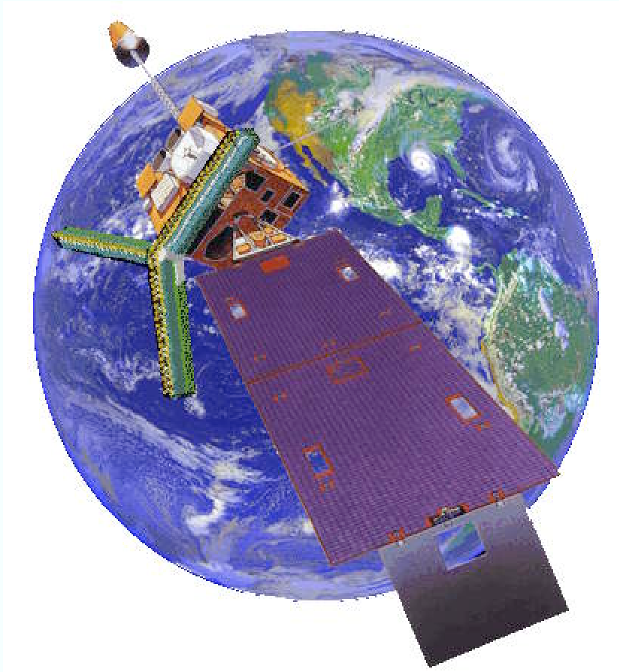
GeoSTAR: Geostationary Synthetic Thinned Aperture Radiometer

ESTC June 23, 2004- Alan Tanner, JPL



GeoSTAR Team

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Overview

- **GeoSTAR is a microwave radiometer for atmospheric sounding from GEO**
- **Functionally equivalent to AMSU**
  - Tropospheric temperature sounding @ 51-56 GHz with ≤ 50 km spatial resolution
  - Tropospheric water vapor sounding @ 183 GHz with ≤ 25 km resolution
- **Using *Aperture Synthesis***
  - Also called Synthetic Thinned Array Radiometer (STAR)
  - Requires far less physical aperture than real aperture system
  - No mechanically scanned parts

Aperture Synthesis Example

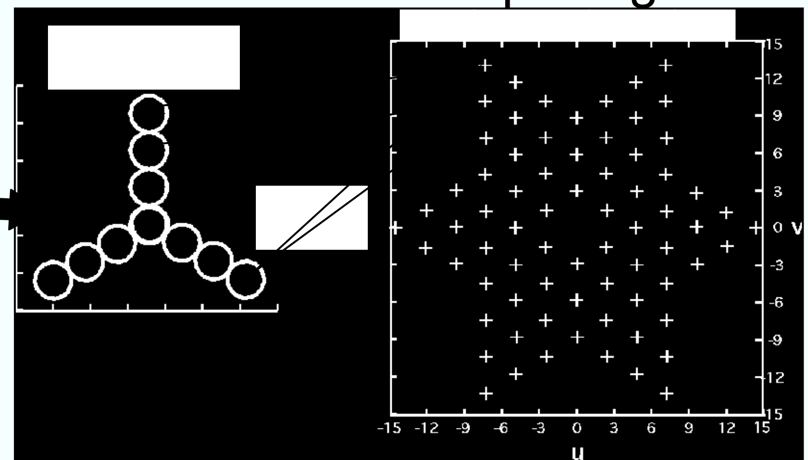
Very Large Array (VLA) at National Radio Astronomy Observatory (NRAO)

In operation for many years

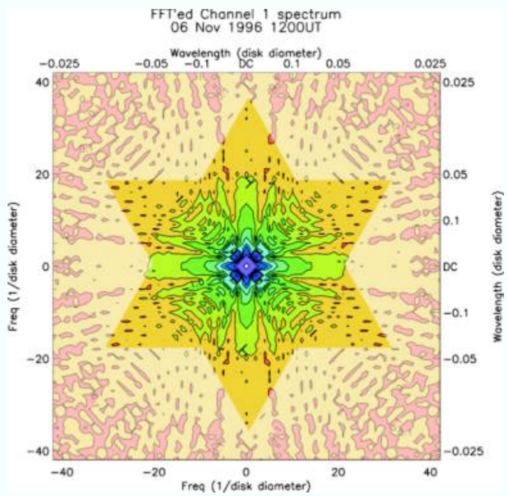
Synthesis Basics

UV element spacings

An array of correlation interferometers are formed from all pairs of antennas in the array

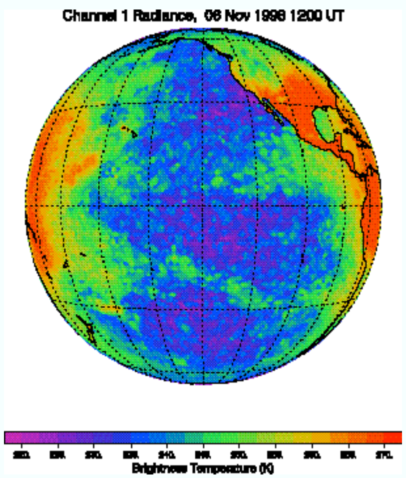


Cross-correlations versus **U-V** spacing are called the **visibility function**.



visibility function

FFT of Visibility function forms an image



T_B image

Fourier Transform

GeoSTAR Design Inputs for 50 GHz channel

- RF frequencies: 50-56 GHz
- Bandwidth: 200 MHz
- Field Of View = Earth diameter from GEO = 17 degrees from GEO
  - array spacing of 3.5 wavelengths, or 2.25 cm
- Number of antenna elements for 50 km earth resolution: 100 per arm
  - 300 elements total
  - 30,000 complex correlators
  - 2.25 meters array arm length

Calibration

- **GeoSTAR is an *interferometric* system**
  - Therefore, *phase calibration* is important
- **Multiple calibration methods**
  - Noise diode distributed to multiple receivers
  - Natural calibration targets (e.g., sun's transit, Earth's limb)
  - Possible ground-beacon transmitted from earth
  - Other methods, as used in radio astronomy
- **Absolute radiometric calibration**
  - One conventional Dicke switched receiver measures "zero baseline visibility"
    - Same as Earth disk mean brightness temperature (Fourier offset)
  - Also: compare with equivalent AMSU observations during over/under-pass
  - The Earth mean brightness is highly stable, changing extremely slowly

Technology Development

- **MMIC receivers**
  - Required: Small (2 cm wide ‘slices’ @ 50 GHz), low power, low cost
  - Status: Receivers off-the-shelf @ < 100 GHz; Chips available up to 200 GHz
- **Correlator chips**
  - Required: Fast, low power, high density
  - Status: Real chips developed for IIP & GPM; Now 0.5 mW per 1-bit @ 100 MHz
- **Calibration**
  - Required: On-board, on-ground, post-process
  - Status: Will implement & demo GEO/SAMS design in Proto-GeoSTAR
- **System**
  - Required: Accurate image reconstruction (Brightness temps from correlations)
  - Status: Will demonstrate capability with Proto-GeoSTAR
- **Related efforts: Rapidly maturing approach & technology**
  - European L-band SMOS now in Phase B; to be launched ~2006-8
  - NASA X/K-band aircraft demo (LRR): candidate for GPM constellation
  - NASA technology development efforts (IIP, etc.); various stages of completion

GeoSTAR Prototype Development

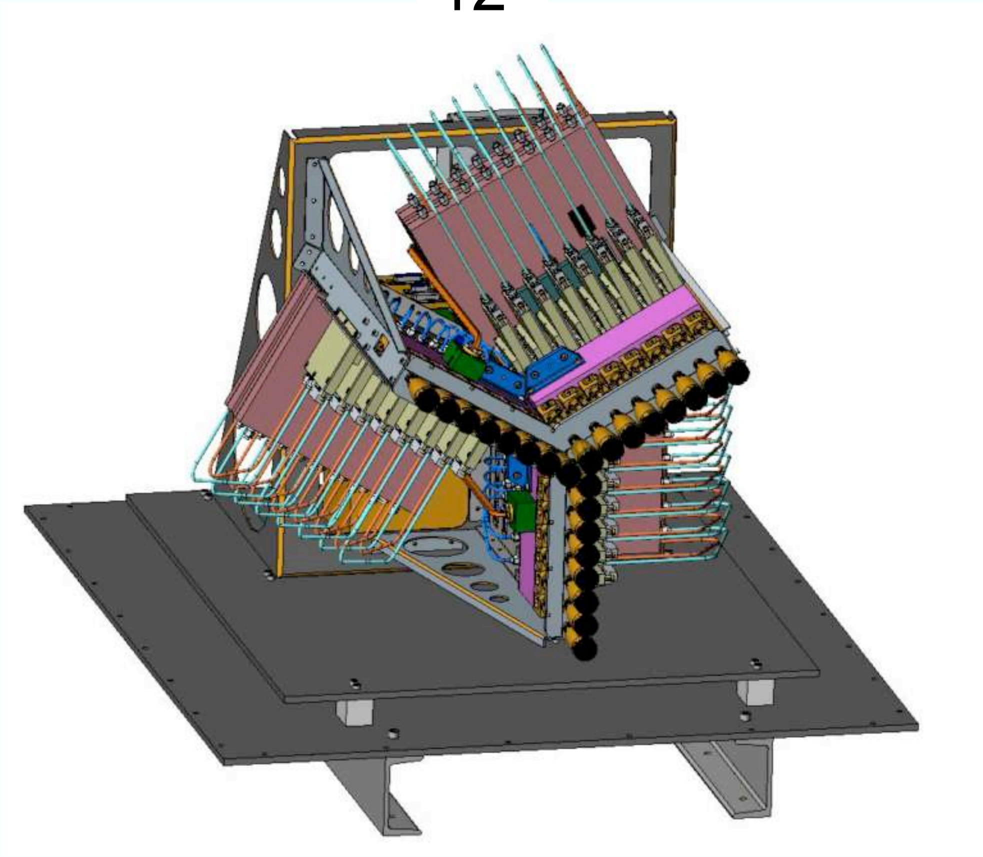
- **Objectives**
  - Technology risk reduction
  - Develop system to maturity and test performance
  - Evaluate calibration approach
  - Assess measurement accuracy
- **Small, ground-based**
  - 24 receiving elements - 8 per Y-arm
  - Operating at 50-55 GHz
  - 4 tropospheric AMSU-A channels: 50.3 - 52.8 - 53.71/53.84 - 54.4 GHz
  - Implemented with miniature MMIC receivers
  - Element spacing as for GEO application (3 λ)
  - FPGA-based correlator
  - All calibration subsystems implemented

Roadmap

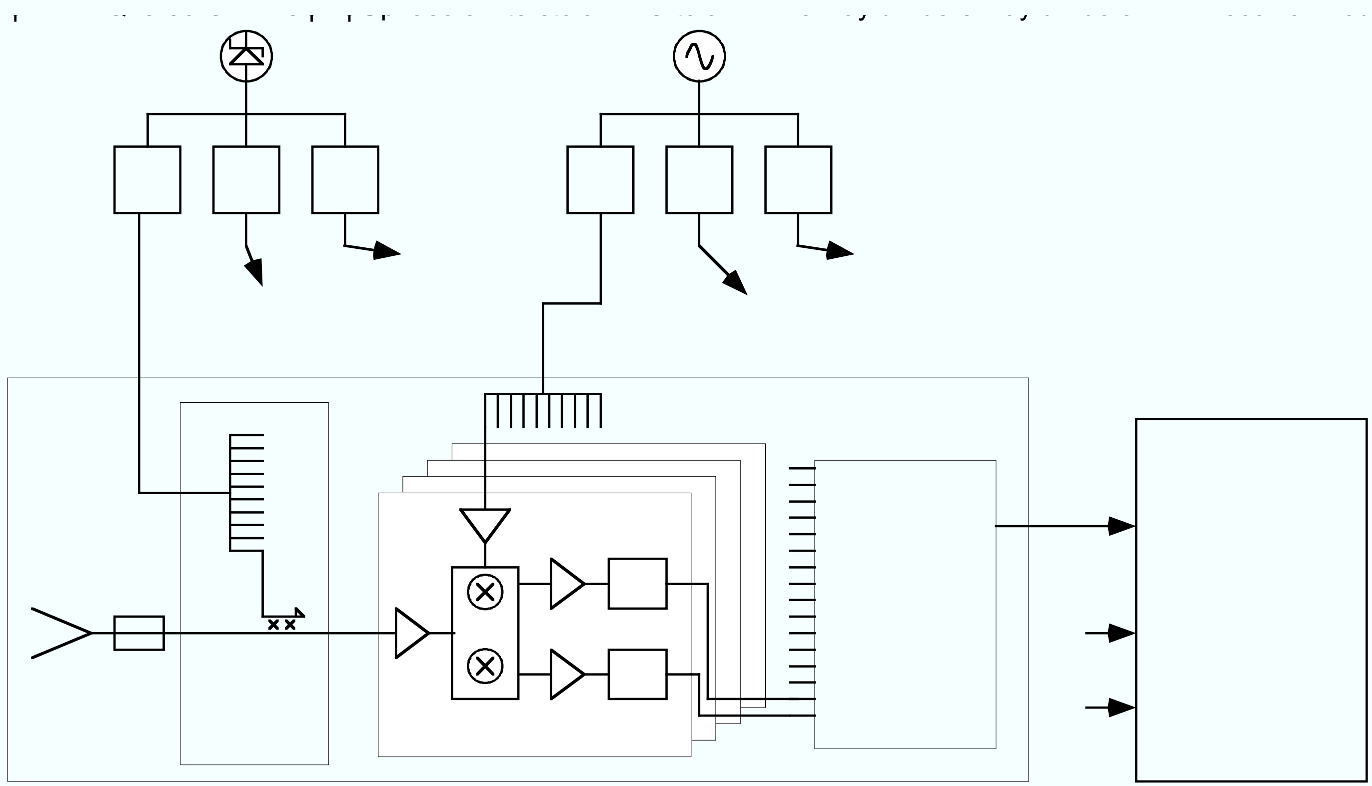
- **Prototype: 2003-2006**
  - Functional system expected ready in < 1 year
  - Fully characterized in < 2 years
- **Further technology development: 2005-2008**
  - Develop efficient radiometer assembly & testing approach
  - Migrate correlator design & low-power technology to rad-hard ASICs
    - Expect power consumption to reach 0.1 mW per correlator in this time frame
    - Overall power consumption is then trivial: < 100 W for the entire T/q-sounding correlator
  - Develop signal distribution, thermal control & other subsystems.
- **Space demo: 2008-2012**
  - Ready for Phase B in 2008
  - Ready for launch in 2012: NMP? MEO-demo?
- **Operational mission: 2015+**
  - GOES-R?

GeoSTAR Prototype hardware

← 12" →



Simplified Block Diagram

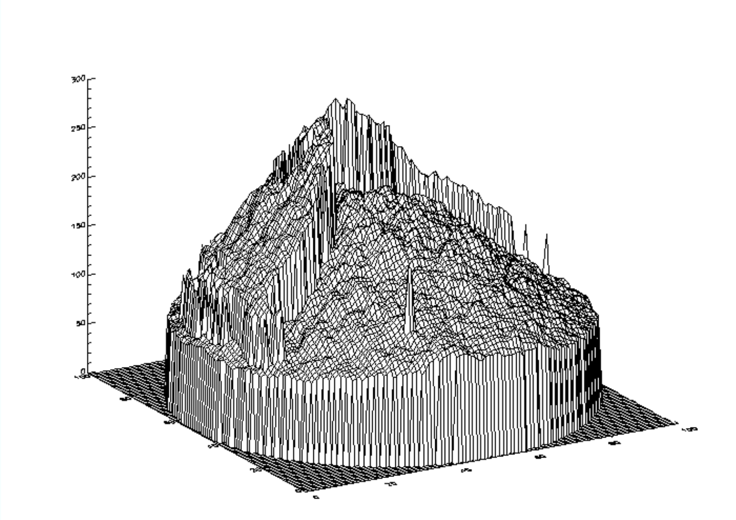


GeoSTAR – System Studies

1. Calibration Error Budget
2. Noise Diode Requirements
3. Digitizer Requirements
4. LO noise requirements
5. Antenna requirements
6. Recent advances in image synthesis

1. Calibration Error Budget

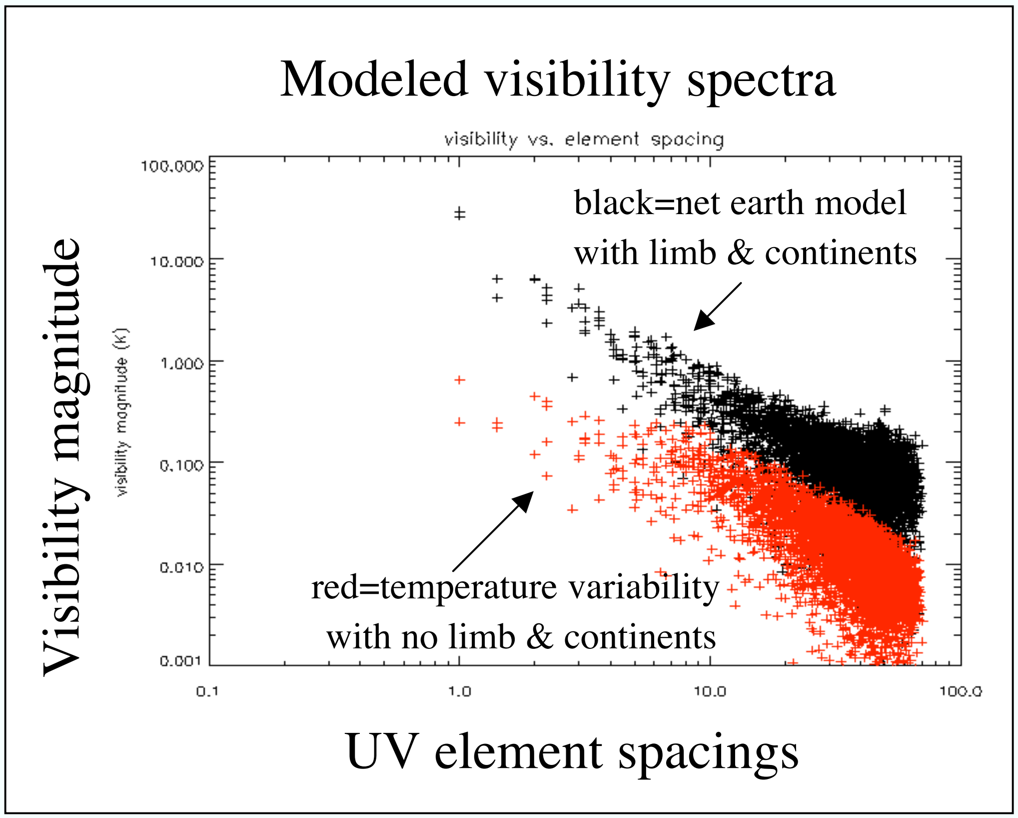
- Based on numerical simulations
- Derived for spaceborne system
- Sets general requirements for prototype



earth model, weighted by antenna pattern

1. Calibration Error Budget

- Simulations reveal how visibility spectra falls off with larger spacings



⇒ gain and phase requirements relaxed at larger UV spacings

⇒ helpful for large arrays

⇒ visibility dominated by earth's limb and continental contrasts

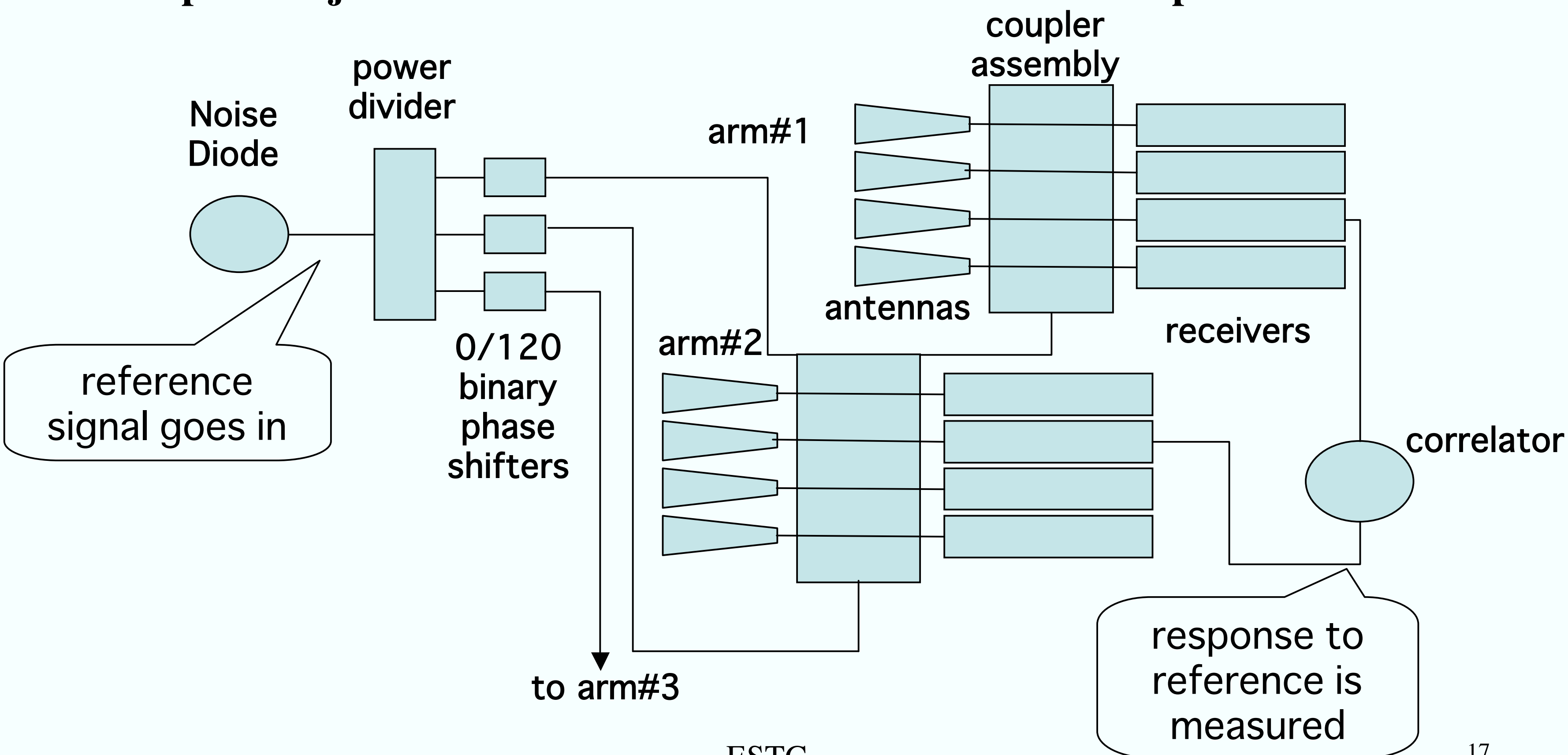
1. Calibration Error Budget- results

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

Error allocations: each contributes 1/root(5) Kelvin to net image error

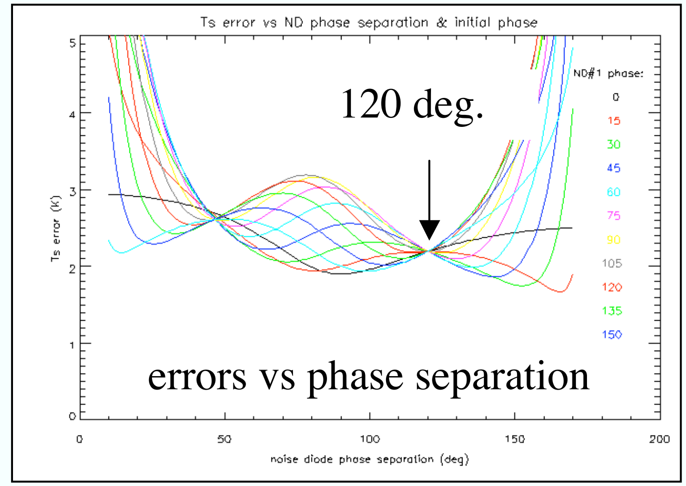
2. Noise Diode Requirements- overview

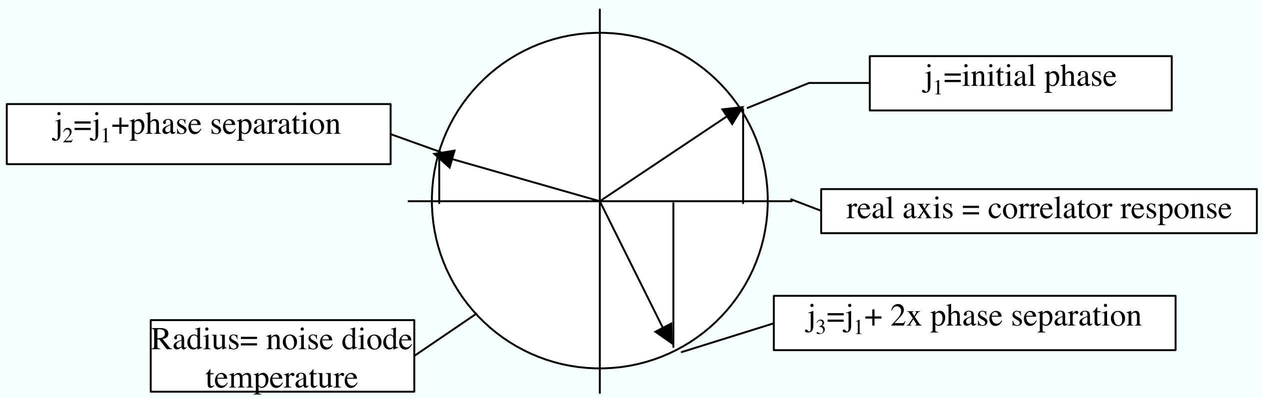
- Noise diode reference is distributed and coupled to all receivers for phase and system noise temperature (Ts) calibration.
- 3-phase injection scheme facilitates simultaneous Ts and phase solutions.



2. Noise Diode Requirements- cont.

- Study revealed that 3-phase noise diode injection at about 1 to 10K noise temperature, with 0/ 120 binary phase shifts at each arm is optimal for Geostar.
- No amplification required..

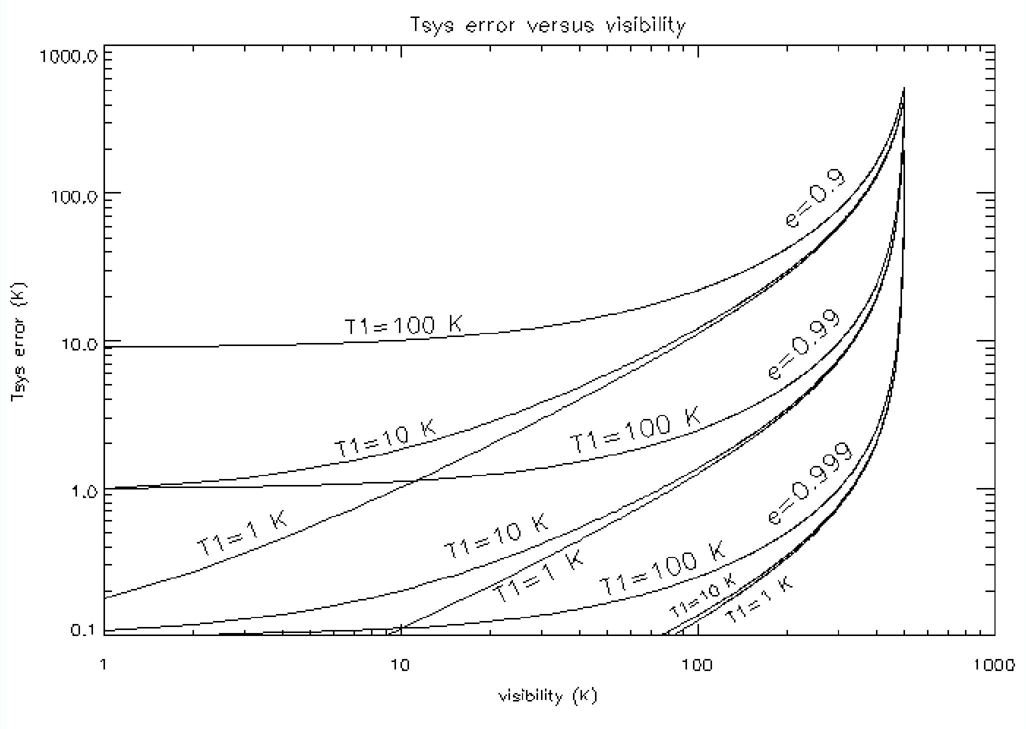




3-phase correlator response

2. Noise Diode Requirements - supplemental

The "hottest" acceptable noise diode temperature is limited by the linearity of 1-bit correlation and knowledge of the correlator efficiency



T_s errors incurred by ignoring correlator efficiency- as calculated from (24) for T_s=500 K. Errors are plotted versus positive visibility for three noise diode temperatures (T_1=1, 10, and 100 K) at each of three efficiencies (0.9, 0.99, and 0.999). The Geostar error budget will allow 0.45% error in the estimate of system noise, or about 2K on this scale.

3. Digitizer Requirements

- Geostar uses 1-bit correlators running at 200 MHz.
- Digitizers are same as LRR; null offset is ~10% of system noise voltage.
- Null-offset is serious concern, given stringent correlator bias requirements (~ 0.5 mK visibility out of 500 K Ts).
- Numerical simulations were used to determine if LRR null offsets are acceptable, given the nonlinear nature of the 1-bit digitizer and our calibration schemes.

3. Digitizer Requirements- cont.

Findings:

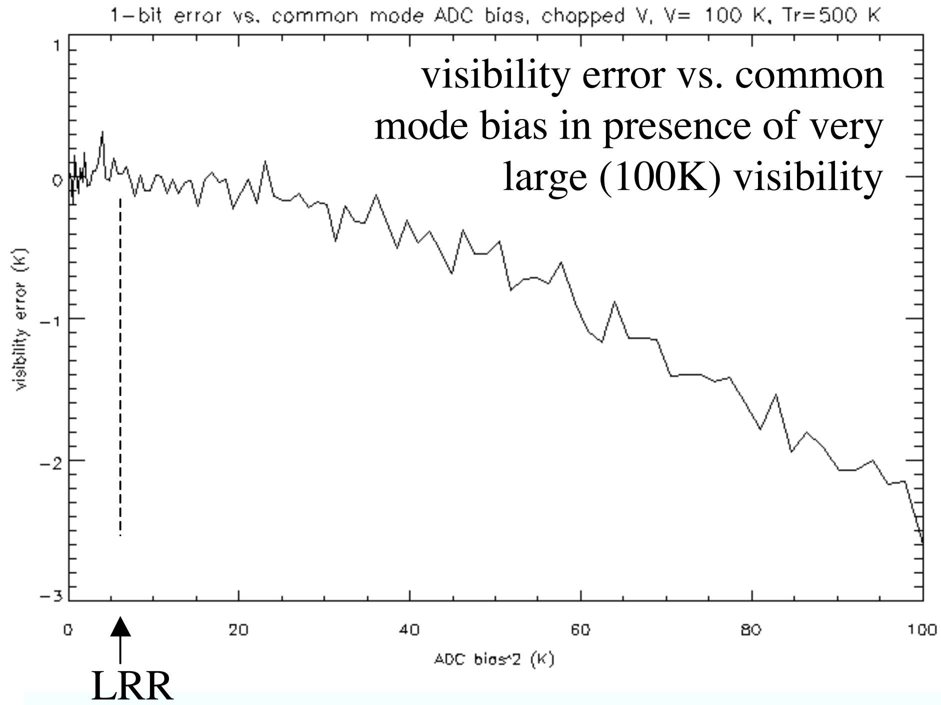
1. Digitizer biases largely mimic additive noise, which will be negated by synchronous demodulation with the phase-switched LO.

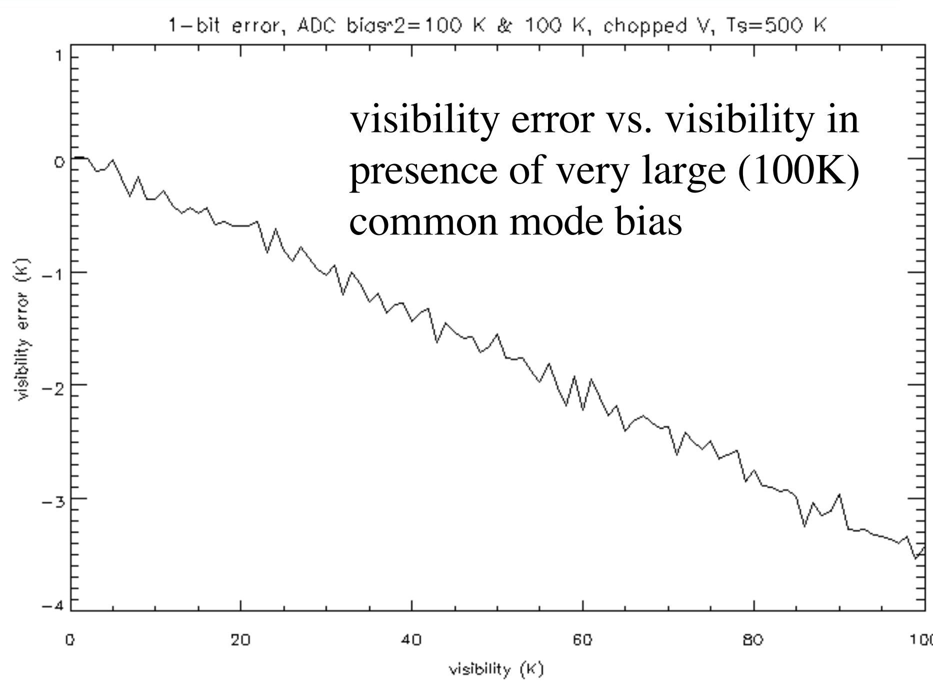
2. Biases of up to 20% of system noise voltage are acceptably linear, and will meet Geostar requirements if the LO phase switch is perfect.

3. 10% LRR null-offsets place tight requirement on LO phase switch amplitude balance: conversion loss must be balanced to ~ 100 ppm. LO power leveling device (e.g. detector and feedback circuit) may be needed.

4. Geostar includes 'totalizers' to estimate biases- as a backup.

3. Digitizer Requirements-supplemental





Digitizer bias results only in minor loss of correlator efficiency.

Graph to left indicates that a whopping 100K bias causes just 3% loss.

Graph above indicates undetectable loss (<0.1%) from LRR bias levels.

4. LO Noise Requirements

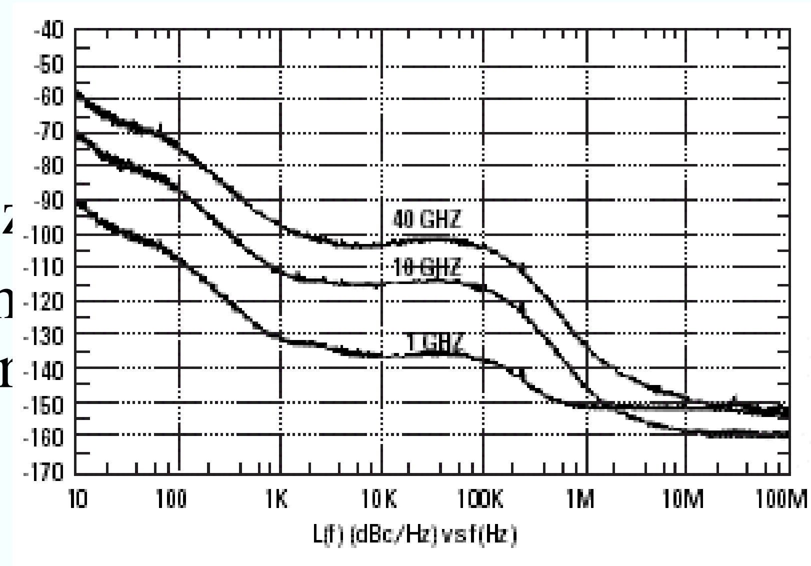
- Sideband noise of LO will leak through down converters to produce correlated noise at IF.
- Calculations show that -141.6 dBc/Hz is required- difficult to meet.
- HP Synthesizer just barely meets requirement.
- Have added another 20 dB RF gain to one prototype module to ease requirement to -121 dBc/Hz.

	Kelvin	dBm/200MHz*
Net permissible delta-V error from Table 2 of 6/18/3 IOM (200x200 pixels):	0.0019	-142.8
Allocation of delta-V to LO noise:	0.0005	-148.6
+40 dB RF gain before mixer:	5.0	-108.6
+40 dB LO-RF mixer isolation:	50,000	-68.6
20 dB null offset removal by phase switching LO:	5x10^6	-48.6
relative to 10 dBm LO signal strength:		**-58.6 dBc**/200 MHz
LO noise requirement per Hz (-83 dB =Hz/200MHz):		**-141.6 dBc/Hz**

* the dBm numbers are calculated as 10*log10(kTB)+30, and both sidebands are included for a total bandwidth of B=200 MHz.

GeoSTAR Local Oscillator Source

- LO Source
  - Phase noise requirement:
    - @ 25 Ghz : < -140 dBc/Hz
- HPE8247C5 with UNR option m
requirement, and will be used for
prototype.



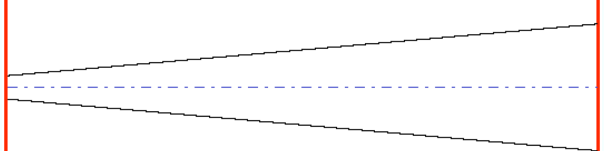
- DRO will also be demonstrated, as this is better candidate for spacecraft

5. Antenna requirements

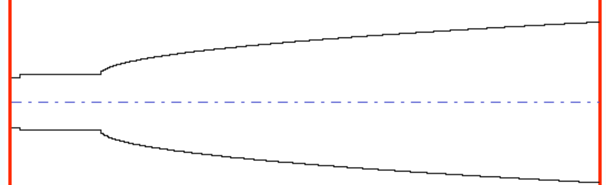
- Error budget from simulation allows only 0.17% uncertainty in antenna gain.

- 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.

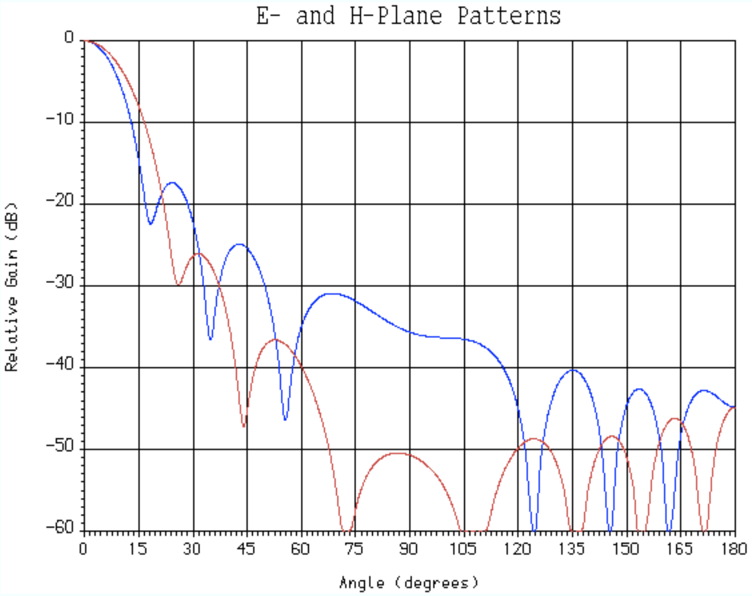


straight conical taper

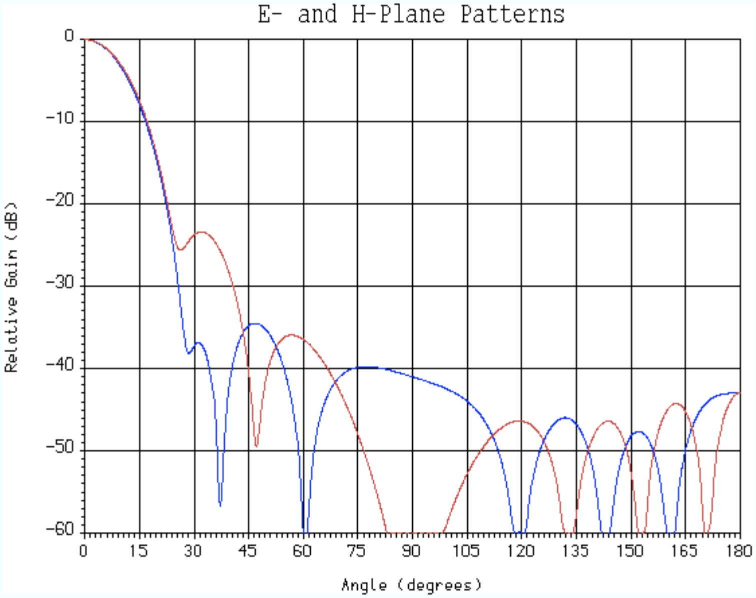


parabolic Potter

5. Antenna requirements- cont.



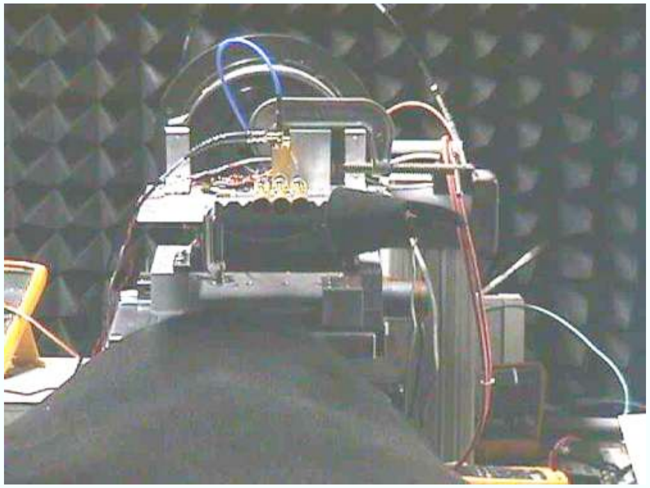
straight taper- poor symmetry and SLL, but highest earth efficiency of ~46%

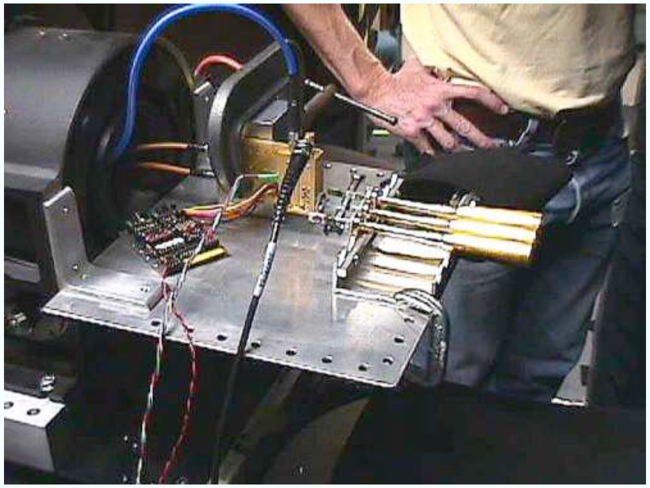


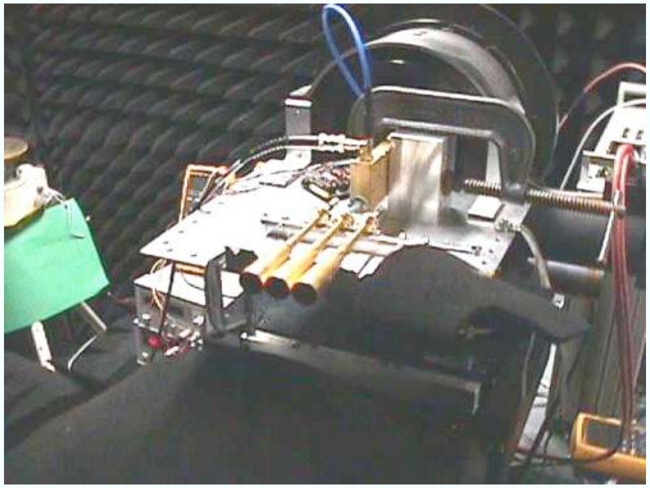
parabolic potter- best symmetry and SLL, but lower earth efficiency of ~40%

GeoSTAR Horns

GeoSTAR- Horn Testing

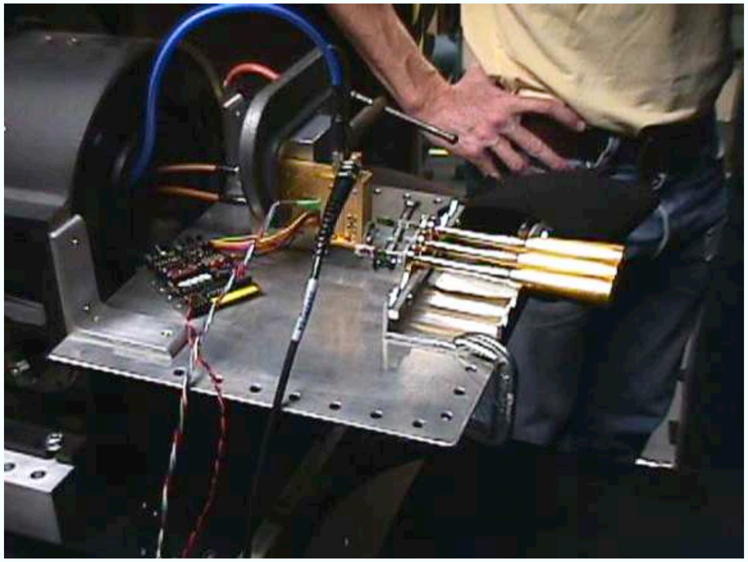






5. Antenna requirements- cont.

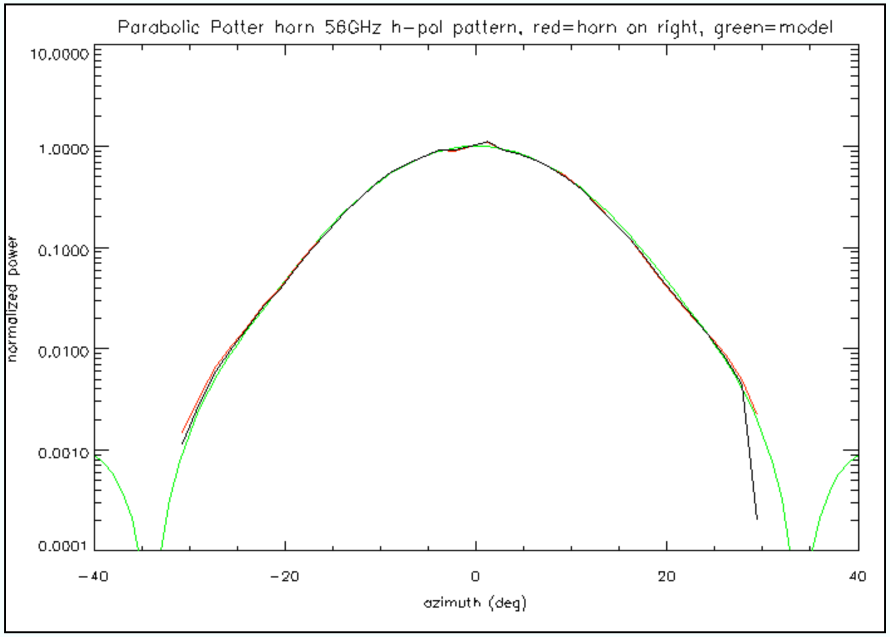
straight taper prototypes



parabolic potter prototypes on antenna range and in test jig

5. Antenna requirements- cont.

- Antennas were tested on an antenna range.
- Primary concern was sensitivity to mutual coupling and scattering as antennas were 'arrayed' in the 3-element test jig.
- Linear horns exhibited as much as 4.6 % gain change as dummy horns were inserted in array test jig- this rules out the linear taper horns.
- Parabolic Potter horns exhibited 0.2% to 0.5% RMS change in gain as dummy horns were placed in array test jig. This is close enough to our requirements to proceed with Parabolic Potter design.



model (green) vs measured patterns with (red) and without (black) neighboring antenna in array test jig

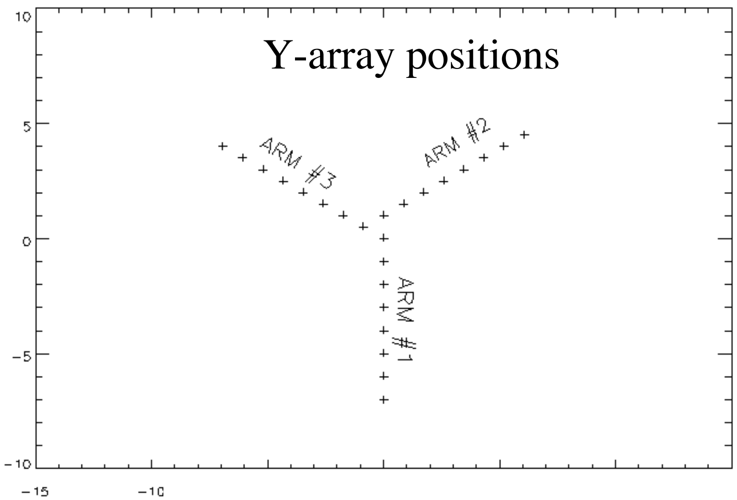
6. Recent advances in image synthesis

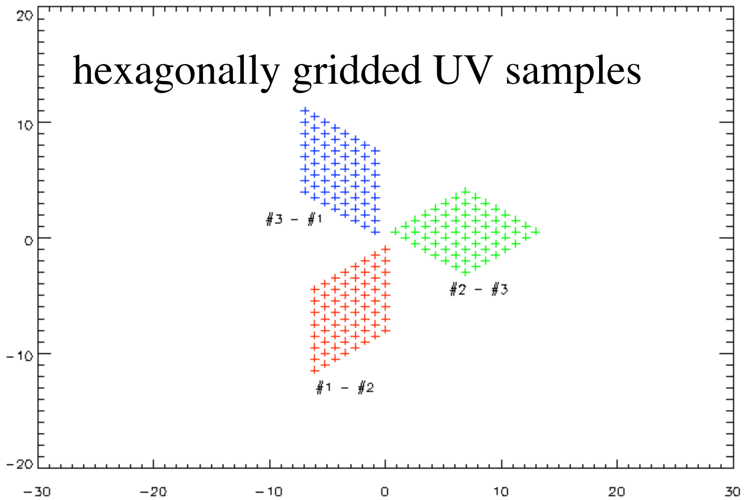
NOAA funded study of geo implementation has provided an opportunity to investigate advanced image processing techniques. This has lead to two promising developments:

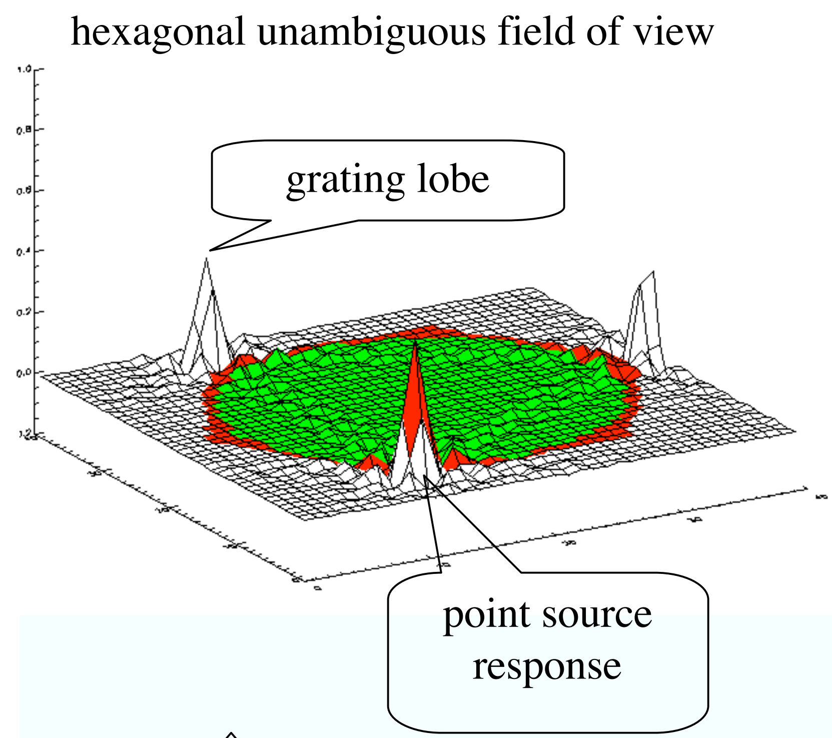
1. New ‘differential’ image reconstruction technique to reduce sidelobe ripples without sacrificing spatial resolution

2. Self-calibration technique which uses the earth’s limb as a reference to correct mechanical distortions of the array

6. Recent advances in image synthesis- cont.

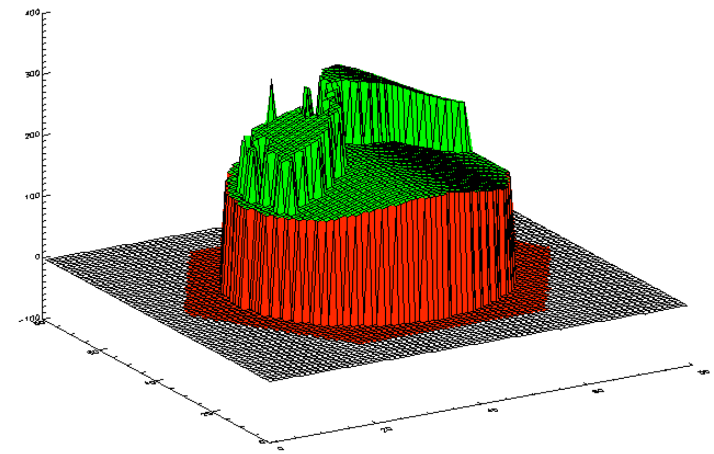






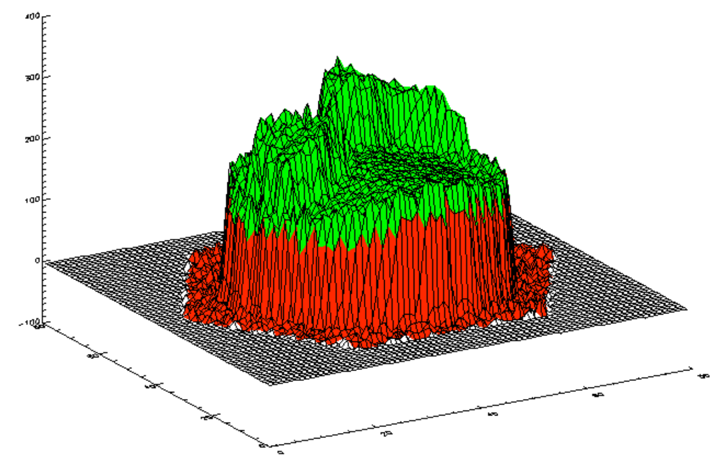
6. Recent advances in image synthesis- cont.

Earth model



synthesized image of model using standard G-matrix algorithm

note sidelobe ripple from earth's limb & continents

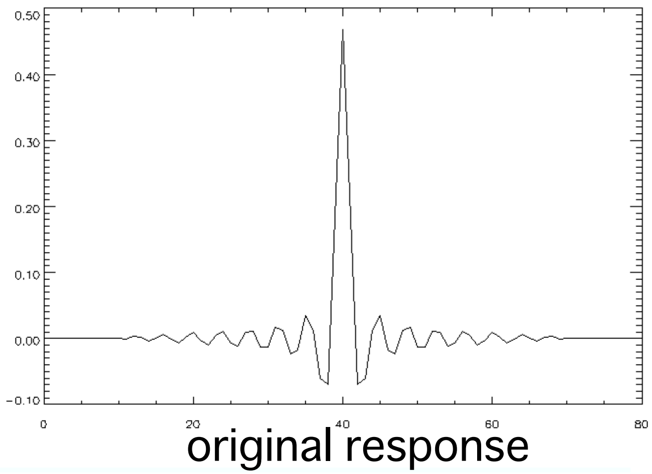


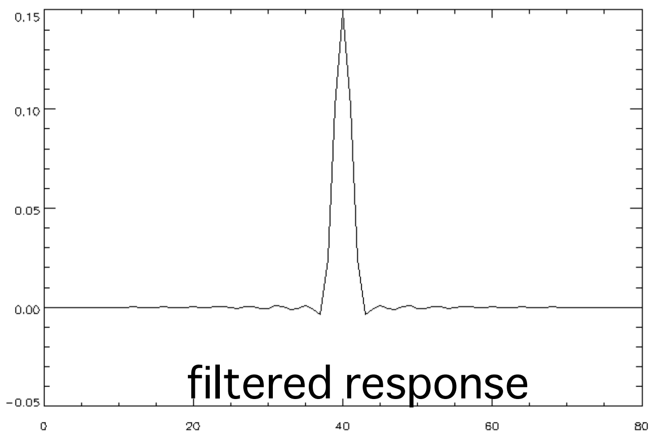
Jet Propulsion Laboratory
California Institute of Technology

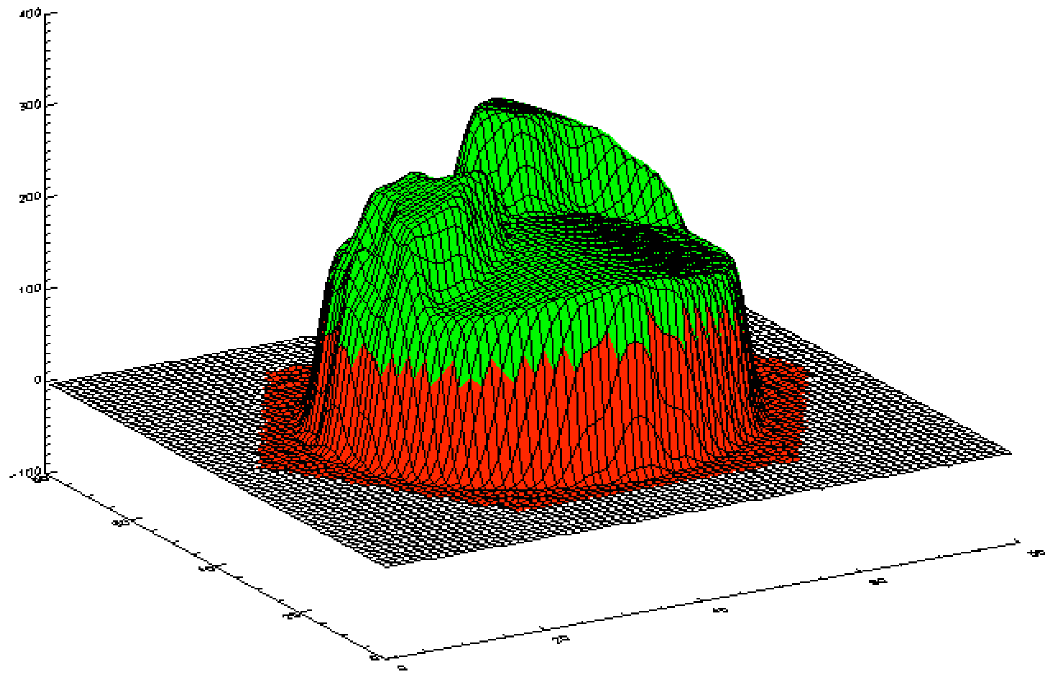
University of MICHIGAN

6. Recent advances in image synthesis- cont.

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







filtered reconstruction of Earth model

6. 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: 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>

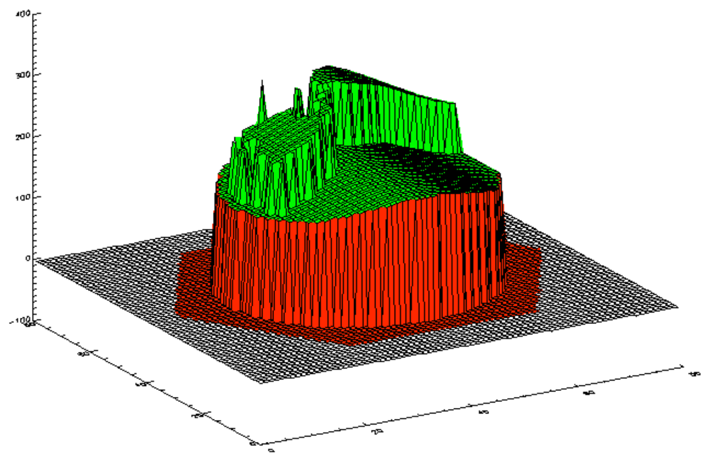
Forward model: V=GT Reconstruction model: $T = T_o + G'(V - V_o)$

where

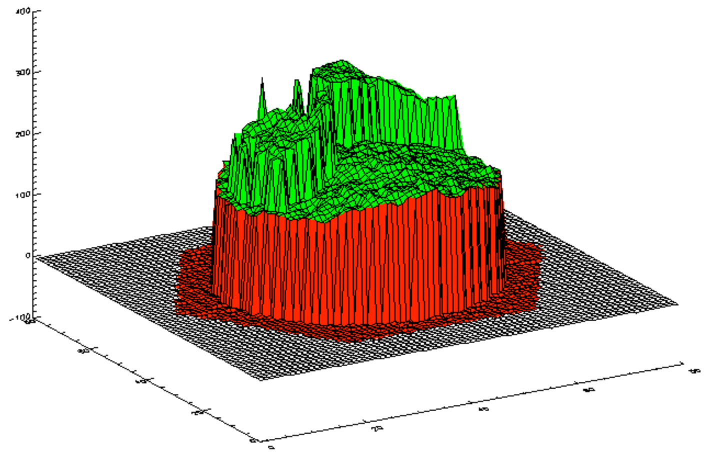
To='average' earth temperature from models
Vo=visibility response to 'average' earth temperature, Vo=GTo

6. Recent advances in image synthesis- cont.

reconstruction of model
using difference technique



reconstruction of earth with
6 K RMS temperature
variations

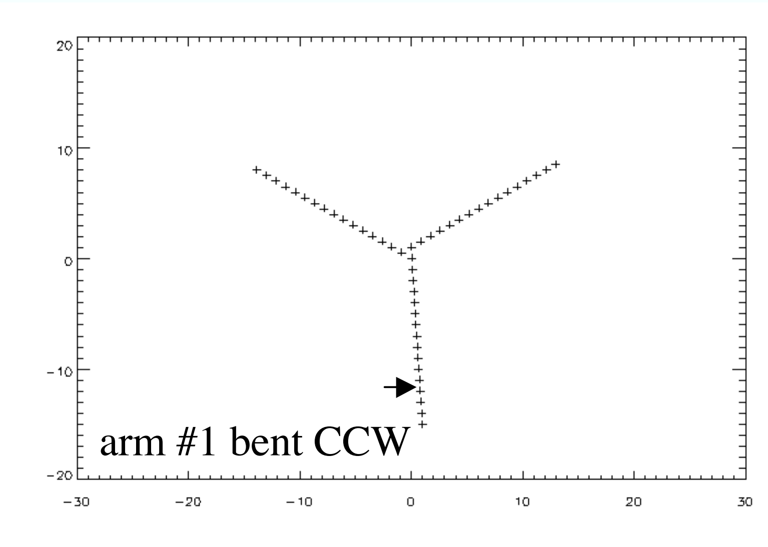


6. Recent advances in image synthesis- cont.

Mechanical distortions of the array can be measured by observing image distortions in unambiguous (UAFOV) regions off of the earth disk where T=2.7K.

Hundreds of independent pixels exist in UAFOV, which should be sufficient to characterize array distortions with finite element model.

Example below indicates how one bending mode maps to distinct image error.



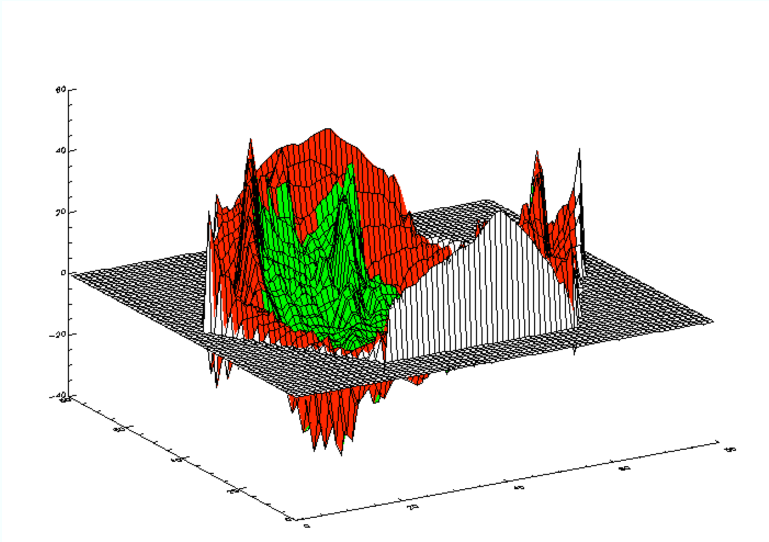


image distortion caused by array bending

Summary of System Studies

- Parabolic Potter horn design performed VERY well; the high immunity to mutual coupling and other array effects will GREATLY simplify the calibration- many thanks to Bill Imbriale

- LRR digitizers should do the job, but we depend on the balance of the LO phase switch to keep the visibility biases low.

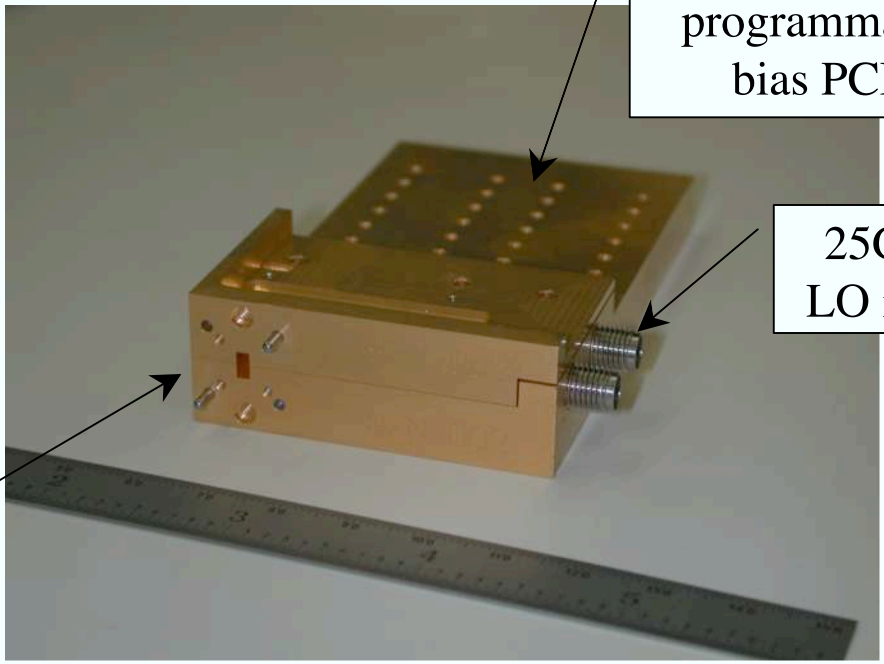
- We are also concerned about LO phase noise, and plan to run the prototype from a laboratory synthesizer until the issue is resolved.

- We have several “aces in the hole”:
    - Programmable LNA gain to decorrelate inputs and measure biases.
    - Totalizers to monitor digitizer null-offsets.
    - LO power leveler- can be retrofitted to the phase switch to improve balance.
    - New differential synthesis techniques which will likely ease requirements compared to current assumptions.

50-55 GHz Radiometers

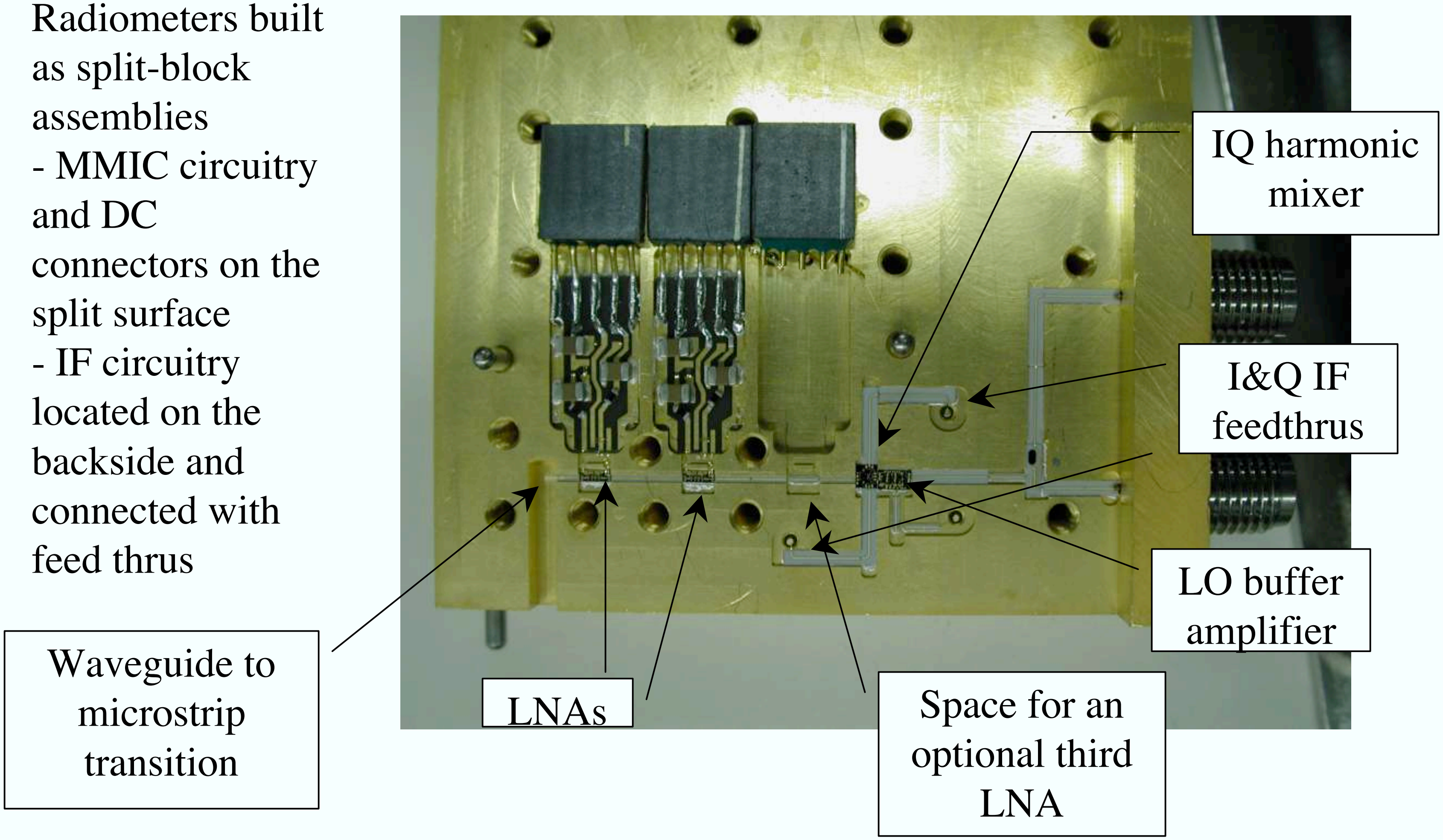
Prototype radiometers (2 units) manufactured, assembled and tested

- built for testing and prototyping different design options
- these were also used in antenna testing as receivers
- two units built to enable testing with a correlator



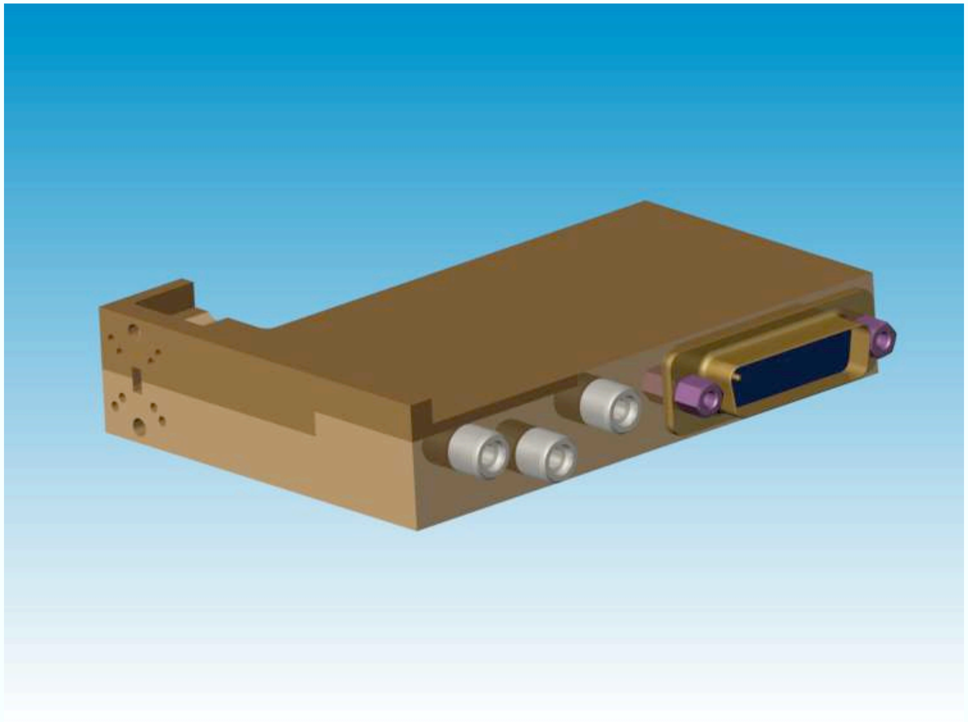
50-55 GHz Radiometers

Radiometers built as split-block assemblies
- MMIC circuitry and DC connectors on the split surface
- IF circuitry located on the backside and connected with feed thrus

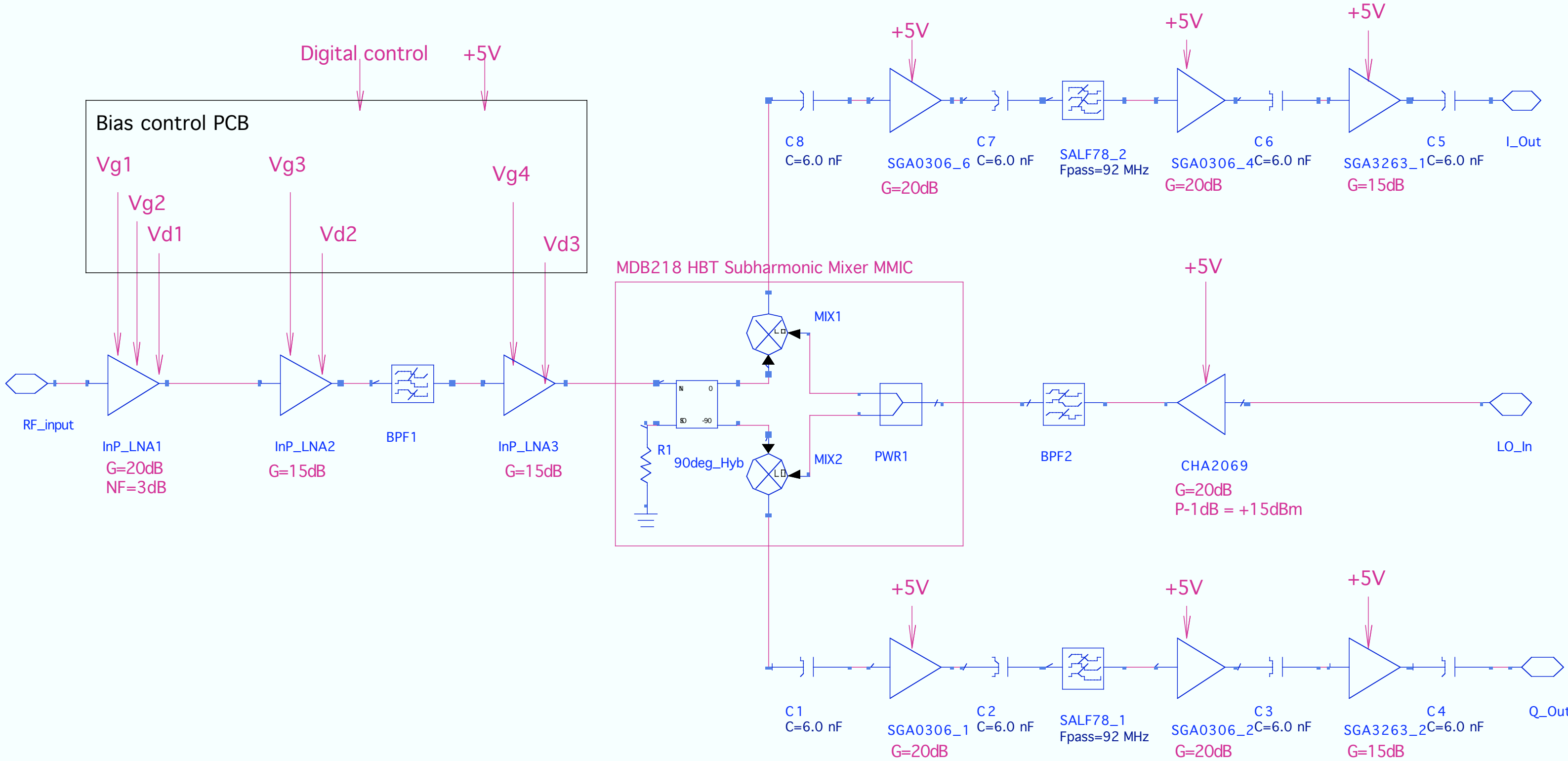


50-55 GHz Radiometers

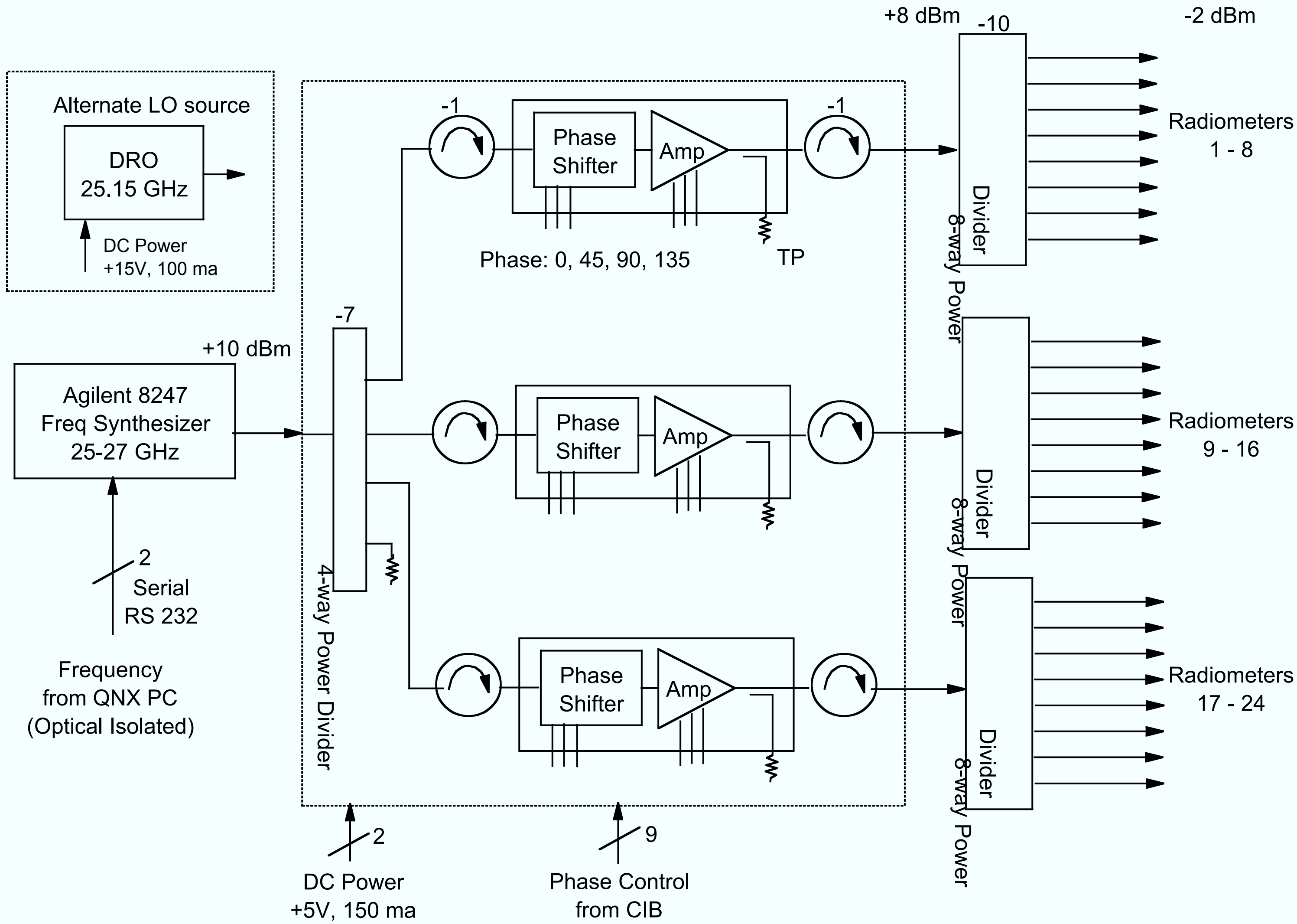
- Manufacture and test of 26 units in February-August 2004
- Final mechanical layout has been designed to simplify the assembly of the system
- Units have an internal programmable DC bias card that is digitally adjusted and controlled for switching between receive/isolate modes



Block diagram of the 50-55 GHz radiometer



GeoSTAR Local Oscillator Source

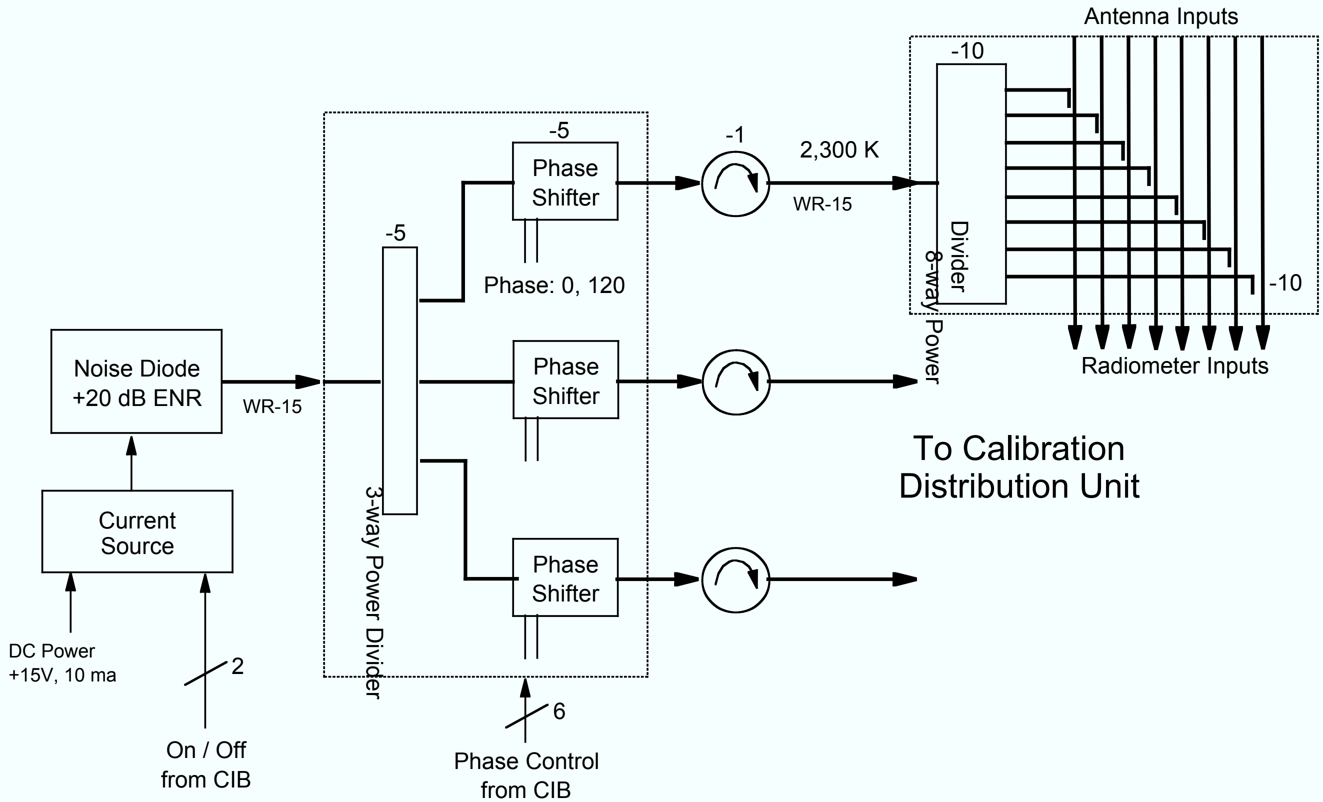


GeoSTAR LO Distribution

- Requirements:
  - Input LO : 25.1-27.5 Ghz @ +10 dBm
  - Outputs: 25 LO channels
  - Phase: 24 LO channels , 3 groups of 8 channels, each group with independent computer controlled phase adjustment in fixed steps of 0°, 45°, 90°, and 135° and 1 LO channel with the same phase as the source
  - Output level: -3.0 dBm
- Power dividers and Isolators in house

GeoSTAR Noise Calibration System

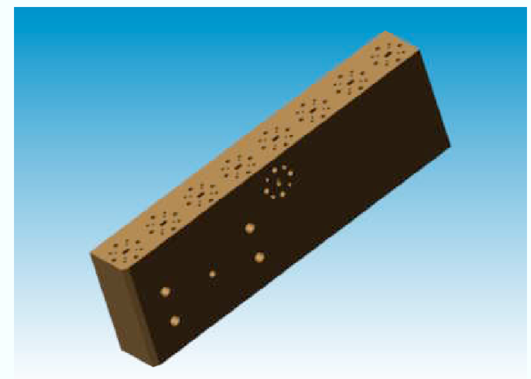
Calibration Assembly



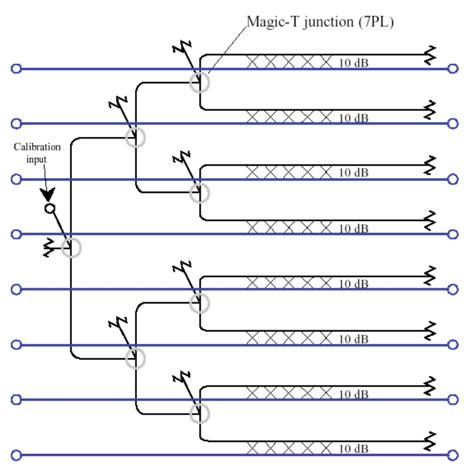
GeoSTAR Calibration Assembly

- Interface and precisely aligns the Horns and Radiometer modules
- 8 Thru ports with built-in 8 way Noise Diode power dividers and 10-dB couplers
- Specs:

Insertion loss:	thru port 0.54 dB
Frequency range:	50.1- 55.8 Ghz,
Interface:	WR-15 (17 ports)



Horns



Radiometers