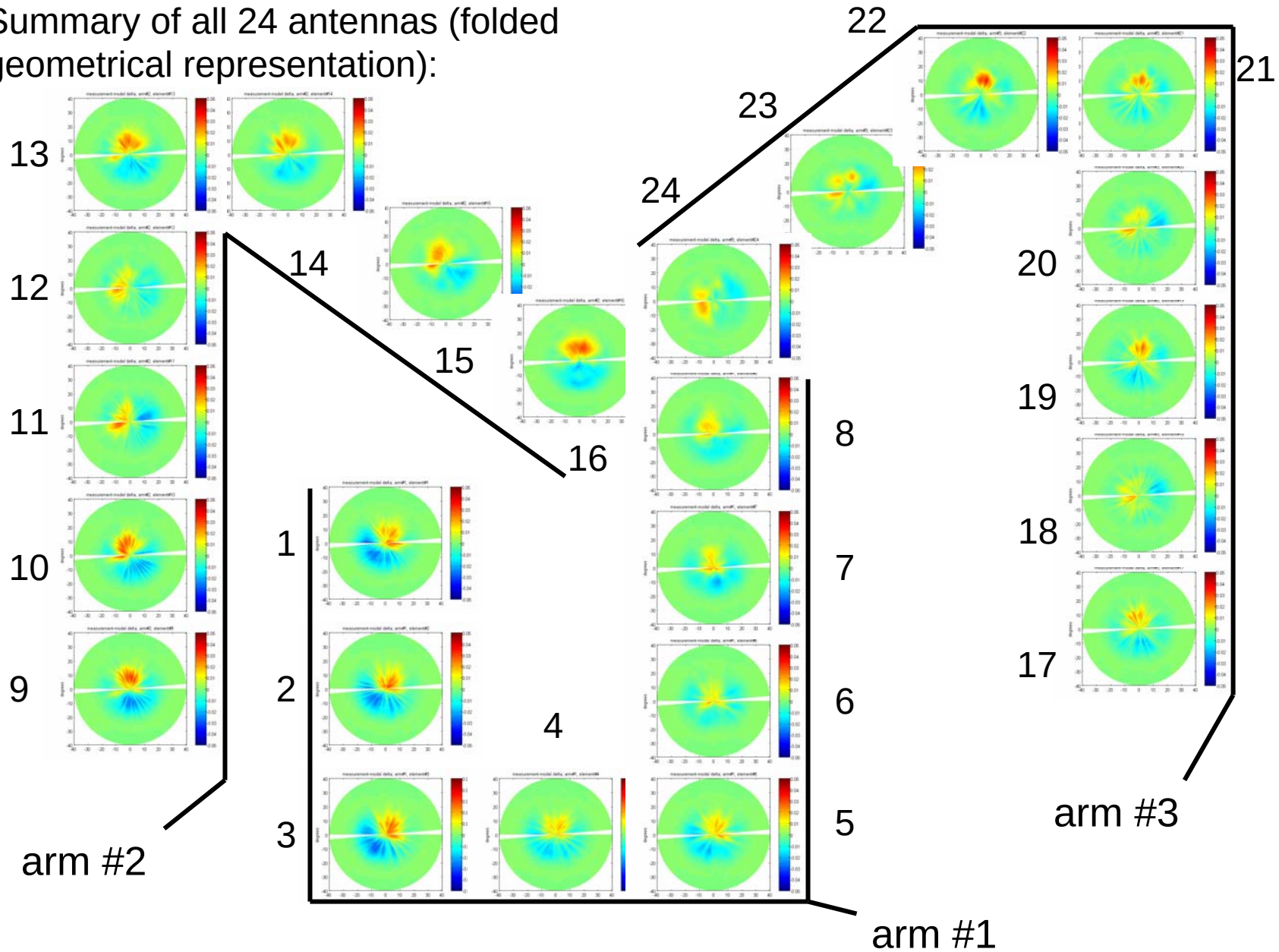


#8

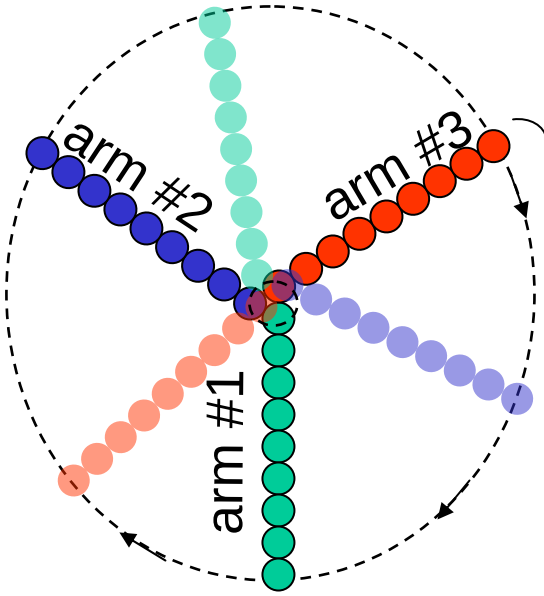


- Maximum errors are about +/- 2%

Summary of all 24 antennas (folded geometrical representation):



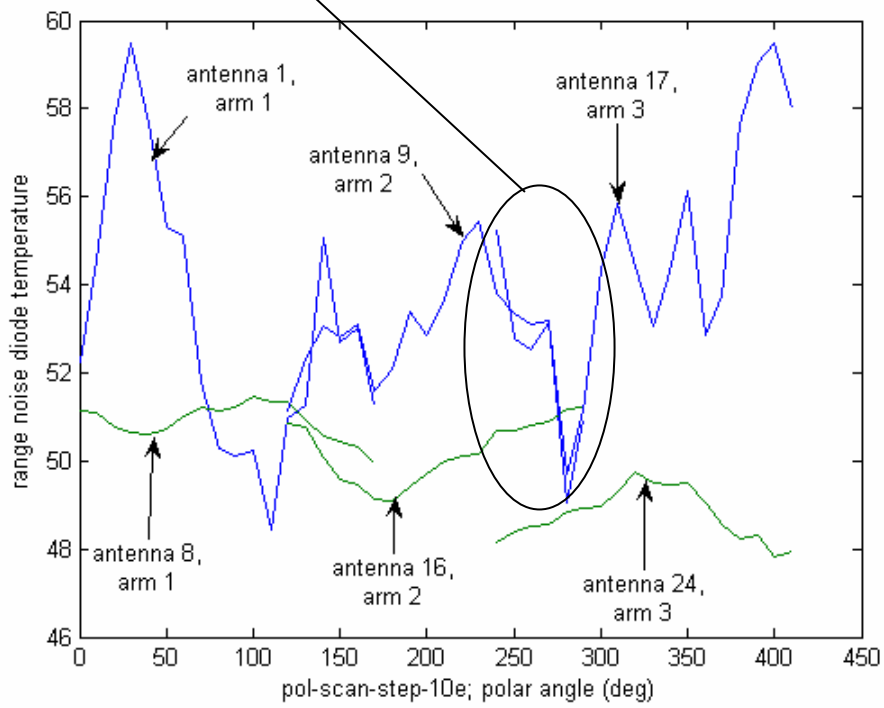
Measurements of “quiet” zone irregularities mapped by observing boresight noise diode brightness vs. polarization



polarization rotation

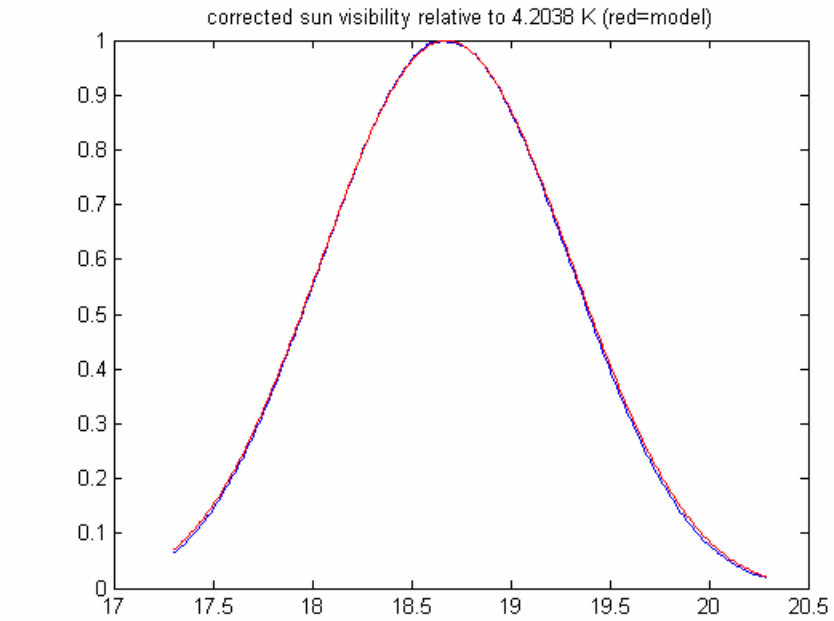
- Over 20% p-p (0.8 dB) amplitude variations measured

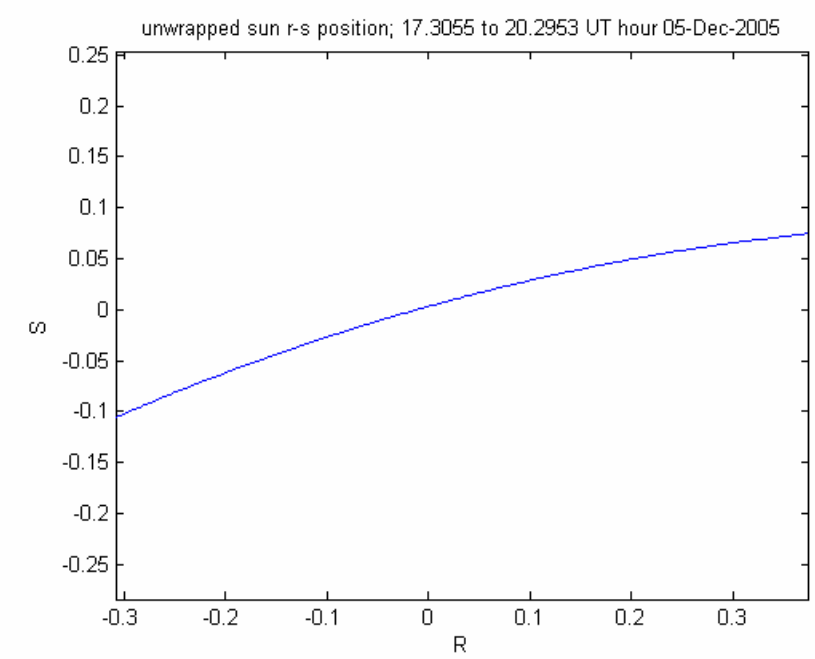
overlap

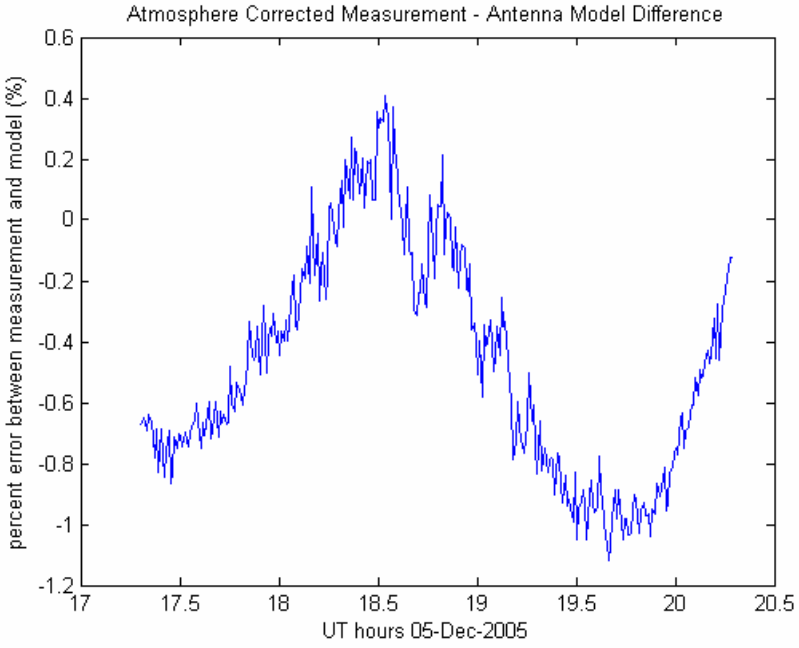


Solar transit observations-

An alternative to the antenna range

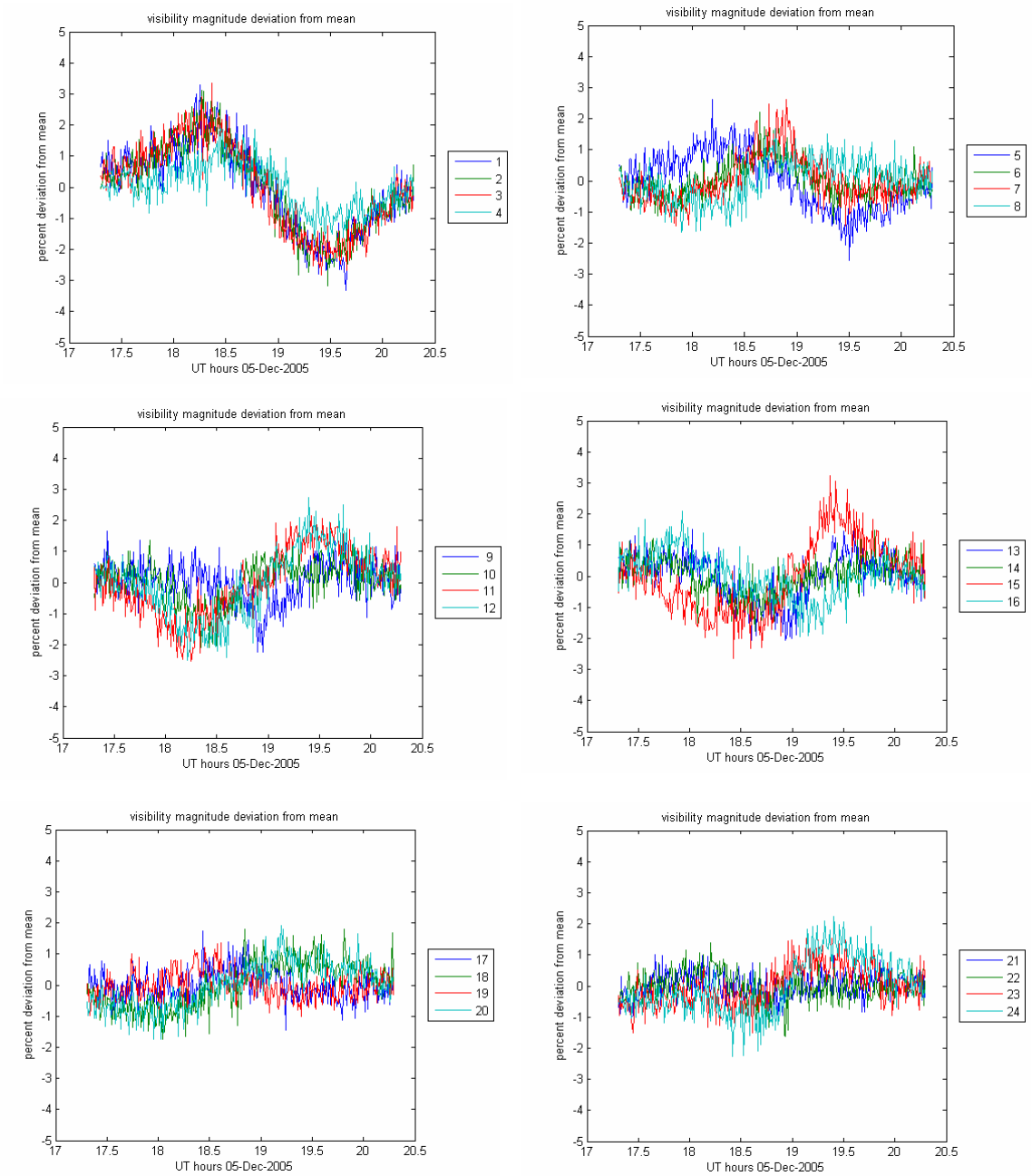




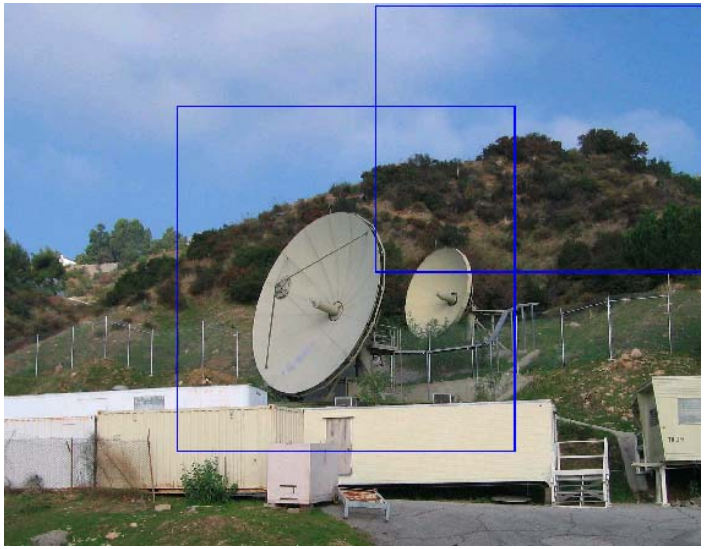


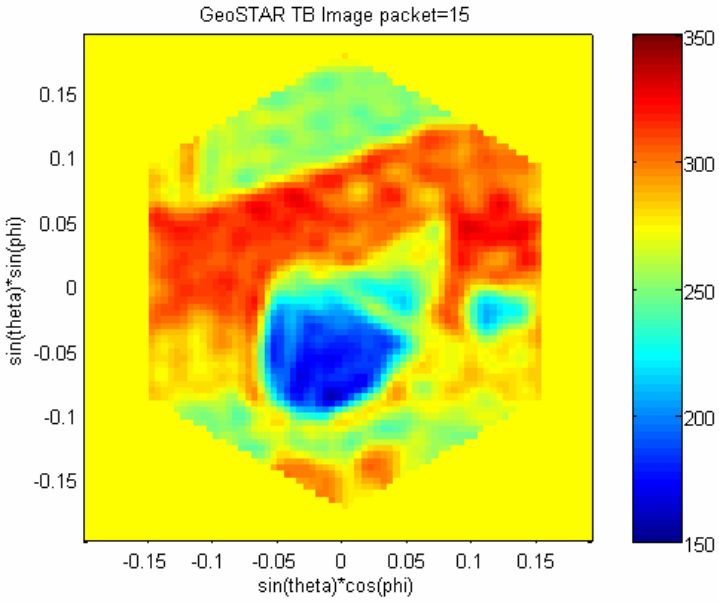
Solar transit antenna patterns

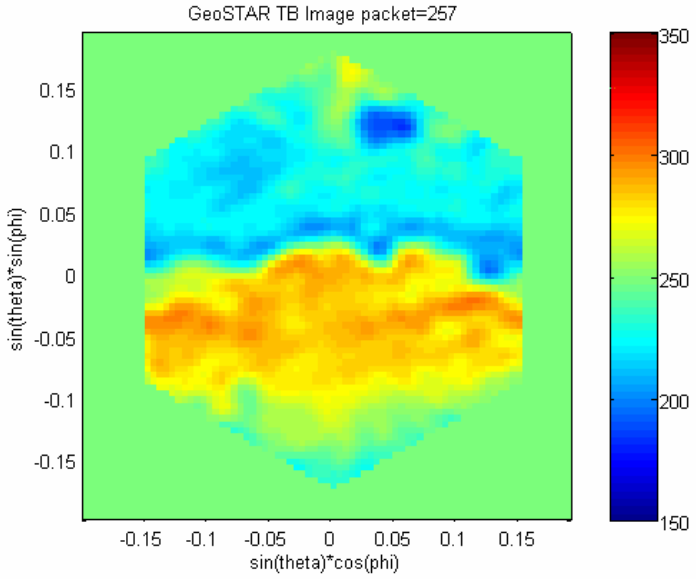
- Isolated to individual elements
- Matches antenna range!
- Residual ~2% pattern errors are largely mechanical, and easy to fix!



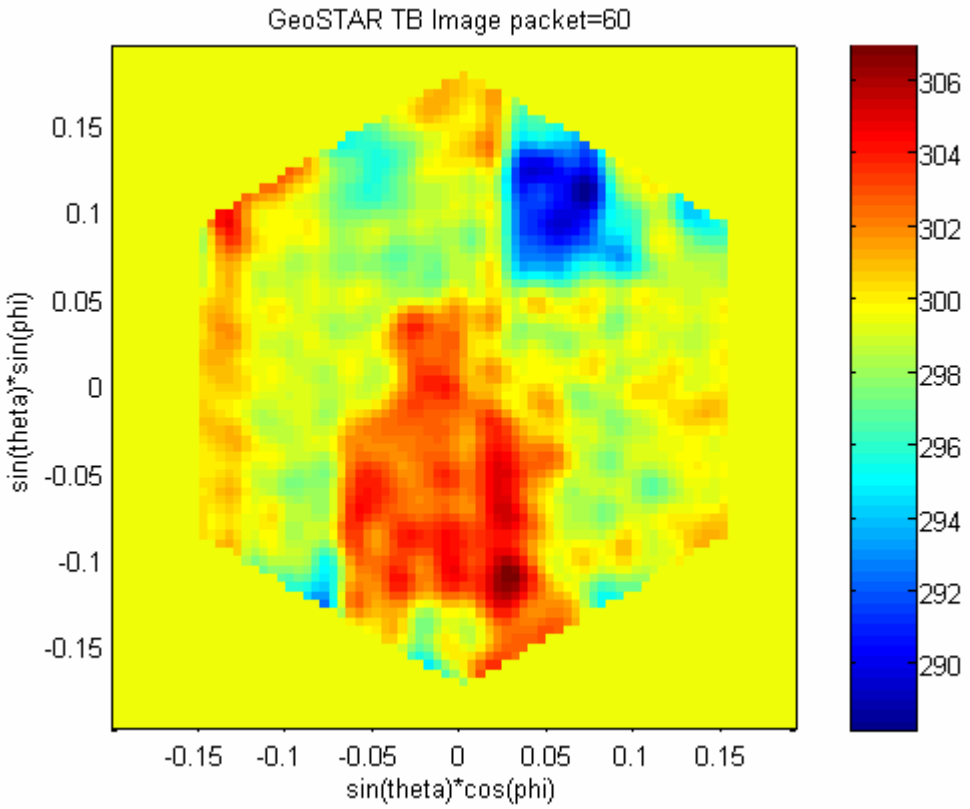
GeoSTAR images of the antenna to the north of building 148 and of the hill behind building 148





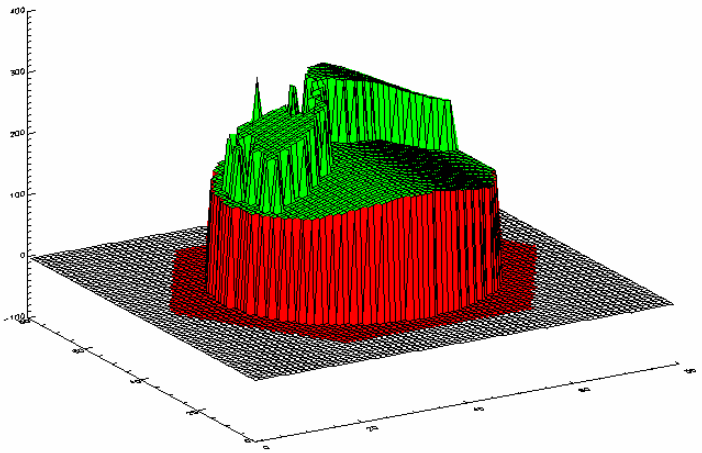


Near field GeoSTAR image of Todd sitting in chair. Integration time was 5 minutes.



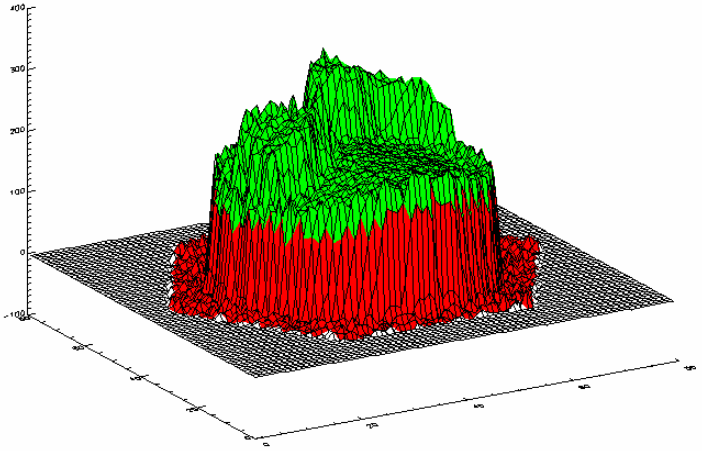
Recent advances in image synthesis

Earth model



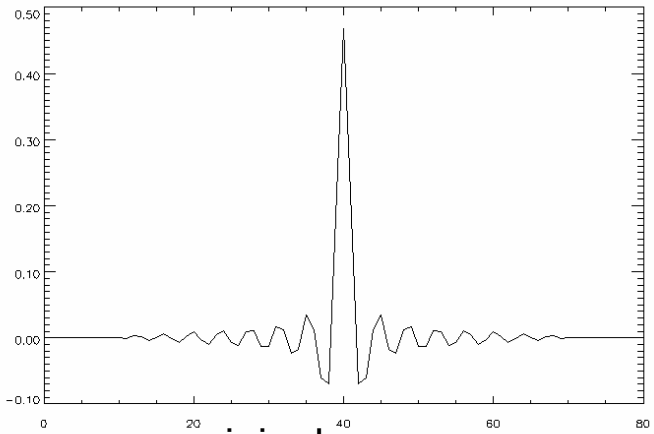
synthesized image of model using standard G-matrix algorithm

note sidelobe ripple from earth's limb & continents

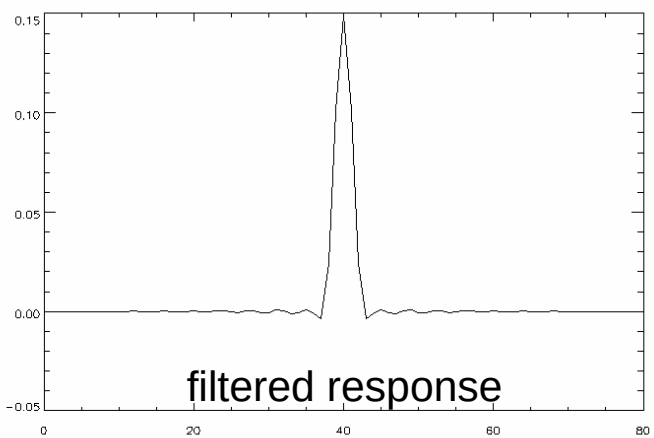


Recent advances in image synthesis- cont.

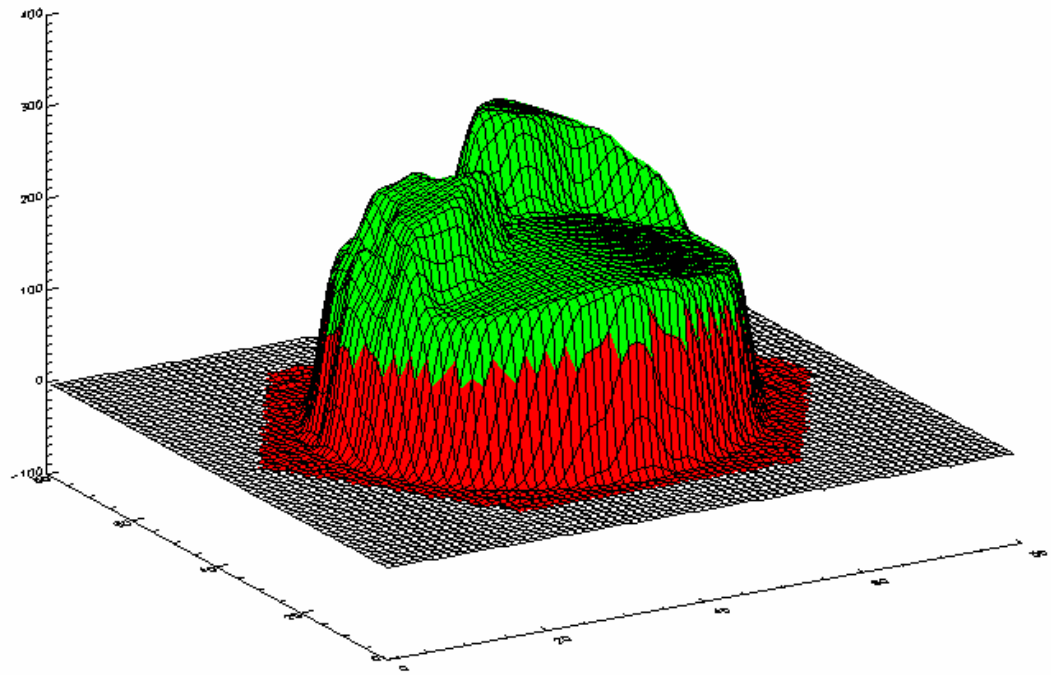
Sidelobes can be lowered using image filter, but spatial resolution suffers



original response



filtered response



filtered reconstruction of Earth model

5. Recent advances in image synthesis- cont.

Better approach to sidelobe problem is to only synthesize *difference* between model and unknown earth temperature.

<u>Old G-matrix algorithm:</u>
based on Projection Theorem- essentially discrete version of Fourier series

Forward model: $V=GT$ Reconstruction model: $\boxed{T=G'V}$

where

V=M-element vector of all visibility samples
T=P-element vector of brightness temperature pixels
G=MxP impulse response matrix, with P>M
G'=PxM reciprocal basis, $G'= G^t(GG^t)^{-1}$

<u>New differential algorithm:</u>

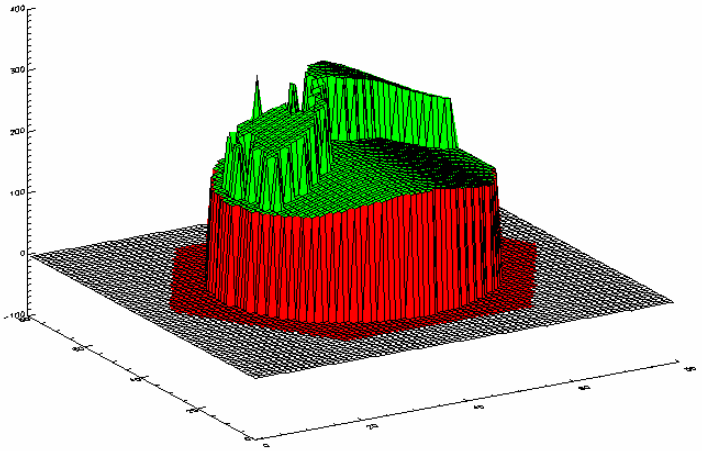
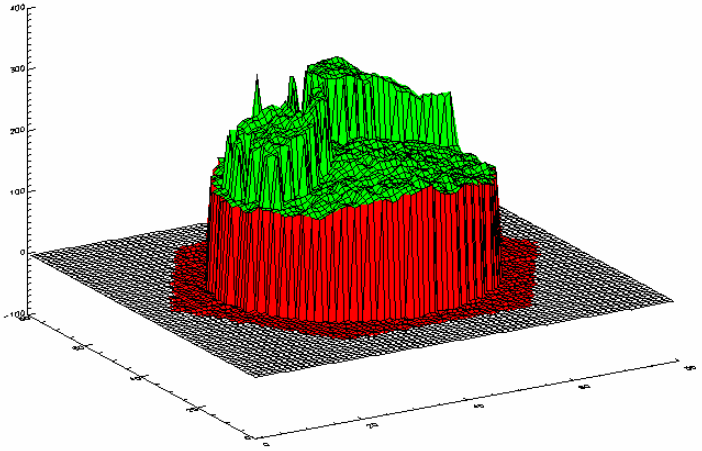
Forward model: $V=GT$ Reconstruction model: $\boxed{T=T_o + G'(V-V_o)}$

where

To=‘average’ earth temperature from models
Vo=visibility response to ‘average’ earth temperature, Vo=GTo

Recent advances in image synthesis- cont.

reconstruction of model using difference technique



reconstruction of earth with 6 K RMS temperature variations