A 4 Meter 180 to 680 GHz antenna for the Scanning Microwave Limb Sounder

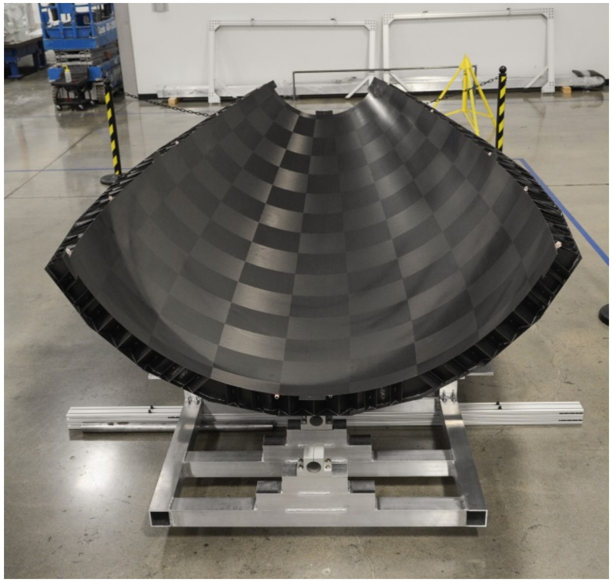
Richard Cofield, Samuel Bradford, Nathaniel Livesey,
and Paul Stek
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA
Eldon Kasl
Vanguard Space Technologies, Inc., San Diego, CA

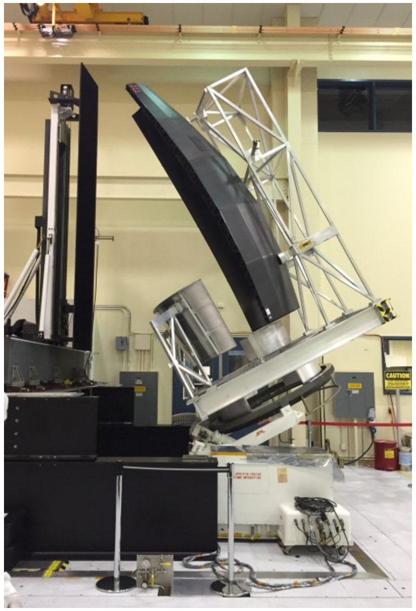
ESTF2016 A3P1

June 14, 2016

NASA ESTO IIP-10-0021

A 4 meter 180 to 680 GHz antenna for the Scanning Microwave Limb Sounder





Richard E. Cofield Jet Propulsion Laboratory

Earth Sciences Technology Forum

June 14, 2016

Project overview

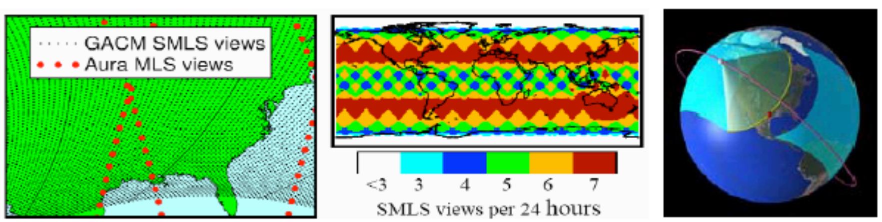
- Overview of tasks remaining after June 2013 ESTO Observation Group meeting:
  - Tasks 1 & 2, Primary reflector fabrication and Thermal test
    - *completed per April 2014 review*
  - Tasks 3 & 4, FEM correlation with Thermal tests and Breadboard Antenna /Near-Field Range Fixture (completed on Oct. 9)
    - *addressed in the Oct.27 2015 Final review*
  - Task 5: Beam Patterns on Near-Field Range
    - *covered in March 2016 d-Final Review*
- Summary

Research Team Members

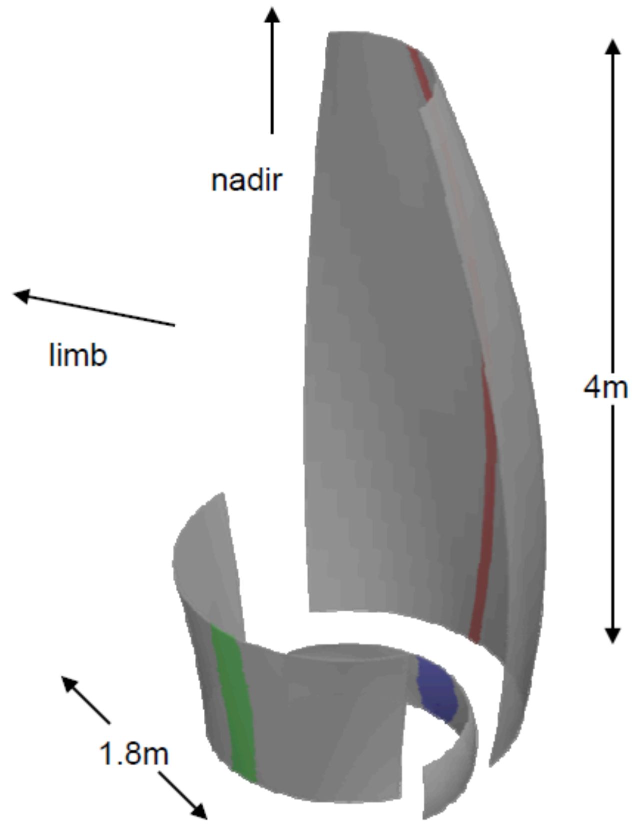
- Principal Investigator: Rick Cofield, JPL
- Co-investigators
  - Paul Stek (SMLS instrument lead)
  - Nathaniel Livesey (MLS science lead)
  - Bill Read, JPL (Measurement science)
  - Mark Thomson, JPL (ALPS facility)
  - Greg Agnes, JPL (Thermal Testing in ALPS)
  - Eldon Kasl, Vanguard Space Technologies (Primary Reflector)
- Other JPL contributors continuing
  - Barry Orr (mechanical lead for breadboard antenna and NFR fixture),
  - Paul MacNeal (Finite Element Models, breadboard antenna & fixture engineering),
  - Tim Newby (Mechanical integration of breadboard, fixtures and scanner),
  - Jacob Kooi (NFR electronics design),
  - Stephen Baker (NFR beam pattern tests)

SMLS measurement concept

- The toric Cassegrain antenna designed for SMLS provides azimuth-independent scanning over a ±65° swath of a conical scan from the 830km GACM orbit.
  - Primary, Secondary and Tertiary surfaces are generated by rotating conic sections about a common toric axis in the nadir direction.
  - Proper choice of the conic foci and the toric axis transforms a feed pattern with circular symmetry into a very narrow vertical illumination of the Primary.
  - The resulting footprint is diffraction limited in the limb vertical direction and ~20x broader, independent of azimuth, in the horizontal.
  - A small (~10cm diameter) mirror scans the beam over the antenna, while a slower ~2° nod of the entire antenna provides the vertical scan.



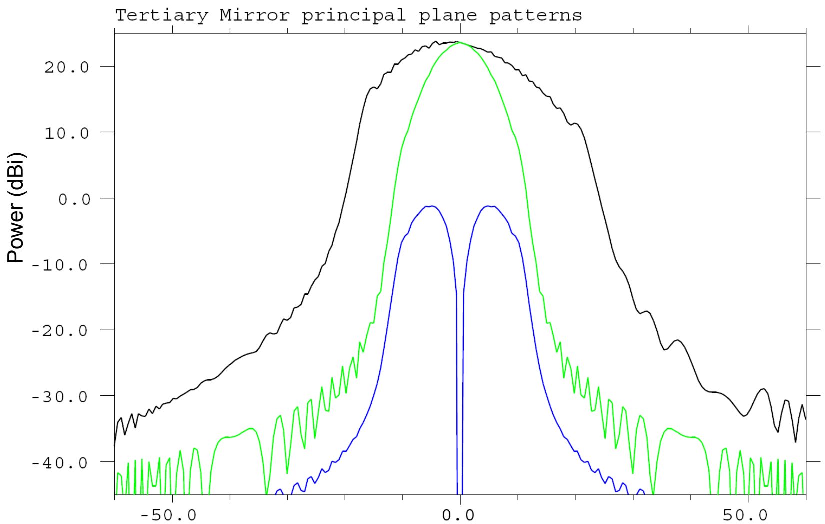
SMLS coverage: (LEFT) compared to Aura MLS for part of 1 orbit; (CENTER) Temporal coverage; (RIGHT) azimuthal scan

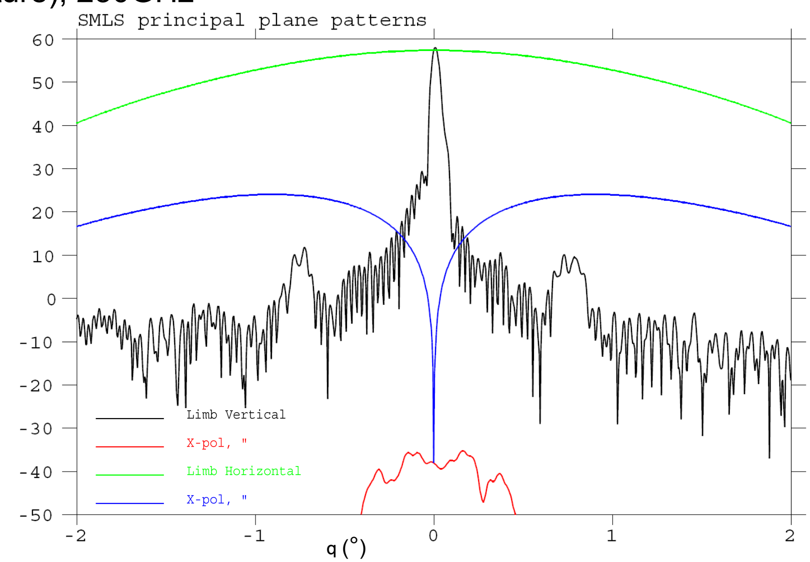


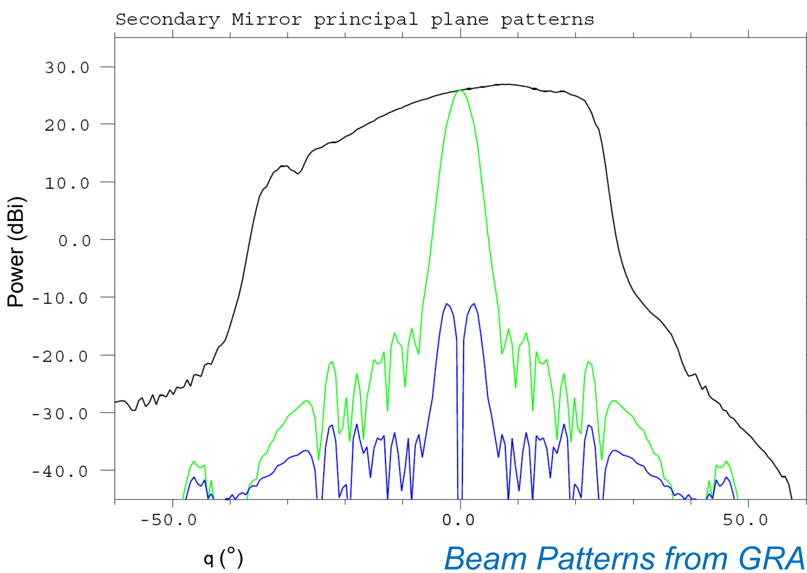
Footprints of the +10° azimuth pixel on SMLS Primary, Secondary and Tertiary reflectors

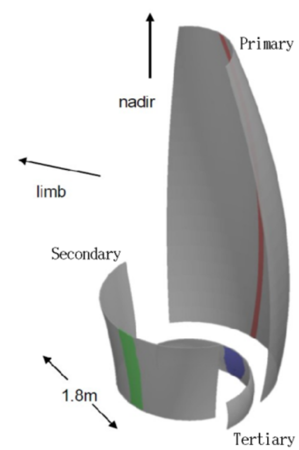
Physical Optics model of SMLS antenna

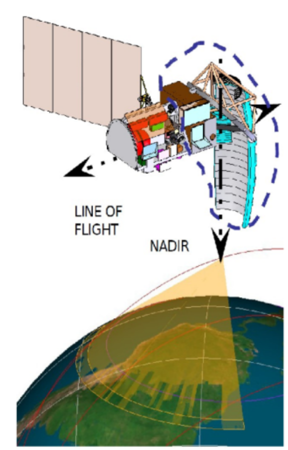
4m Primary (3.2m aperture), 230GHz







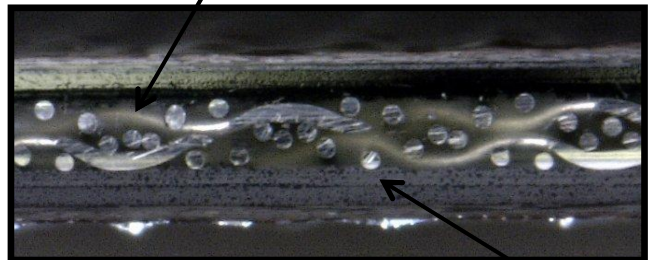




Beam Patterns from GRASP PO model confirm illumination per design

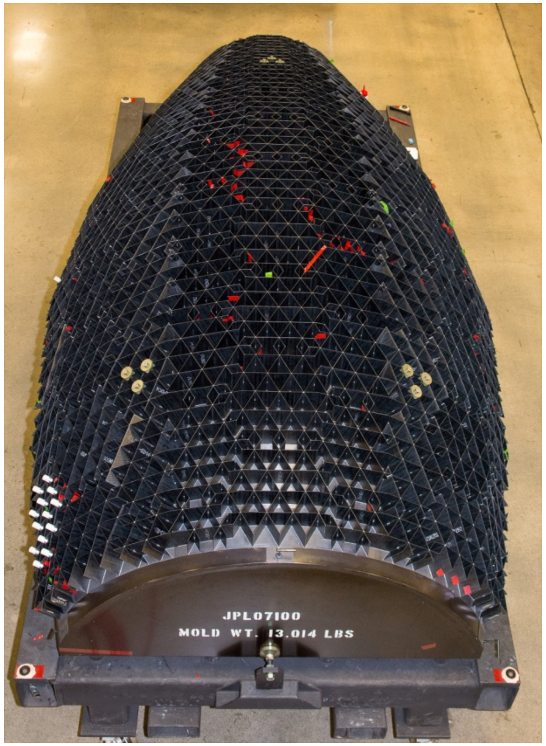
Full-Width Primary completed July 2013

2 plies Aluminum mesh for high thermal conductivity



Core Ribs Cross-Section

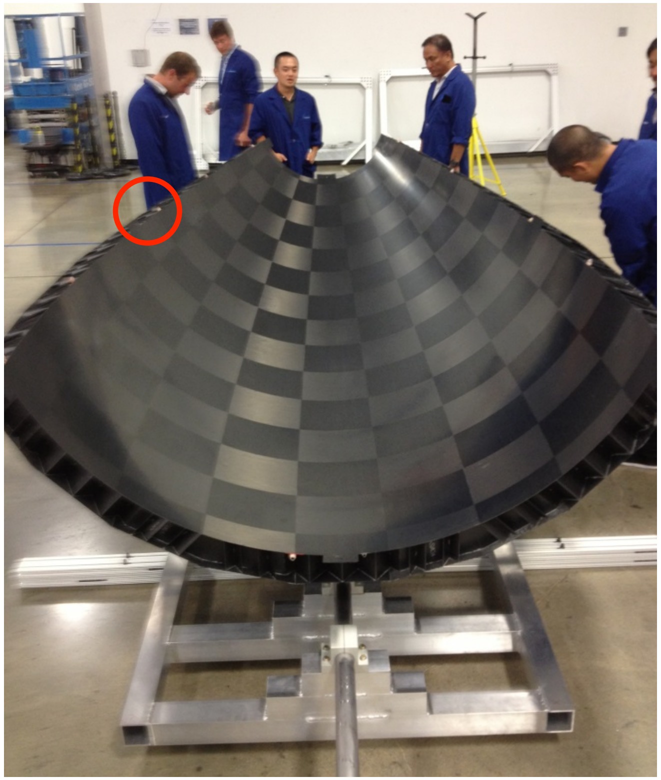
carbon fibers in
cyanate resin for CTE ~0



Primary reflector before
bonding back skin facets

Completed Primary reflector before final cure, wedge/flexure installation, and removal from mold for surface figure measurements pre- and post thermal cycle using laser tracker

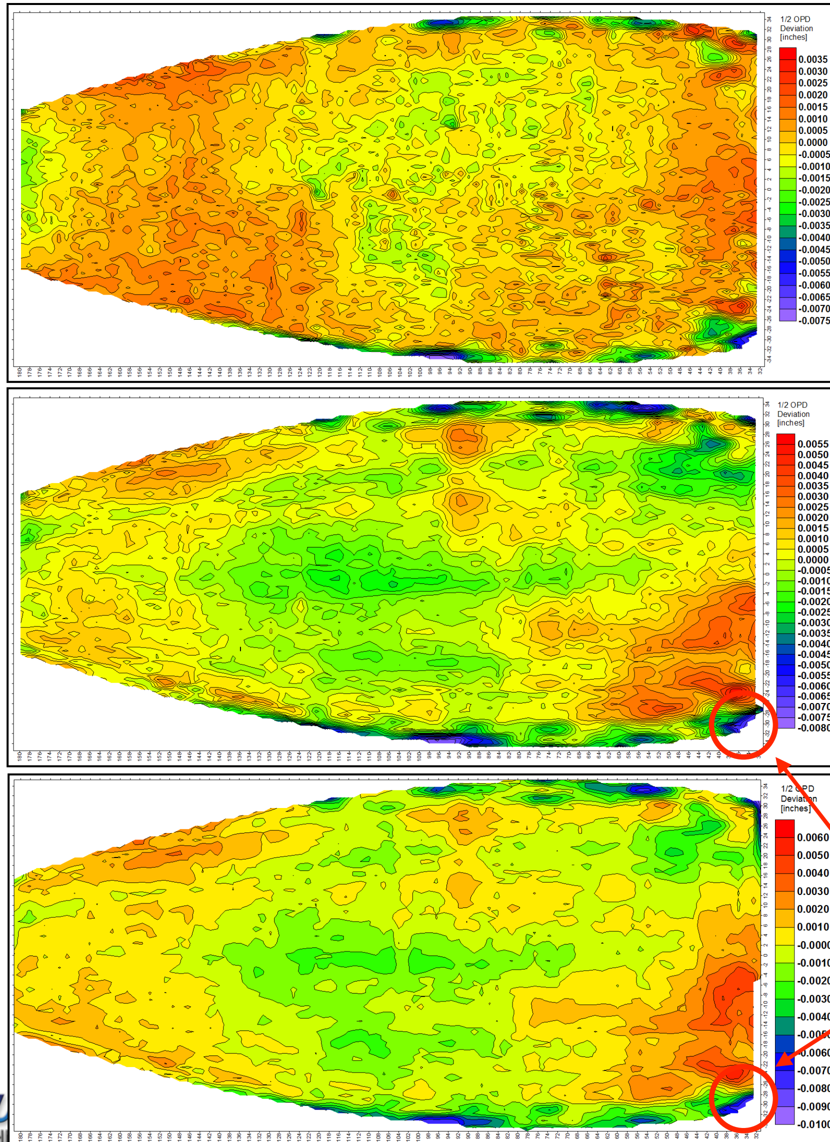
Primary reflector surface measurement



- 12 fiducial features bonded to back of Primary front skin establish coordinate frame for comparing surface alignment data sets
- Conical nests accept 0.5 inch spheres (tooling balls or Spherically Mounted Retroreflectors (SMRs), used here with a laser tracker.

- A separate SMR is swept over the front to generate a large dataset in the coordinate system established by the fiducial spheres (one circled ○ in photos above)
- Vanguard provided contour maps and the regularized data grids in electronic form

Surface contours measured by Vanguard: mold, reflector pre- and post-thermal cycling



Mold:
29 micron rms surface

Reflector pre-Thermal cycle:
37 micron rms surface*

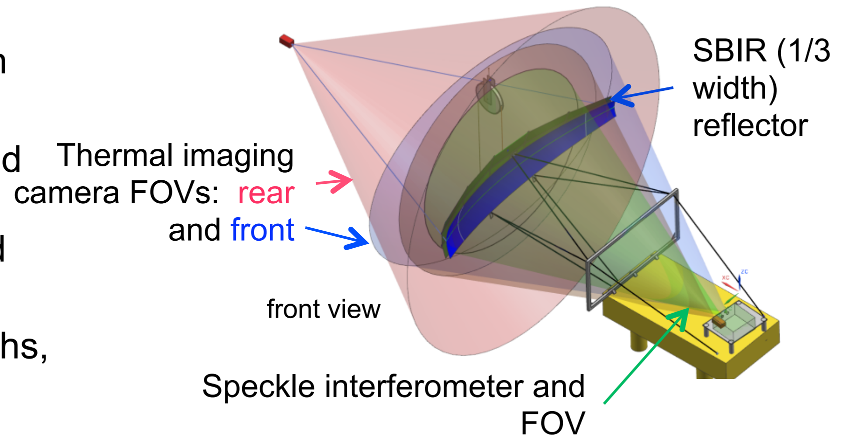
Reflector post-Thermal cycle:
43 micron rms surface*

*excluding damaged corner: <1 inch^2 region of high surface error (635 micron) due to surface sticking when removing skin from mold. Inclusion would raise overall surface error to 55 micron. Region was excluded from thermal gradient and pattern measurements.

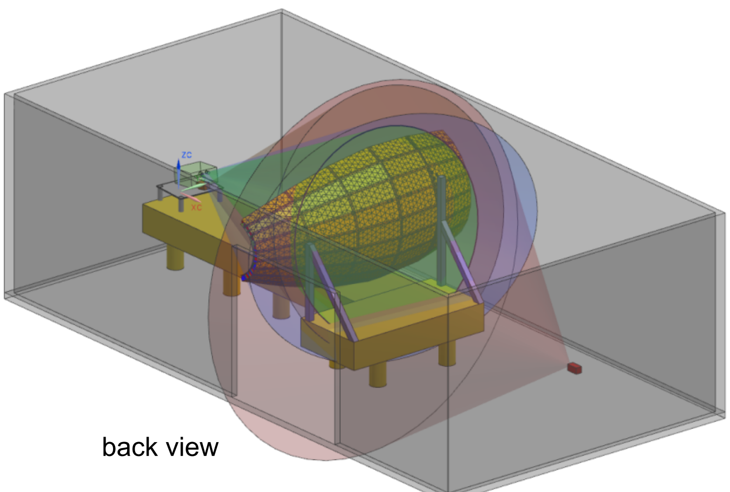
Thermal gradient tests of Primary Reflector

- Measure deformations under thermal gradients in JPL's ALPS facility
  - Support primary reflector in a closed test enclosure with stable environment controlled by air conditioning
  - View reflector with 2 thermal imaging cameras (front and rear) plus an Electronic Speckle Interferometer (ESPI), during transients and steady state, while heat is applied using surface contact (Minco) heaters
  - ESPI detects relative deformations at optical wavelengths, (<< SMLS wavelengths), but gradients are << those expected in GACM orbit
    - Invoke linearity to infer predicted orbital performance
- ALPS I measurements (SBIR) completed June 2012
  - Custom mounts bonded to core edge to suspend reflector
  - ESPI system sensitive to 10-nm-scale vibrations; metering structure iterated to achieve stability of the metrology path
  - Correlated with FEM to within 14% of peak deformation
- ALPS II (Full-width Primary) July-December 2013
  - Reflector support via Vanguard mounts on an optics bench simplifies metering structure and reduces blockage
  - lessons learned in 1/3-width test were incorporated into the test program for the full-width reflector

1/3-scale reflector as tested (ALPS I)

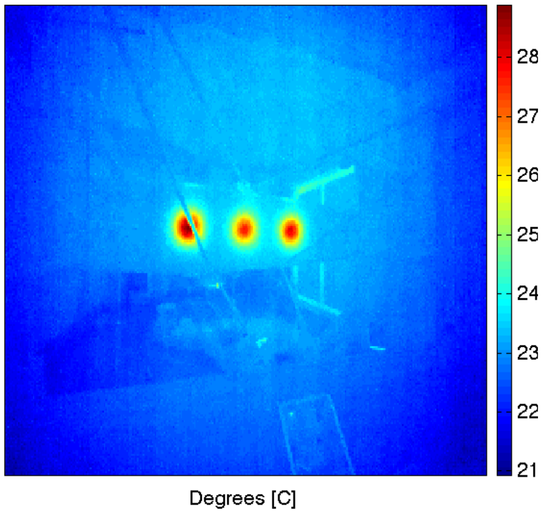


Full-scale reflector mockup (ALPS II)

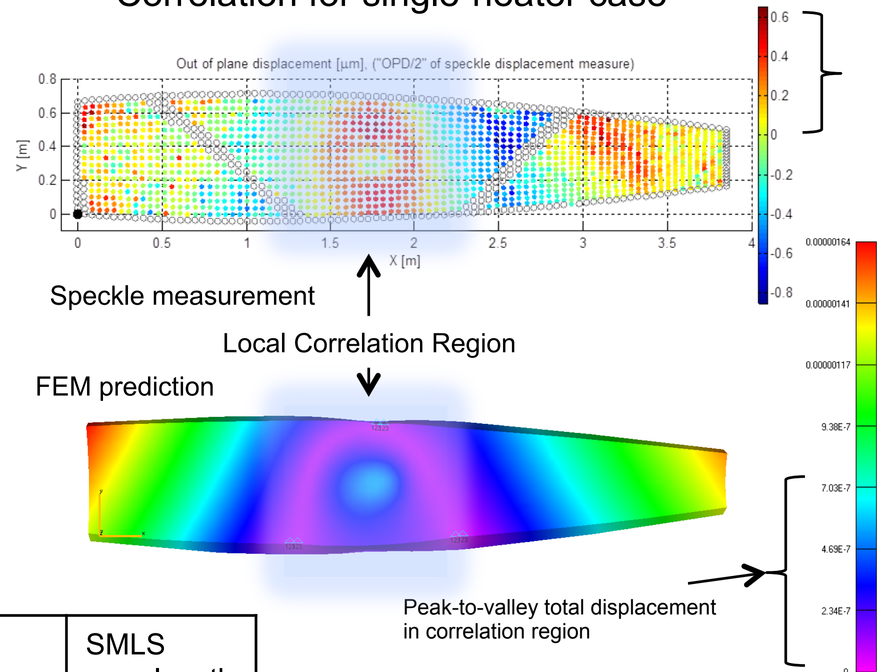


ALPS I Thermal Gradient Result

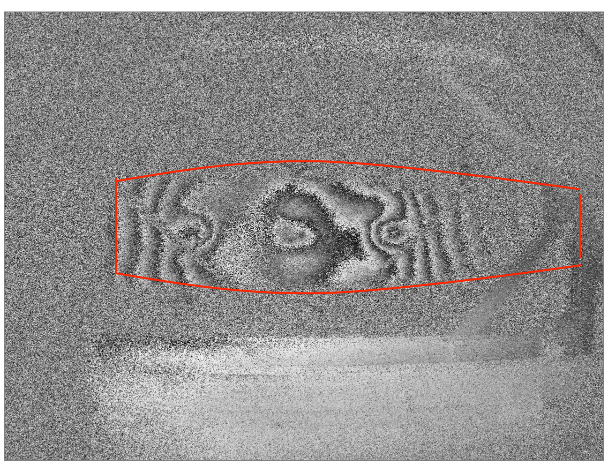
Front temperatures due to 3 back side heaters



Correlation for single-heater case



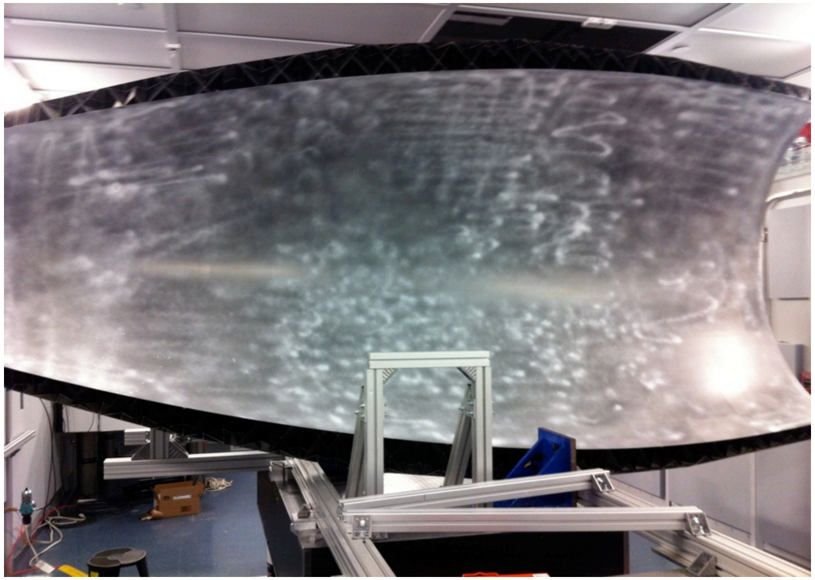
corresponding speckle image

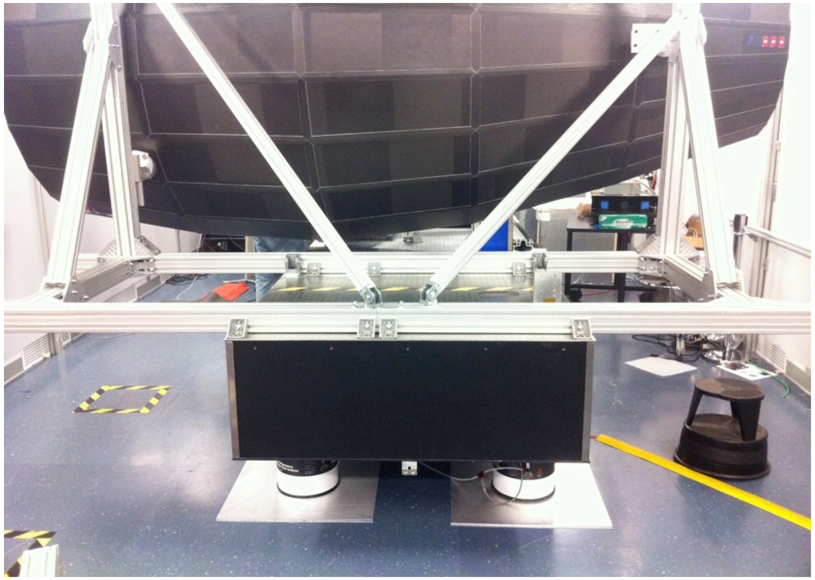


Fringe spacing		SMLS wavelength @ 680GHz
$l_{speckle}/2$		
250 nm	«	440mm
Speckle resolution		Thermal gradient budget
25 nm	«	310 nm (scaled test)

- **FEM correlation to measurement 14% at peak deformation**
- Remaining cases to be analyzed after interpolation across blockages of thermal (easy) and speckle (hard, phase-wrapped) FOVs

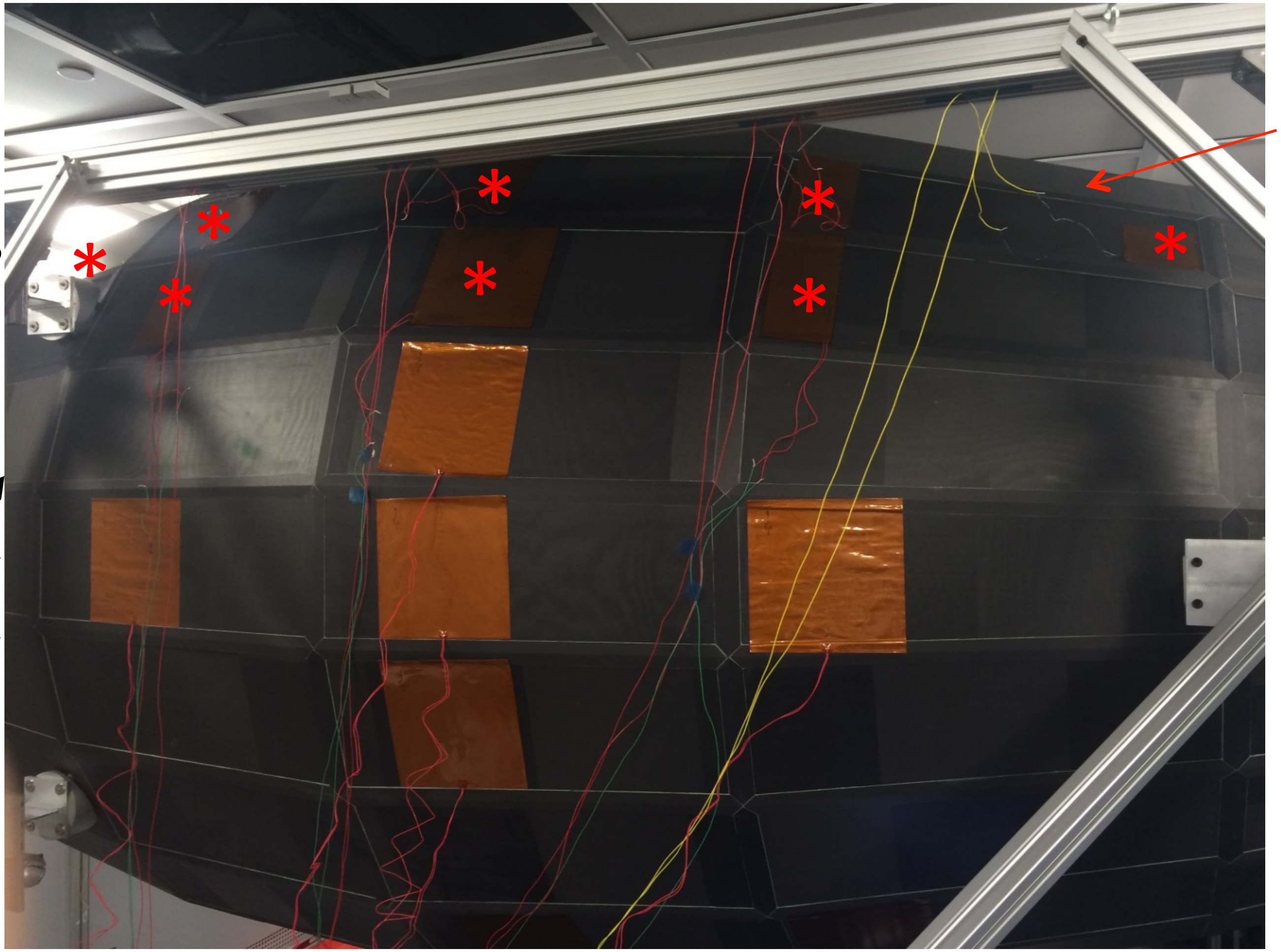
SMLS reflector mounted on kickstands in the Precision Environmental Test Enclosure (PETE)





- Front surface was sprayed with talc for speckle interferometry before installing in the PETE (talc removed after test)
- Tables are independently floated then tied together with metal frame
- Room and tables all floating (room isolation system was taken out of calibration by the MGSE and SMLS movements during installation)

ALPS 2: additional off-axis heaters to simulate orbital heat loads



*3

*2

1

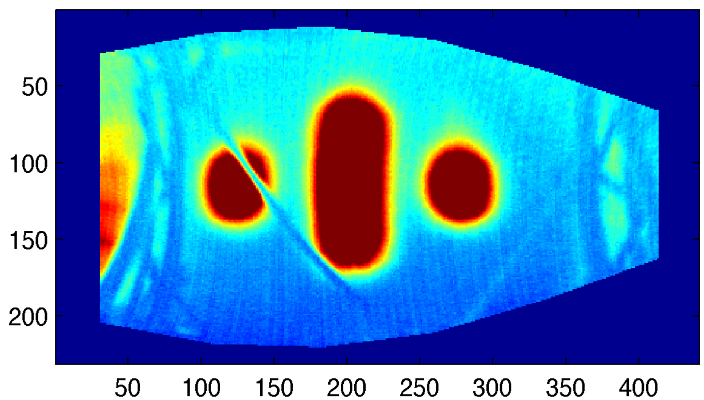
Row 0

5 heaters (Rows -1,0,1) replicate ALPS1 test of 1/3-width SBIR reflector

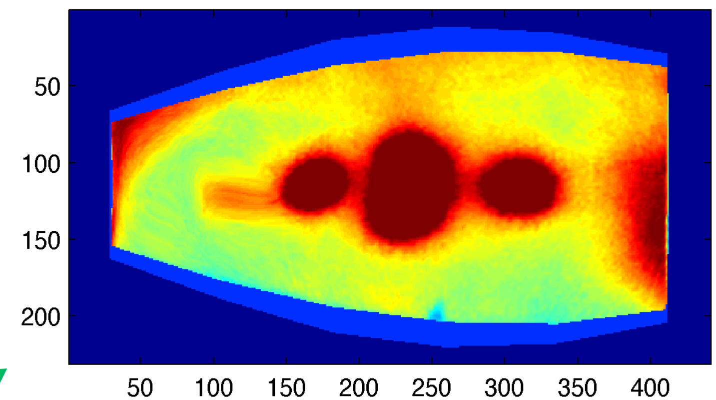
Row 4 inaccessible, except at narrow end with additional repointing of speckle camera

ALPS Thermal, speckle images on IIP Primary

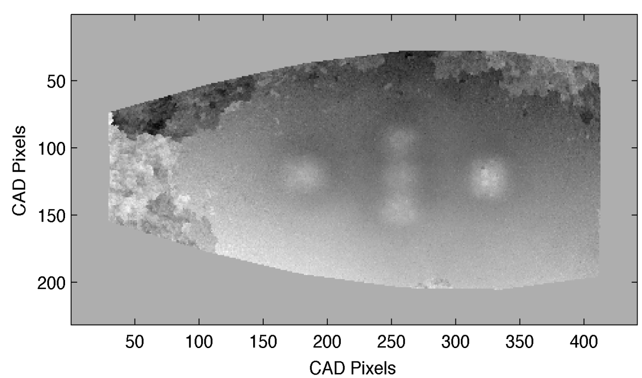
Back thermal data in CAD coords



Front thermal data in CAD coords

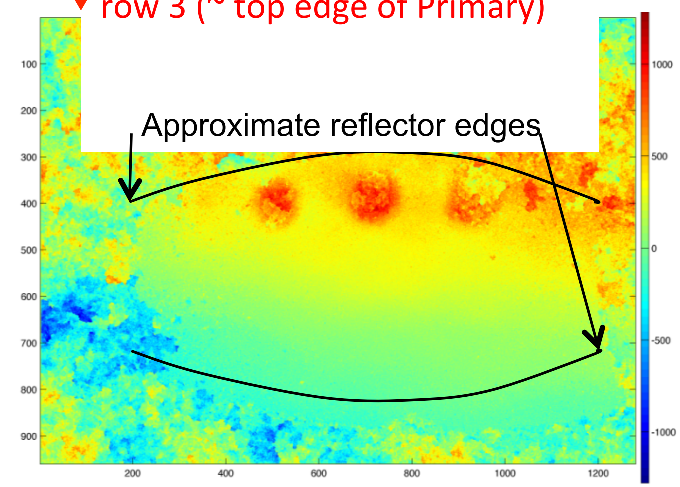


Load case: 5 heaters matching ALPS 1



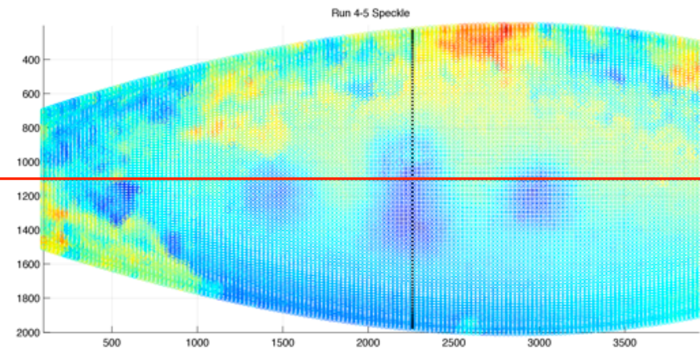
(Front) speckle image unwrapped and masked

Load case: 3 inner facets in row 3 (~ top edge of Primary)

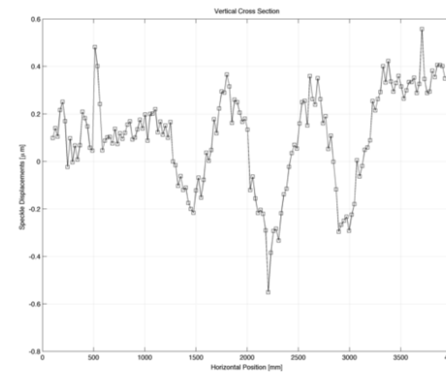


Unregistered and partly unwrapped speckle image

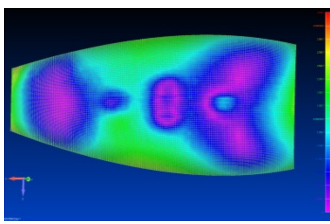
ALPS 2 Measurement/model Correlation



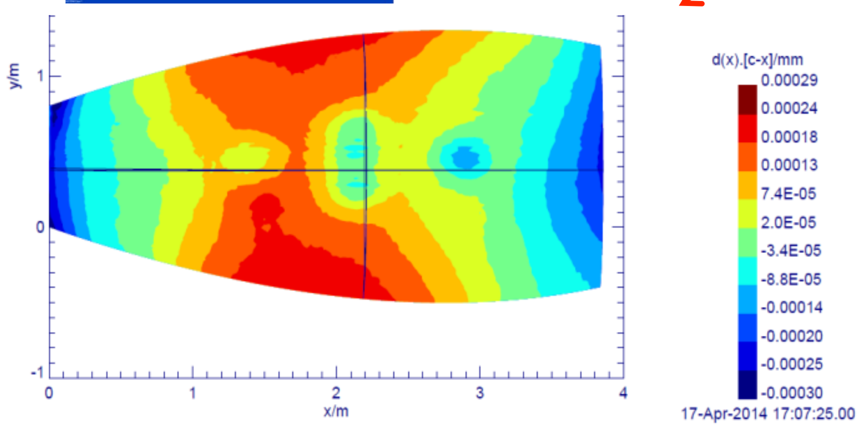
y=const. cut

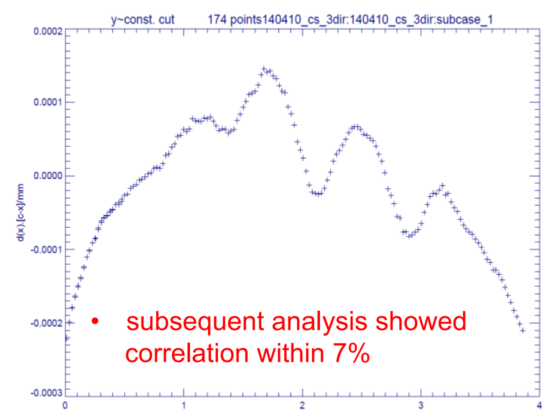


1 micron



FEMAP displays |$\underline{d}$| or x,y,z component;
Speckle interferometer sees projection along local camera ray OPD/2 = $\underline{d}(\underline{x})\cdot(\underline{c}-\underline{x})/||\underline{c}-\underline{x}||$



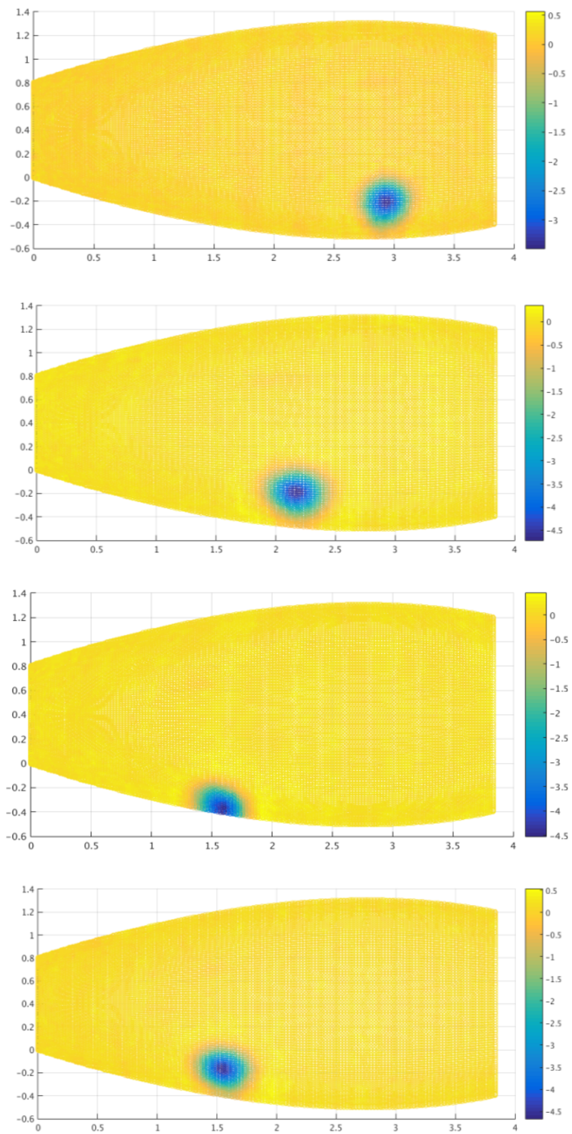


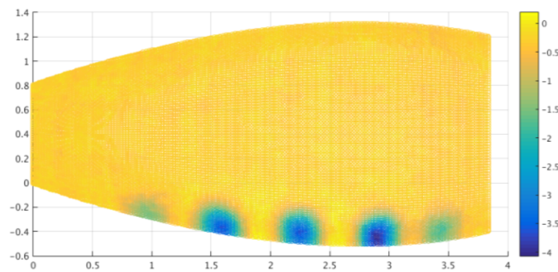
1 micron

- subsequent analysis showed correlation within 7%

- Debugging FEM resolved most large low-spatial order deformation anomalies.
- Remaining ALPS 2 cases better simulate orbital asymmetry

ALPS 2 cases not yet correlated



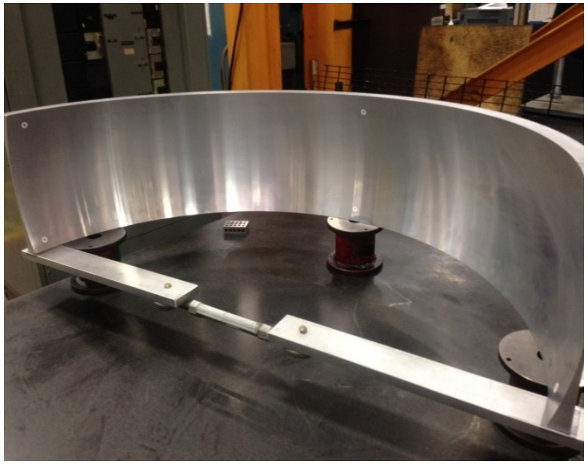


- *Reflector is inverted in these front-thermal-camera images (heaters were on back top half)*
- 2 diagnostic cases not shown: lateral support w/ and w/o glue

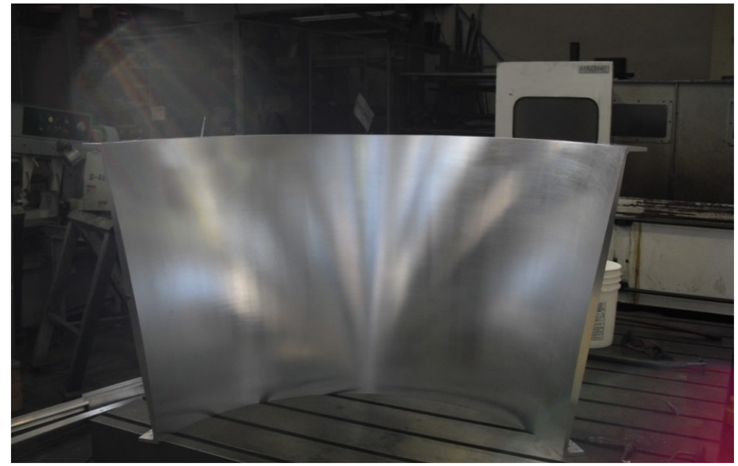
- FEM analysis was put on hold ca. June 2014
  – full data set SMLS.zip was delivered Apr.2 2014
  – Documentation to combine datasets from the 3 carmeras was completed ca. May 2014
  – staffing prevented completion of catalog (ALPS onto other projects, SMLS onto BB antenna build)
  – 2 cases, shown earlier, have been registered and correlated so far: the 3-4 case used to debug FEM, and the top-heated case. Correlation was to 7%

We assert that TRL has advanced based on similarity of deformations to ALPS 1 results

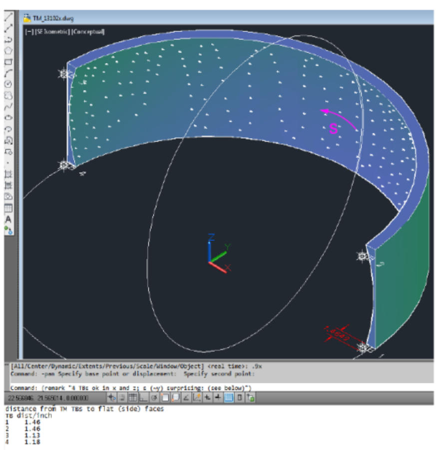
Breadboard Secondary and Tertiary Reflectors

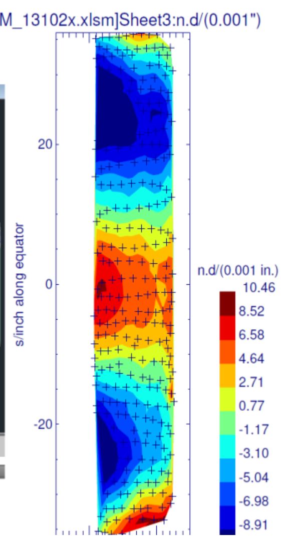


Tertiary with spreader bar for match-drilling

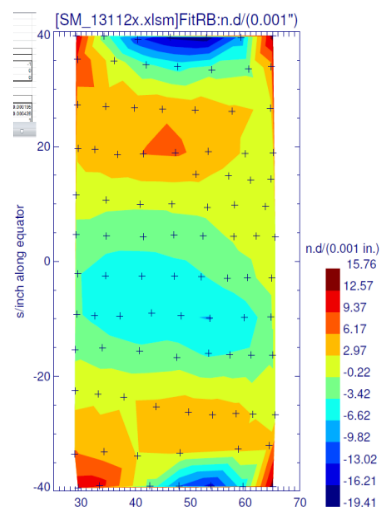


Secondary, pre-ship



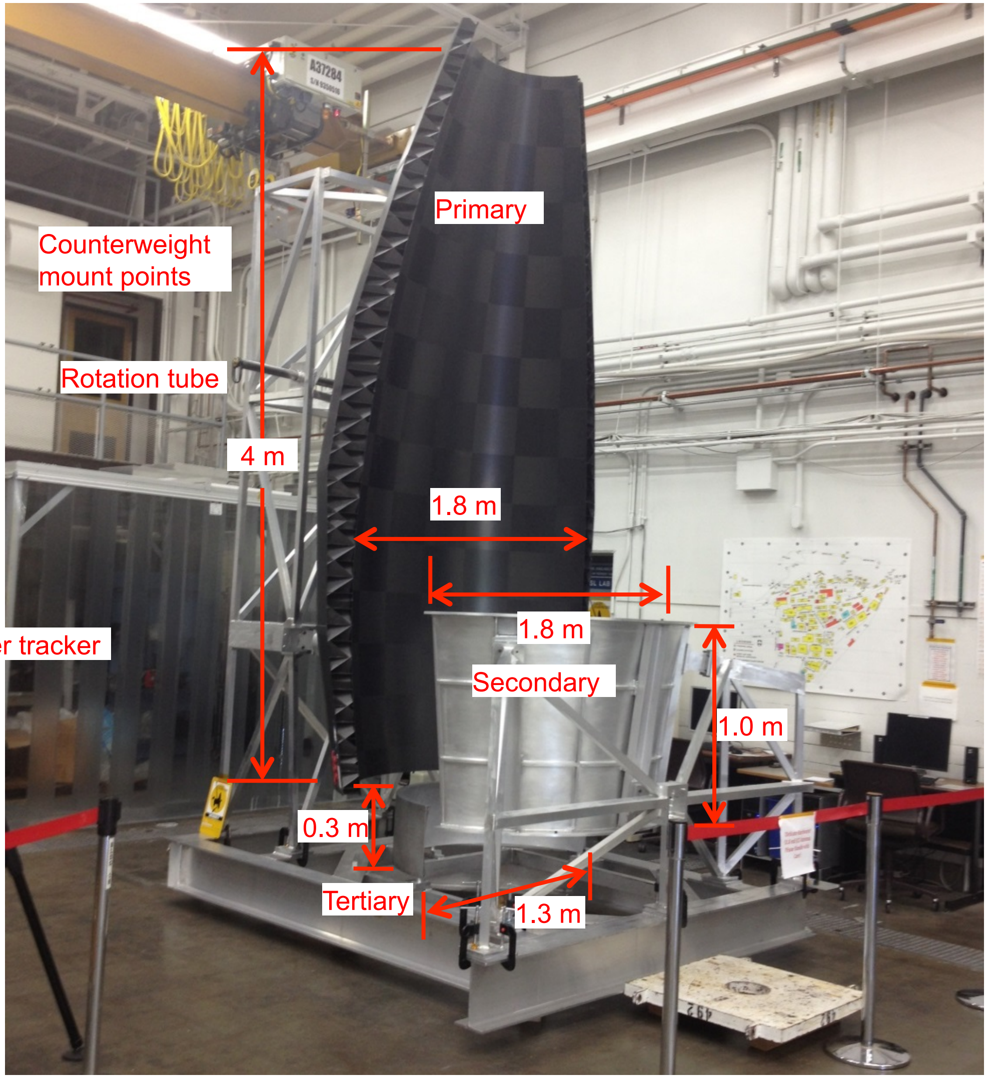


Tertiary surface accuracy within ±0.01inch



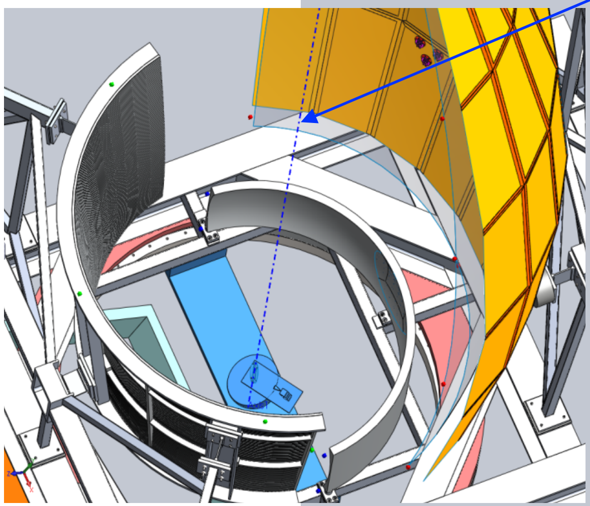
- Free-standing surface accuracy within ±0.02 inch (0.0055 inch rms)
- With adjustment at mounts, alignment improved to ±0.004 inch
- Surface confirmed April 2014 at JPL within 0.0046 inch rms

Breadboard antenna: assembly and alignment

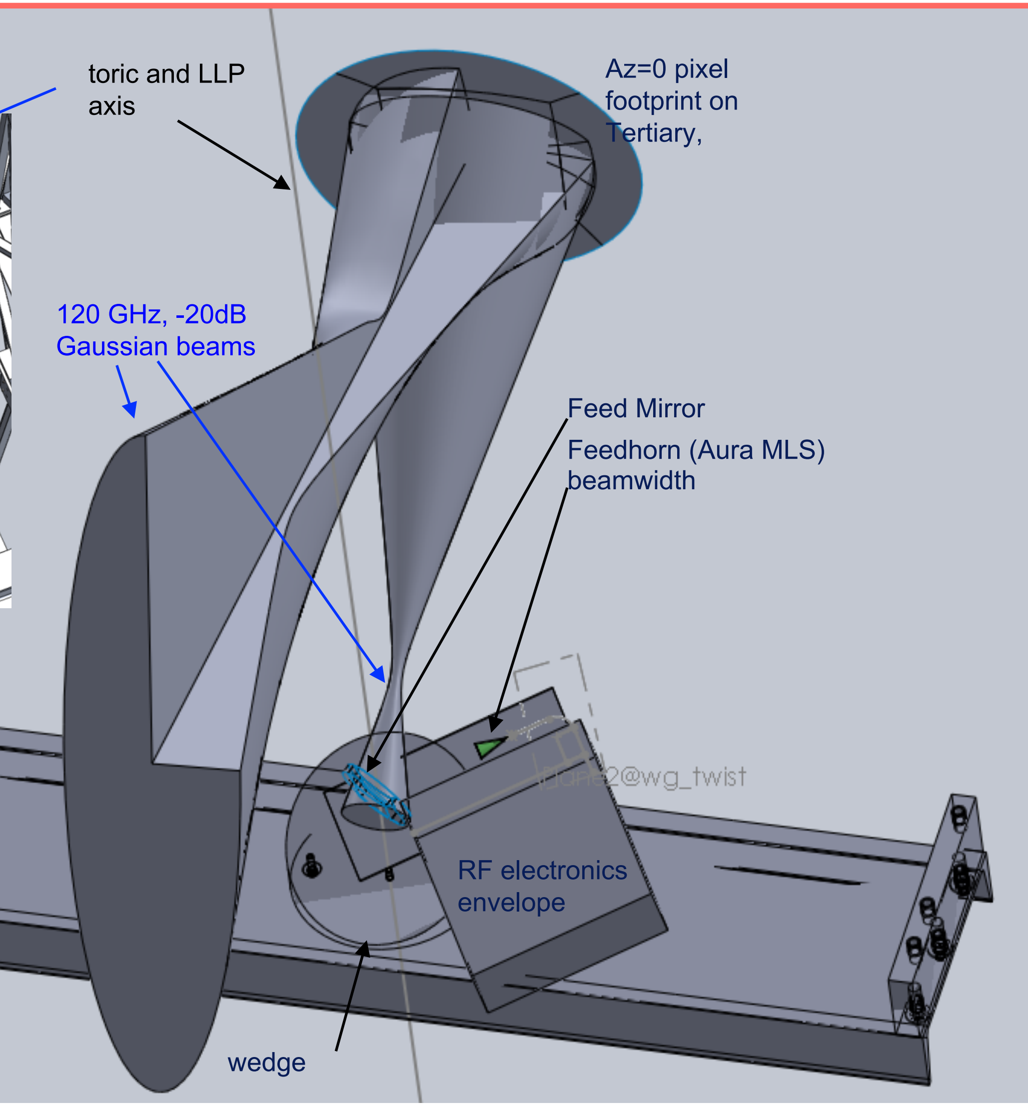


- Measured alignment using laser tracker and spherically mounted retroreflectors (SMRs)
- SMRs on each reflector verified edge contour (hence surface figure) last measured by vendor before delivery
  - including all 12 on Primary before installation; subsequently used lower 6 to align
  - Secondary figure directly measured after removing over-constraint by support
    - Relaxed figure very close to vendor data
- Subsequent steps:
  - Completed shimming and alignment June 2014
  - Estimate residual ½-path error, due to surface figure and final alignment, as 0.5 mm =l/5 at 120 GHz: acceptable for beam patterns)
  - Moved to 306 for final assembly and pattern tests

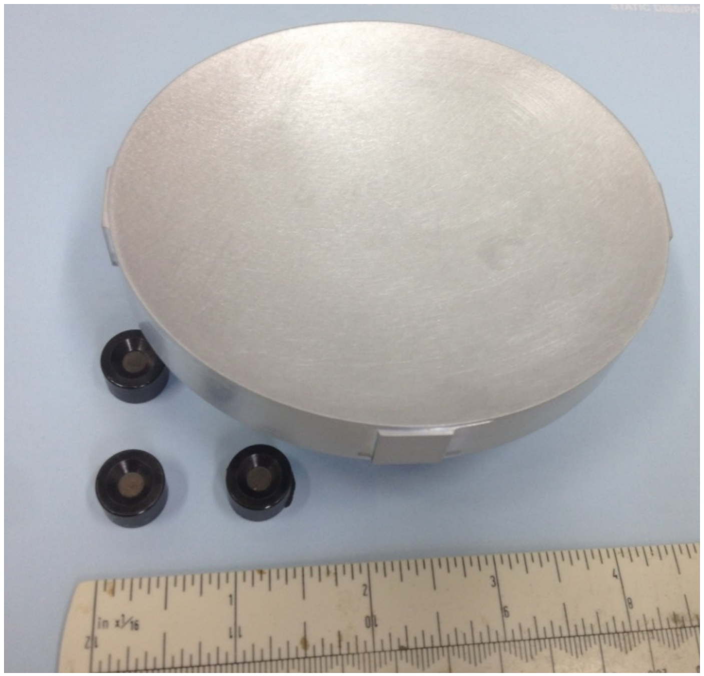
Feed system design



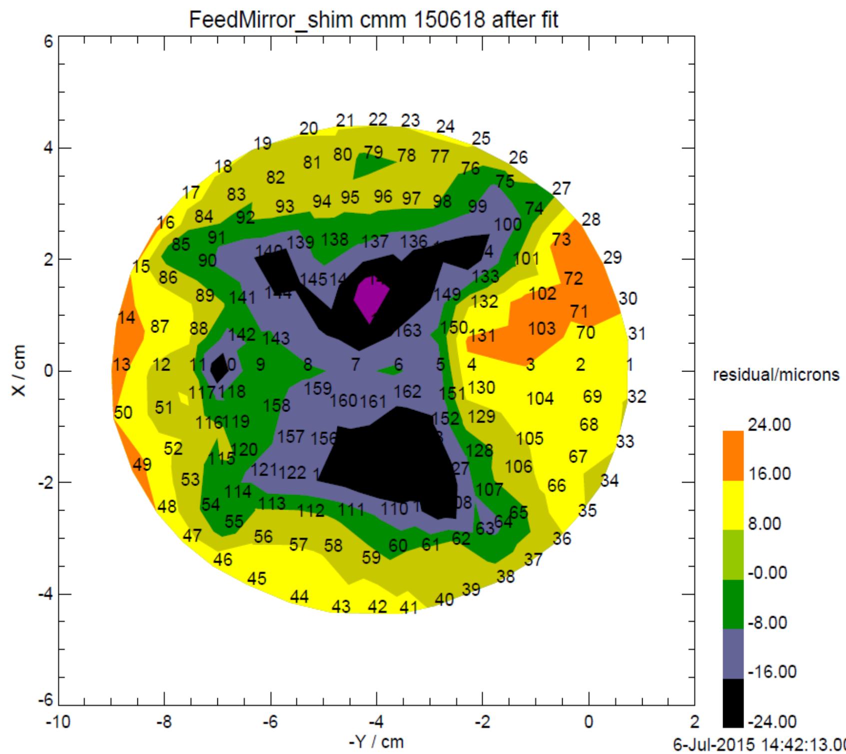
Feed concept in breadboard antenna



Feed Mirror surface and fiducial inspection result

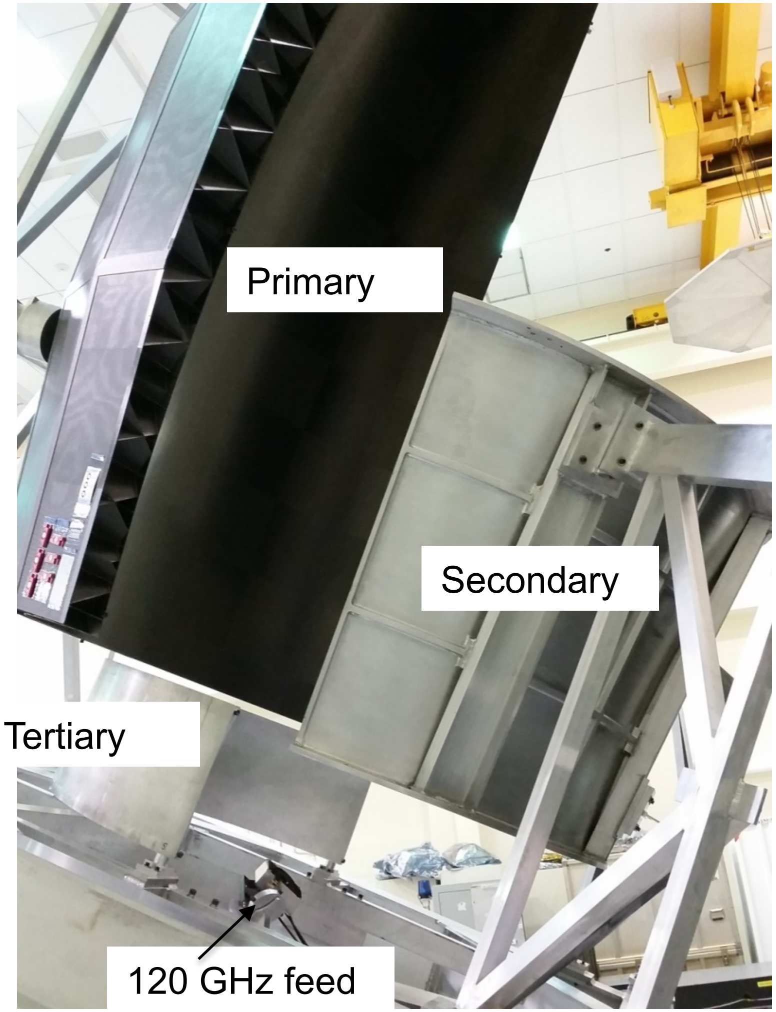


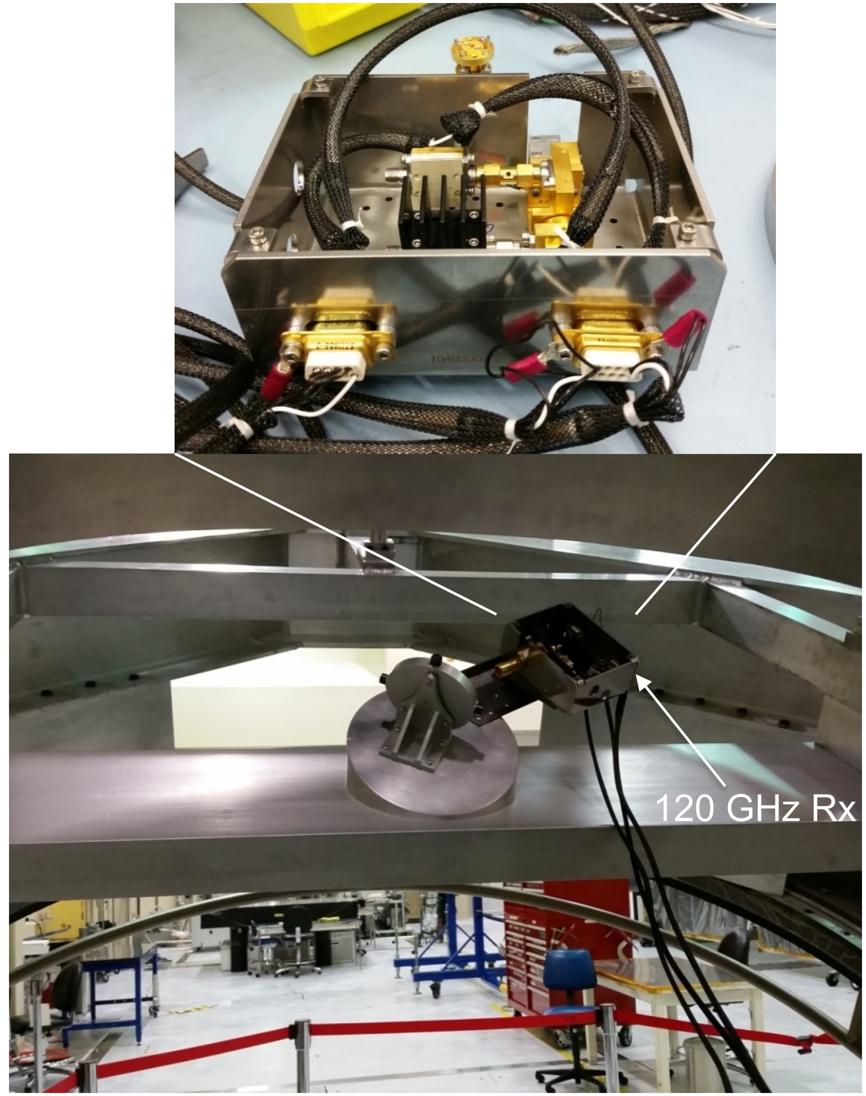
- Feed mirror and Fiducials (SMR nests) before bonding and CMM inspection,



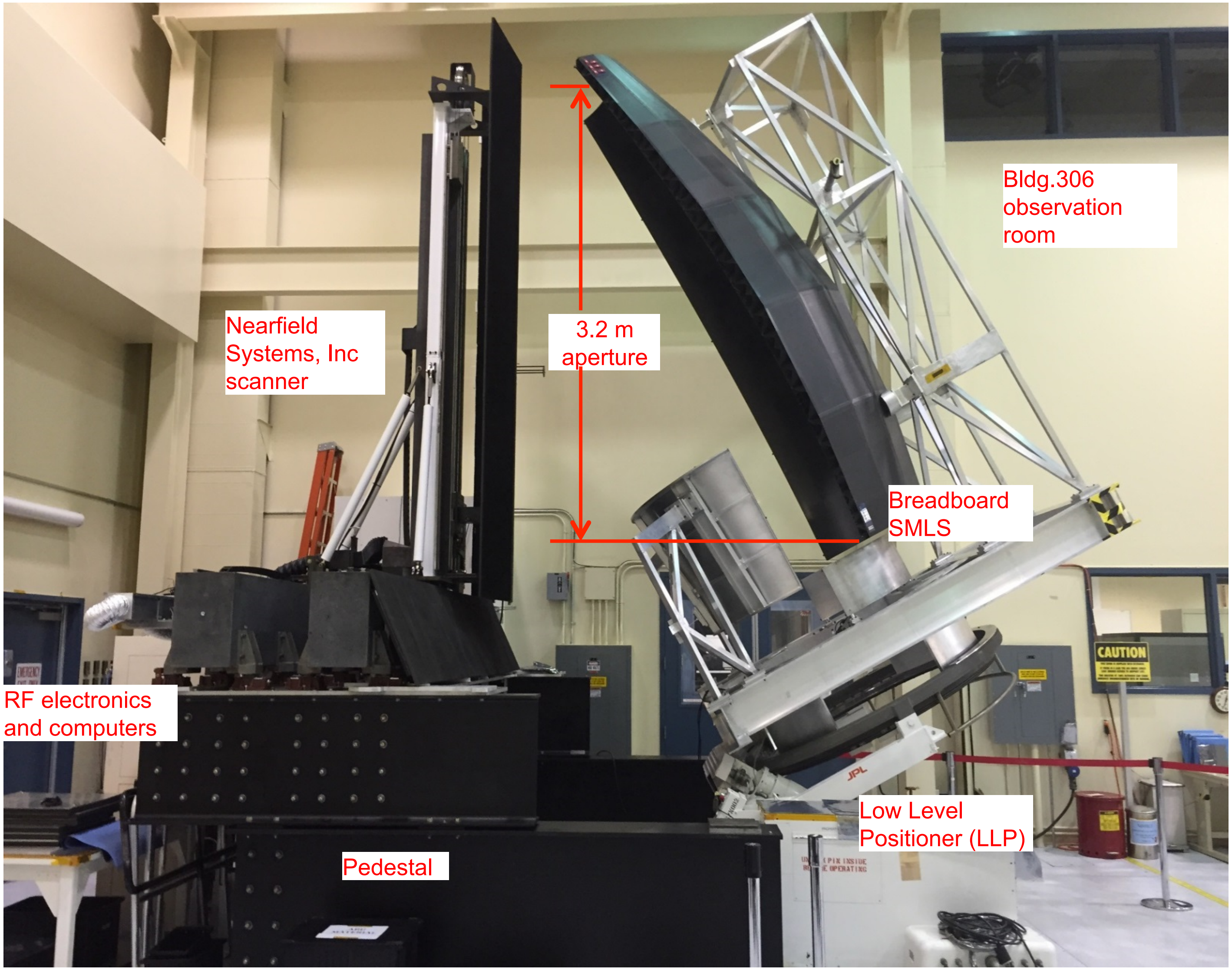
- 3 shims (thickness 0.006 to 0.015 inch) reduce as built surface error of 150 micron rms to 12 micron rms shown here. Thicknesses were incorporated in feed bracket fabrication.
  - cf. 25 micron required for 120 GHz
- also measured Fiducials (SMR nests) for reference aligning to horn and antenna.

feed in SMLS breadboard antenna

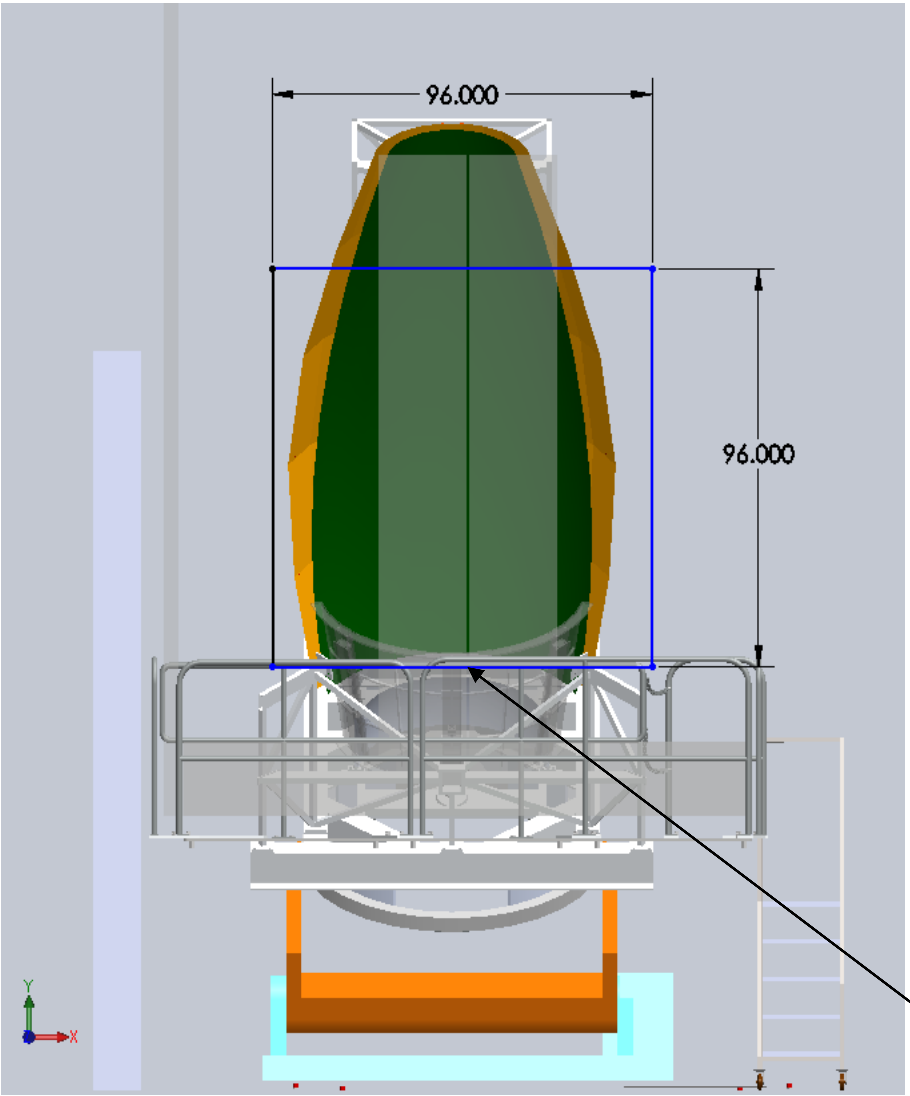




SMLS breadboard in Near Field Range



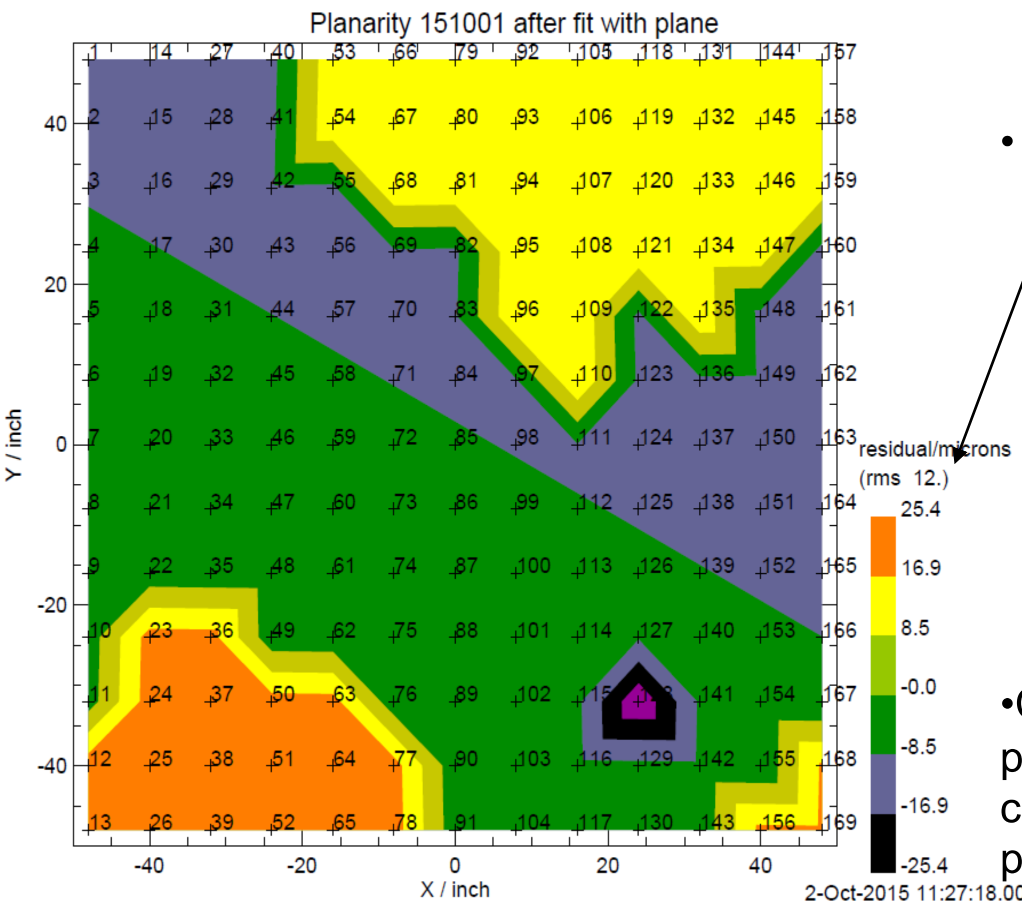
As-built scan range



- 8x8' scanner covers only lower 2/3 of SMLS aperture
- We can extrapolate performance through entire aperture by using the Physical Optics model
  - 5.9' width of reflector is within scan range, esp. since illuminated width is much less for a given pixel
  - 3 scan positions enabled by wedge feed support (+30º, 0º shown and -60º Azimuth offer sufficient sampling of ±65º design coverage

higher eyebrows expose 6.5 inch margin below Primary

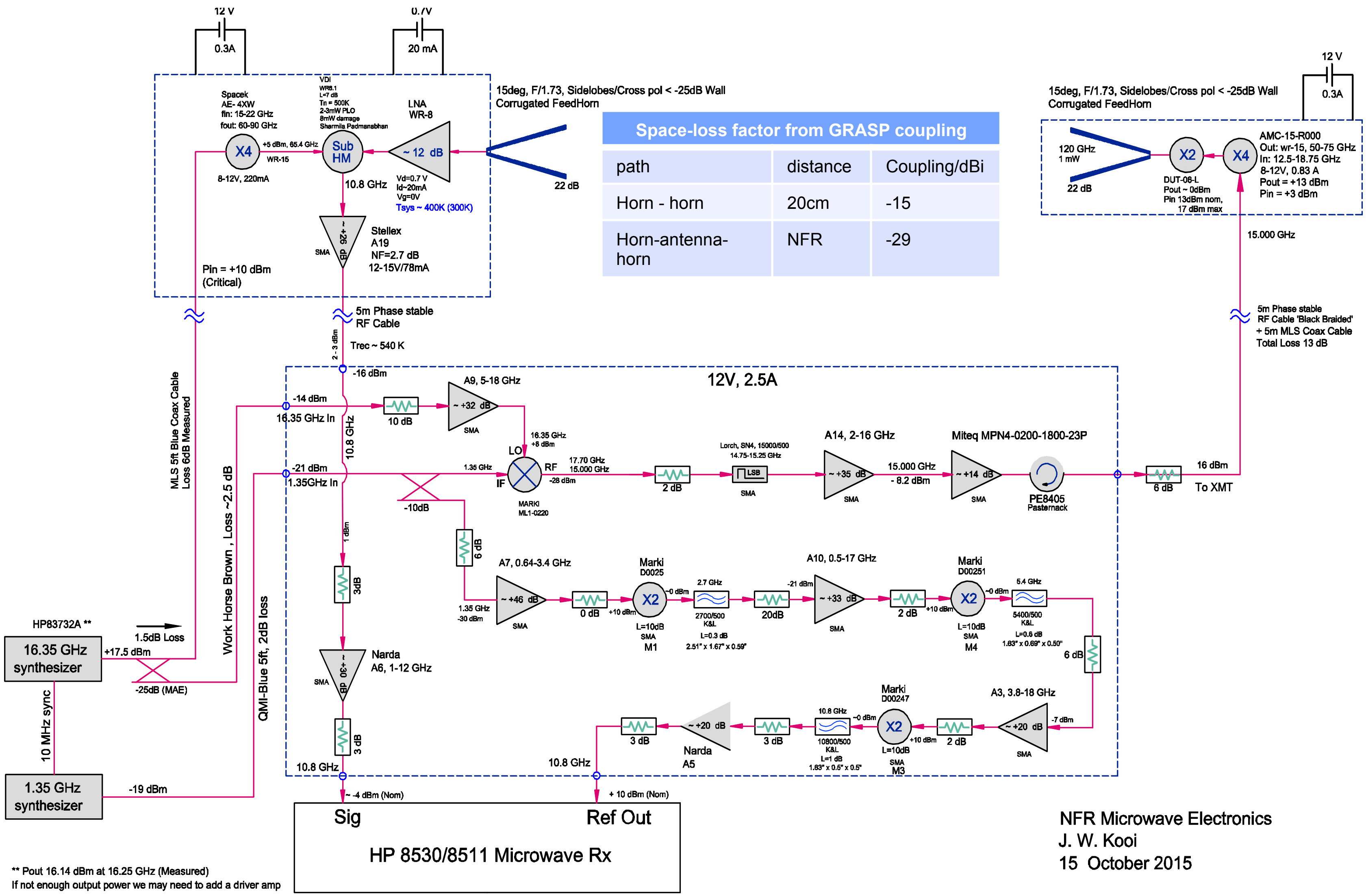
Scanner Planarity after 2 rounds of leveling



- 54 micron stability in 1st installation of scanner on pedestal exceeded 25 micron goal
- In 2nd measurement 12 micron planarity acceptable for 120 GHz patterns
  - Improvement could be due to
    - better temperature stability
    - pedestal stiffening measures
    - colocation of NSI laser on seismic pad (unlike 1st measurement)

•Could monitor planarity during beam patterns and apply software corrections ("K-correction") in post-processing of Near-field data
  - was not required for SMLS measurements

Near-Field electronics block diagram

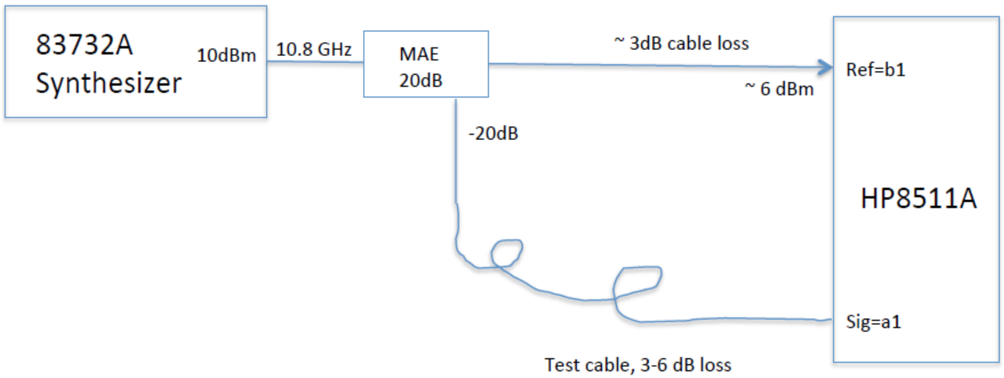


Space-loss factor from GRASP coupling

path	distance	Coupling/dBi
Horn - horn	20cm	-15
Horn-antenna-horn	NFR	-29

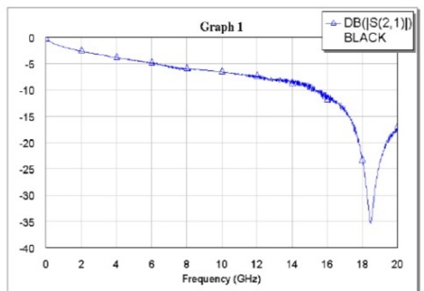
NFR Microwave Electronics
J. W. Kooi
15 October 2015

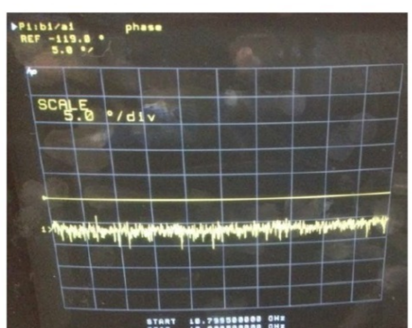
RF electronics stability tests on bench, in rack and in Near-Field Range



Loss 6.9 dB @ 10.8 GHz (0.46 dB/ft)

15 ft Black Braided Flex Coax Cable

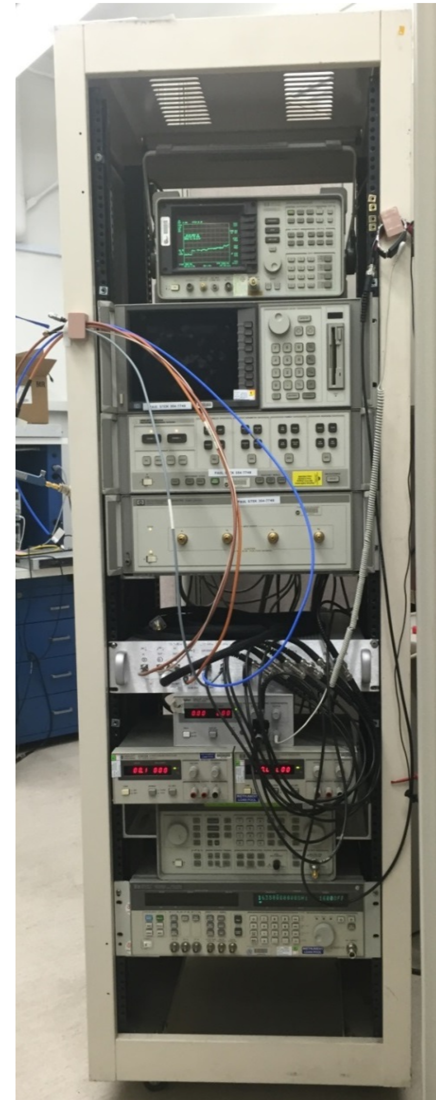




HP receiver-limited stability, all cables, +6dBm ref (b1):

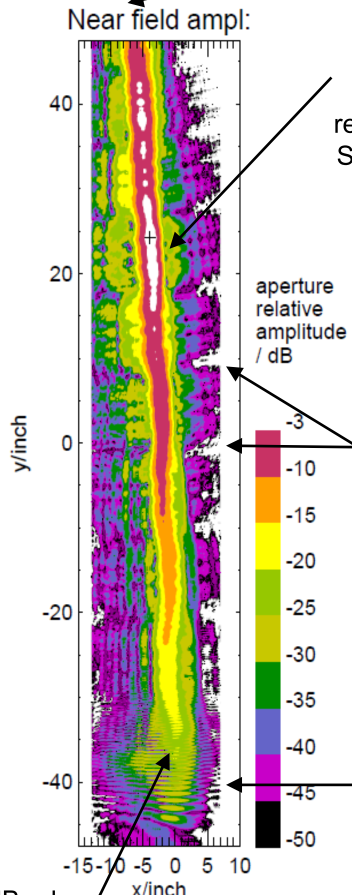
- ± 0.15 dB Ampl.
- ±1.5° Phase

- in rack: same phase stability w/ NFR cable and 1’ horn separation (totally limited by HP 8530/8511 receivers)
- in range: 0.98 dB drift in 10.5 hr,reduced to 0.05dB, <0.5° phase in 10 min. intervals by NSI’s Motion Tracking Interferometry



120 GHz Near field patterns, center azimuth pixel

Top of 3.2m SMLS aperture is above 8'x8' scan plane

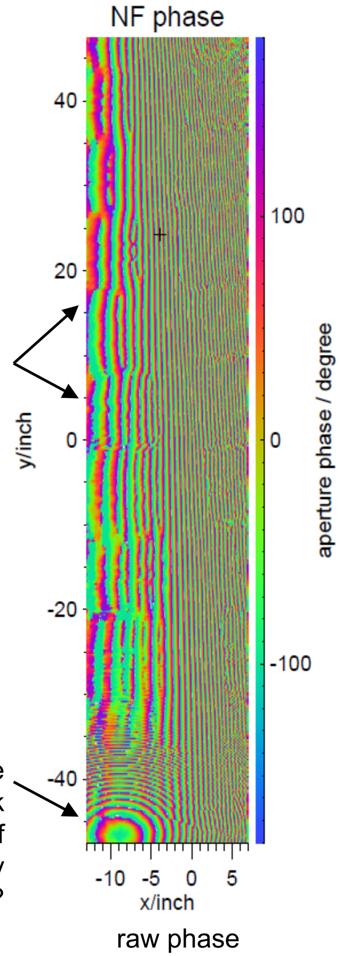


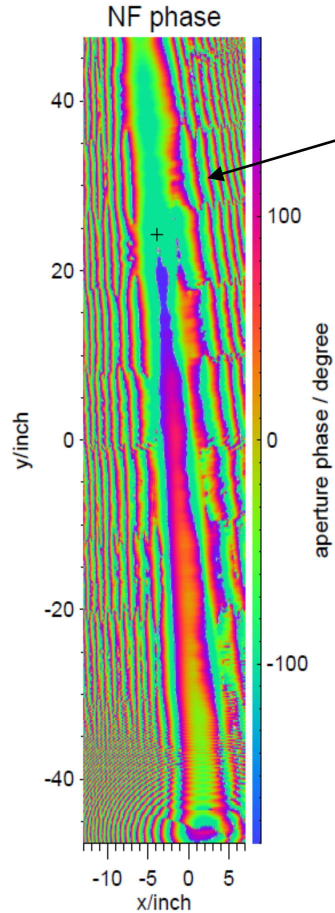
~20:1 beam aspect ratio resulting from SMLS design

evidence of uncoated 12" tiles (orthogonally tiled fibers seen under epoxy top layer)?

standing wave due to back side of Secondary reflector?

-20 dB edge taper as desired in vertical aperture





2 fit(s) removed 9.561 0.234 deg. H,V tilt

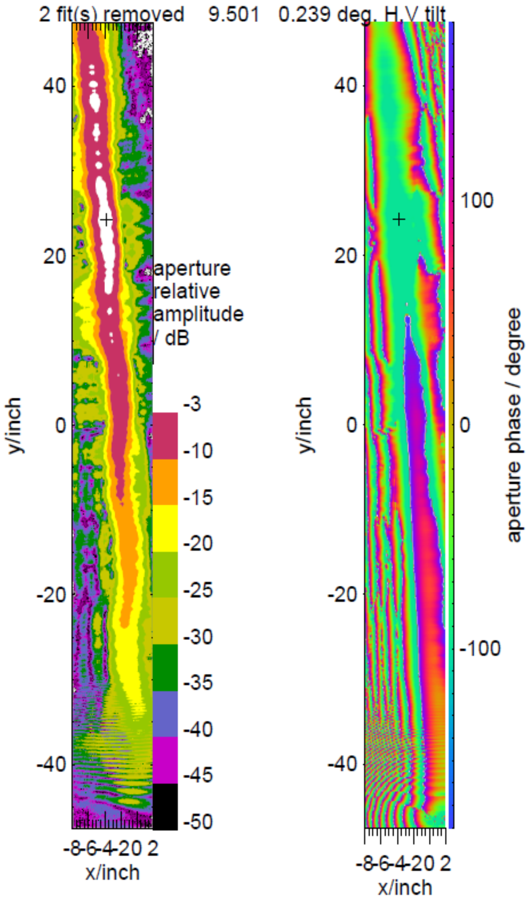
residual fringe pattern after plane removed: consistent with cylindrical phase front of SMLS design

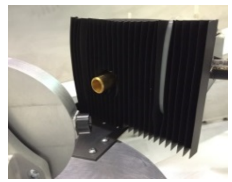
- Radius to be reconciled with model result
- e.g. 60 inch in both best Az=0 measurement and Physical Optics math model

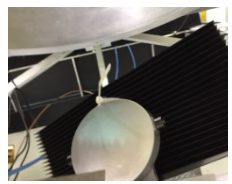
Large tilts, in both phase and amplitude maps, could result from antenna mis-pointing (Low Level Positioner has no fine control), or misalignment residual from hole slop in the feed mirror and horn (these were not aligned)

Critical absorber positions

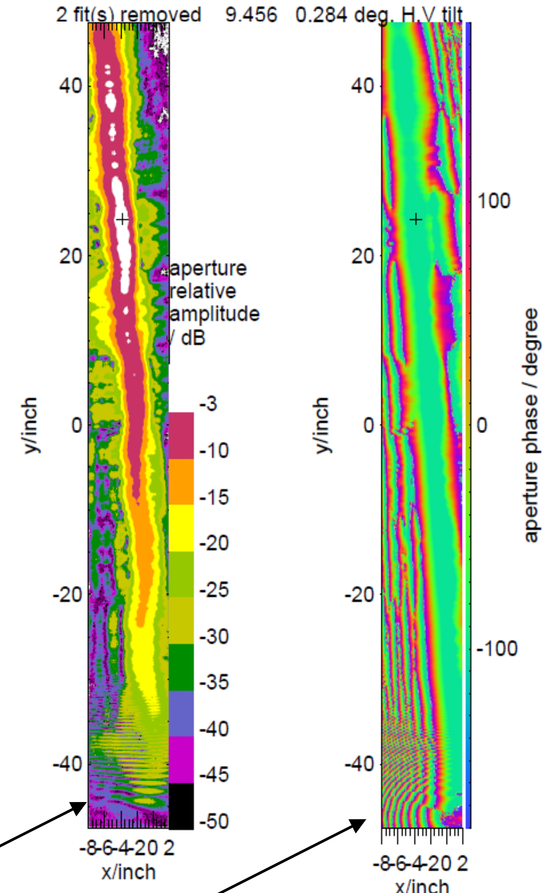
on receiver box face, and behind Feed mirror

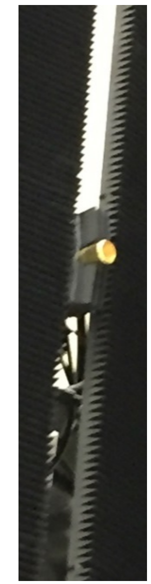






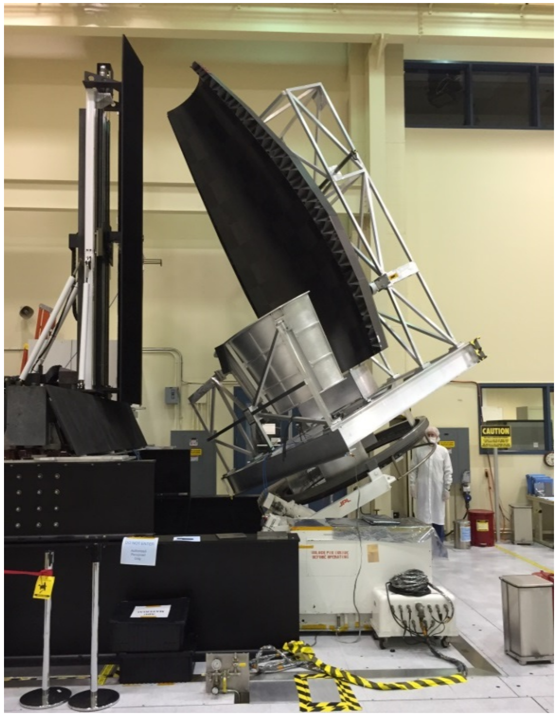
same, plus on Xmitter horn (final config)

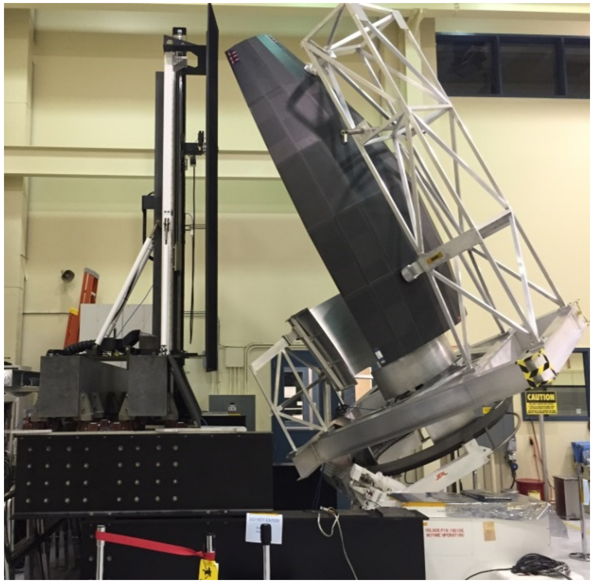


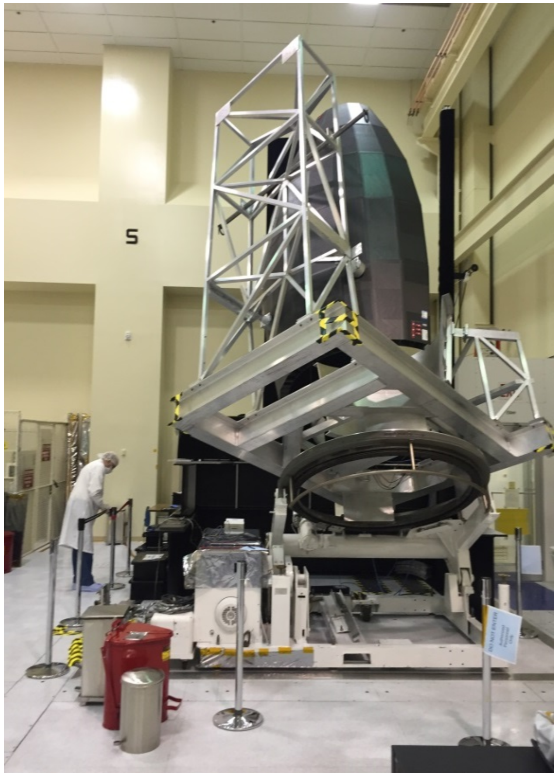


- These ripples due to insufficient absorber in area below/behind Primary Reflector
- Beyond scope of this program but significant in the future flight instrument
- They have negligible effect on main beam and geophysical retrievals

Position at 2 Azimuths following Azimuth 0°



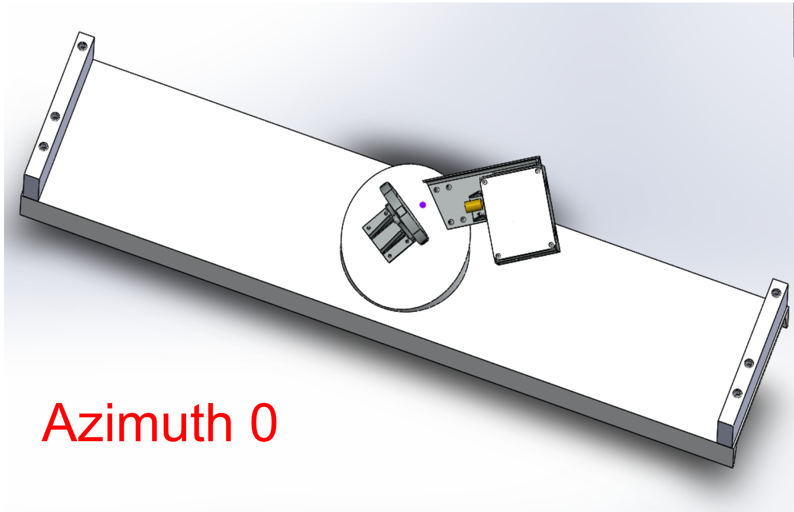


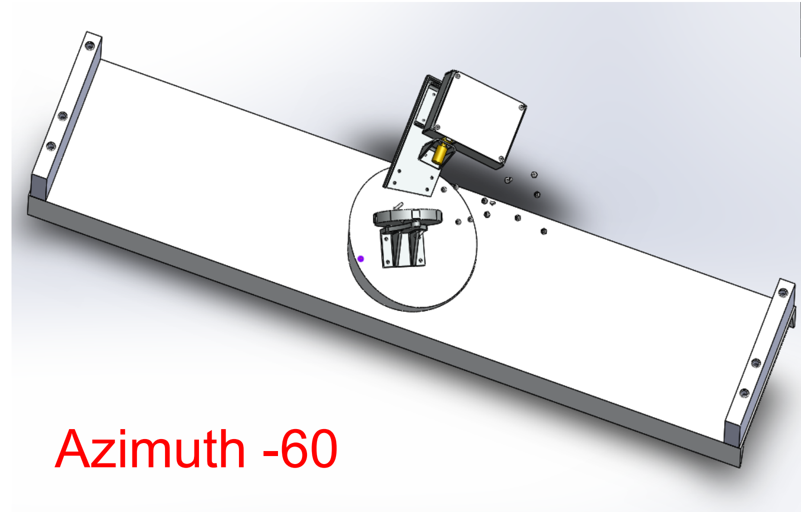


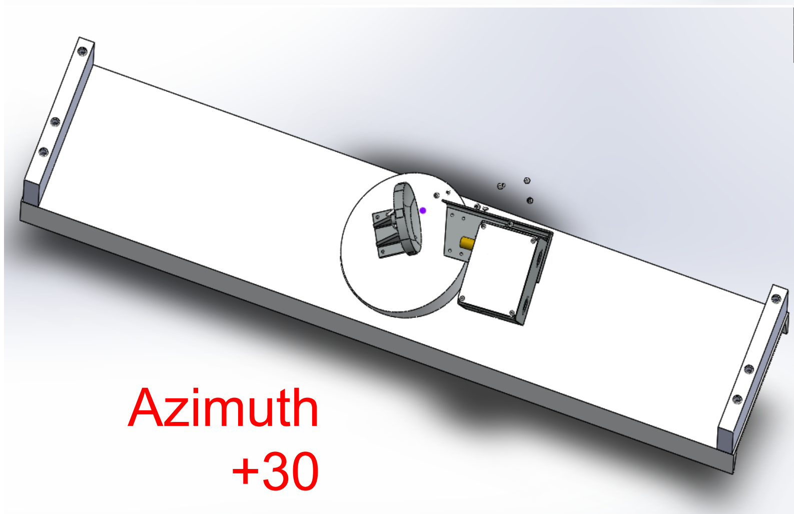
LLP Azimuth +30°

LLP Azimuth -46°; views from East and North

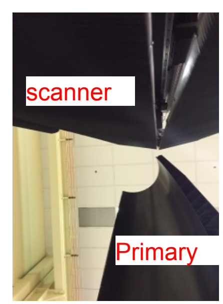
Wedge Azimuth options

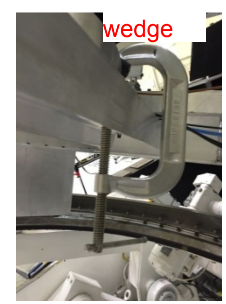




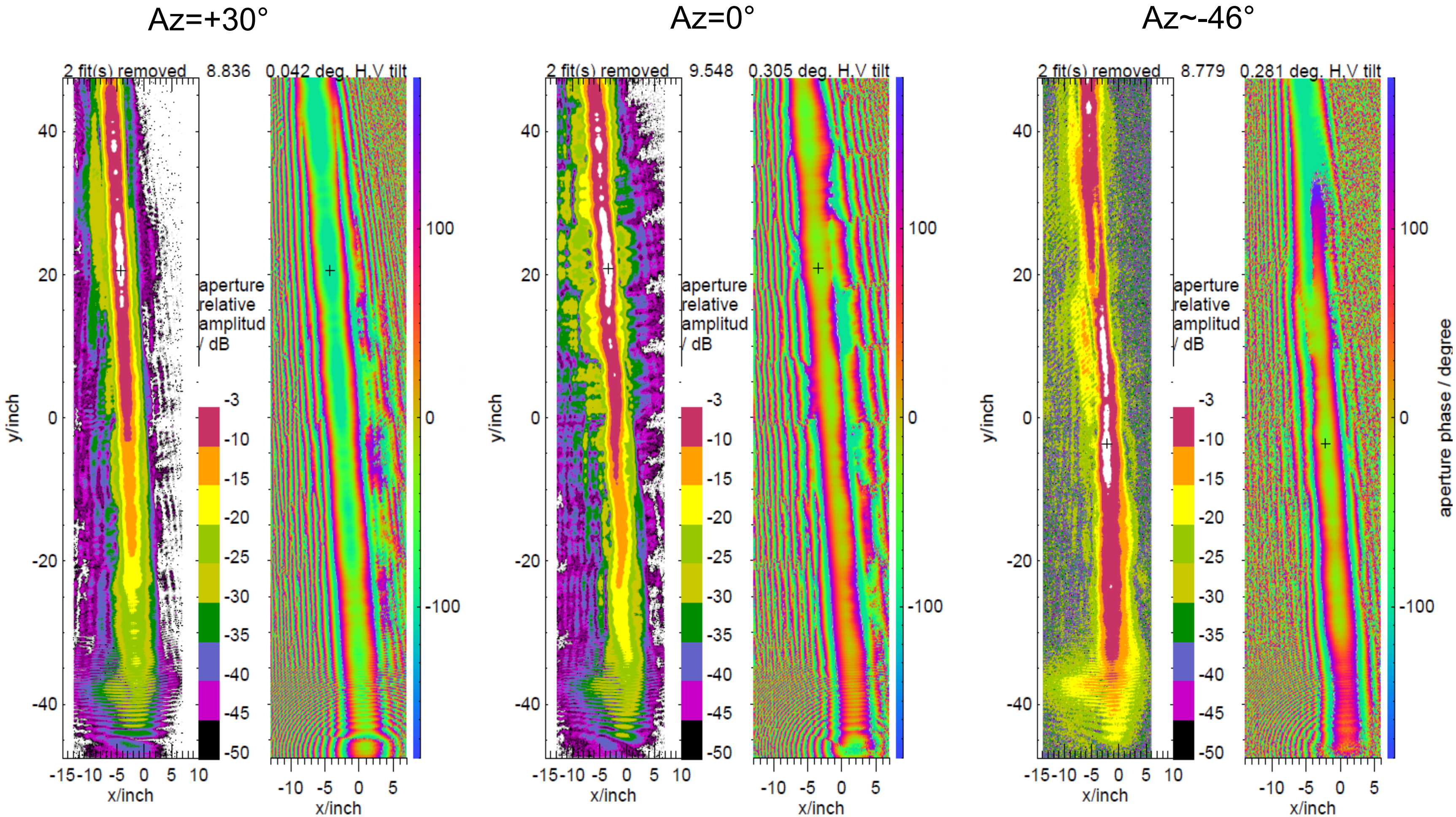


- Az ±60 hole pattern could not be used (Primary top got too close to the scanner)
- Instead, brought LLP to Az-46 and clamped wedge in corresponding position



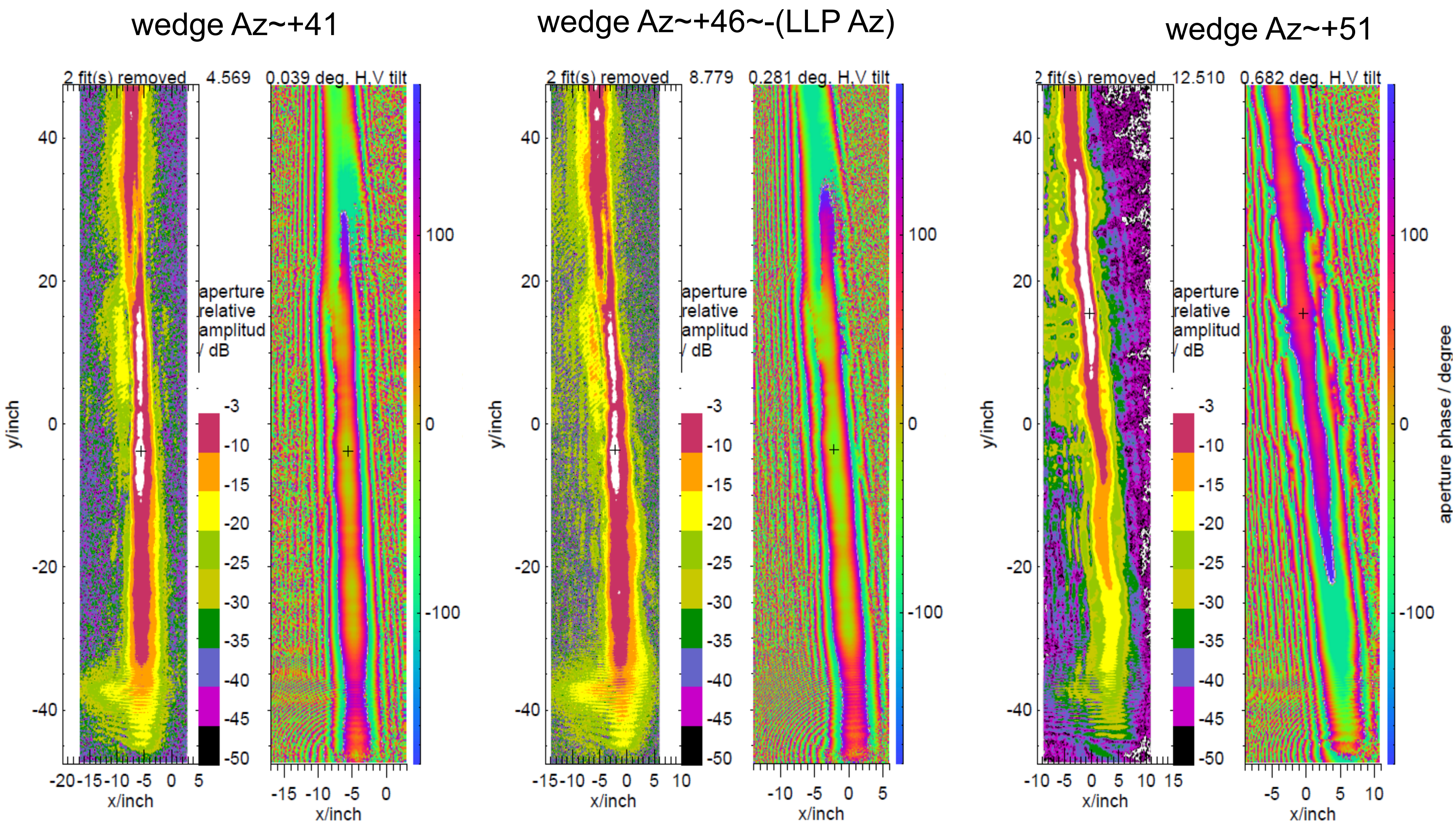


Az +30, 0 and ~-46° pixels (both LLP & wedge)



- similar skews of bright strips suggests misalignment of LLP rather than within antenna
- likewise planar tilts of each phase pattern
- peak NF power at much lower Y for Azimuth ~-46°; still under study

LLP Az~-46; wedge Az +51, +46 and +41°



- skews of bright strip rotate for various wedge positions; plausible and under study
- H-tilts of phase patterns differ by slightly less than the wedge azimuth angle

Validation of Measurements by Math Model

- Method:

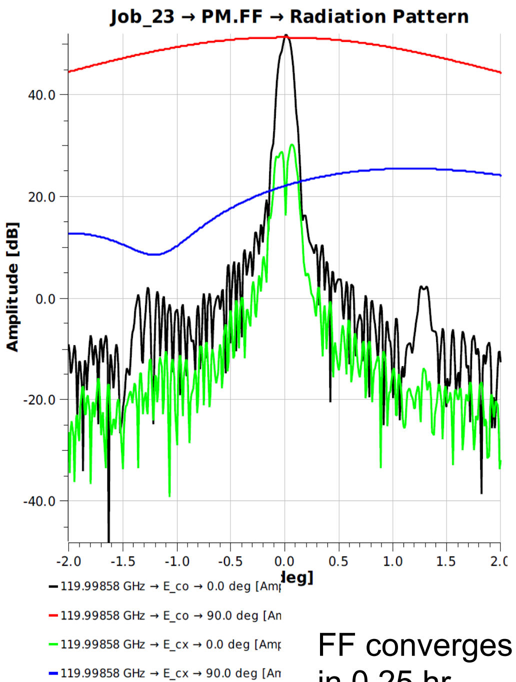
1. project near-field measurements to a cylinder portion using axes best-fit from the phase maps
2. Apply a cylindrical Near-Field to Far-Field transformation developed by JPL for NSCAT [Hussein and Rahmat-Samii, 1991-3]
3. compare to GRASP's calculations of Far Fields shown in previous reviews of this IIP; confirm design intent is met.

- We are still developing this software, although all measurements are complete: grid spacings l/2 (Az.0) or 1l,2l (other Az.) meet the algorithm requirements
- Deem measurements complete based on comparing *Near-Field* Patterns (next slides)

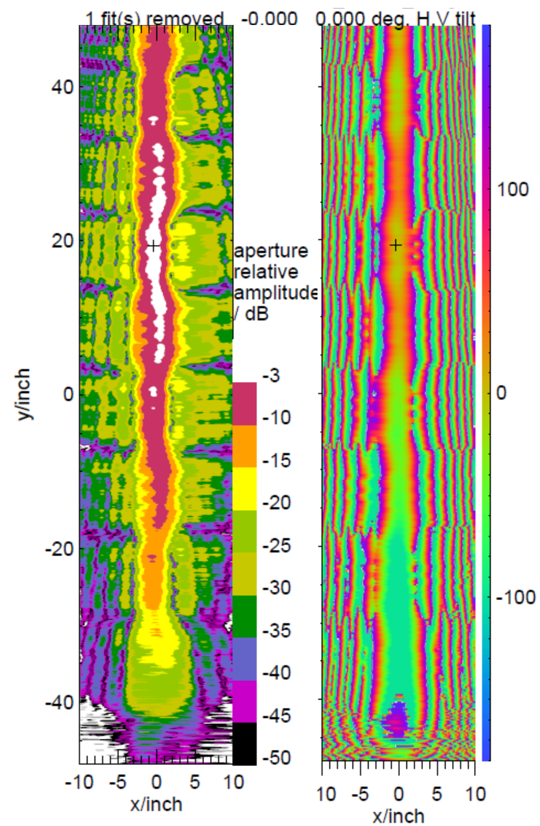
Az 0 pixel: simulation and measurement

GRASP simulation: Far Field and Near Field

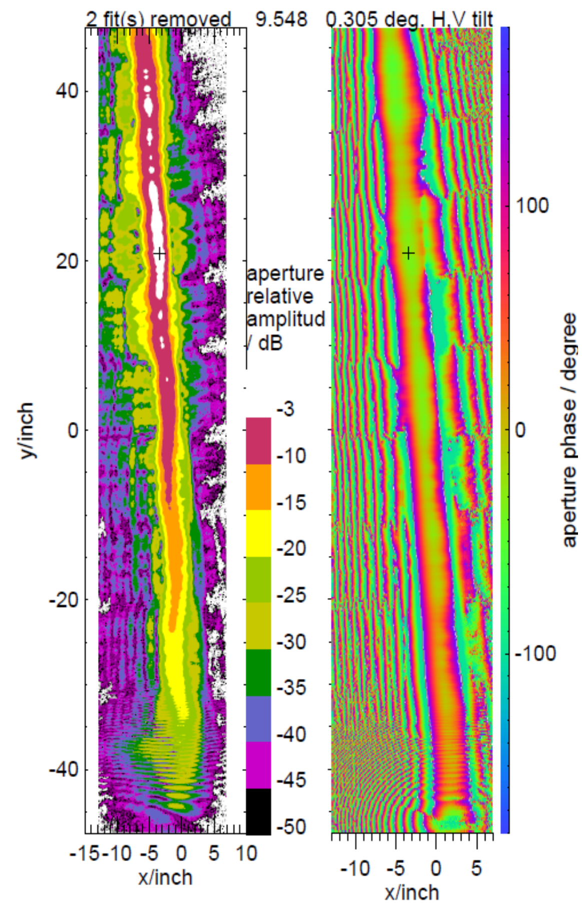
measured Near Field



FF converges in 0.25 hr



NF converges in 7.5-8.5 hr depending on number of tiles

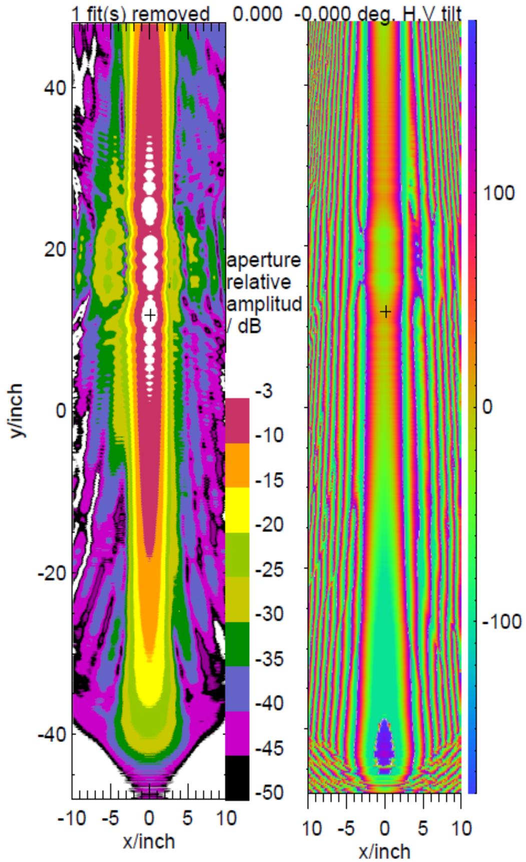


- X-pol isolation is 25-30 dB (FF); 25-35 dB (NF)
- measured -25 (NF), once --45 dB

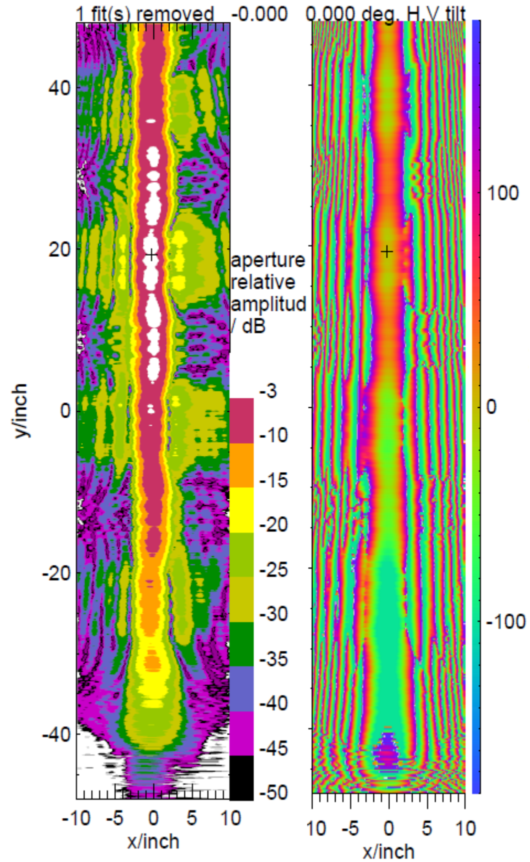
- NF map shapes for both amplitude and phase are similar for model and measurement
  - horizontal cuts of phase map show similar shape (validates cylindrical phase front)

varying front-skin “tiling” in GRASP model

One 12x12” tile near aperture center; tile $dz = \lambda/2 \sec \theta_i$ (50/360) assuming DF =50° in SMLS160225* measured

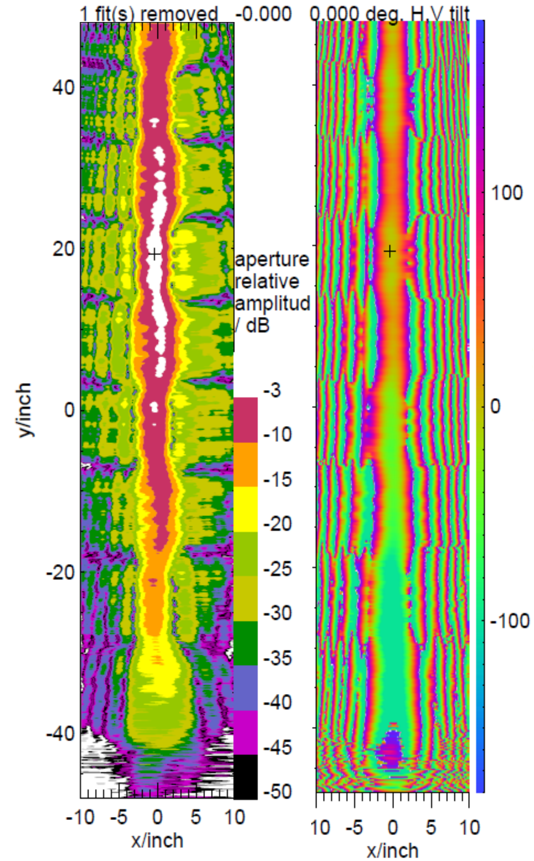


- 1 column tiles, offset in x [-11.25,+0.75] giving phase steps x=+2,-3,-5 inch
- DF (x=+2) = 60 deg ~matching SMLS160225* measured



2 column checkerboard

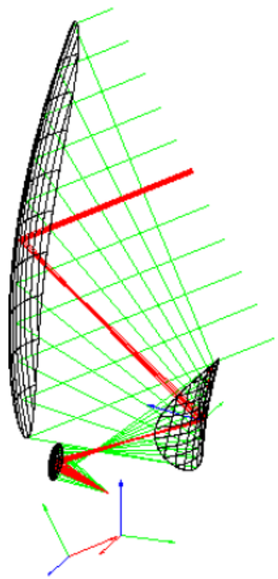
Need this geometrical fidelity to capture “meander” of amplitude contours



Runtime $\propto$ PO grid size: depends strongly on convergence criterion, weakly on # tiles

Antenna model and retrieval simulation

4m Primary (3.2m aperture), 230GHz

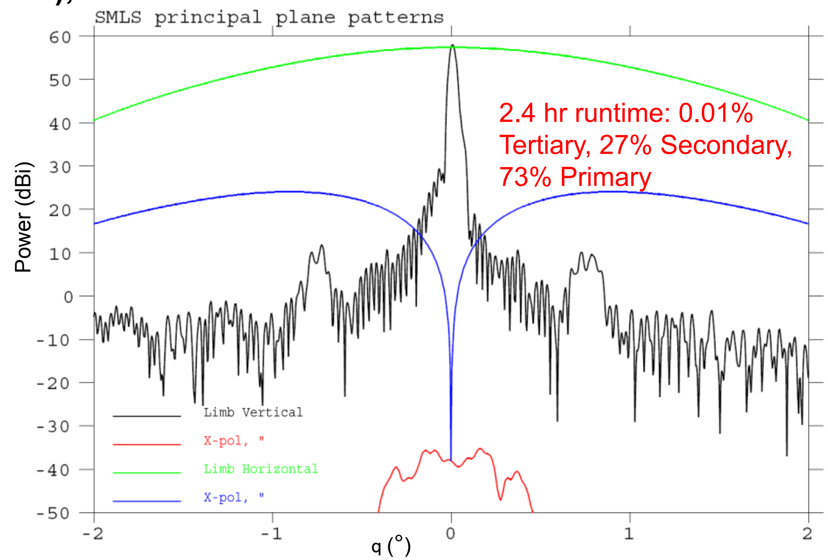


GRASP model, GACM SMLS ray fans

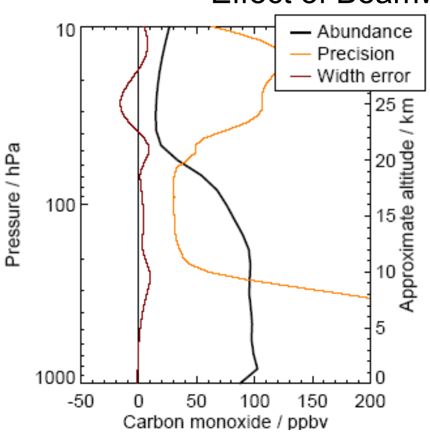
Physical Optics (PO) model captures
- •Diffraction –limited vertical performance
- •20:1 horizontal broadening from toric axis rotation

•Model FOV changes due to modeled/measured distortions

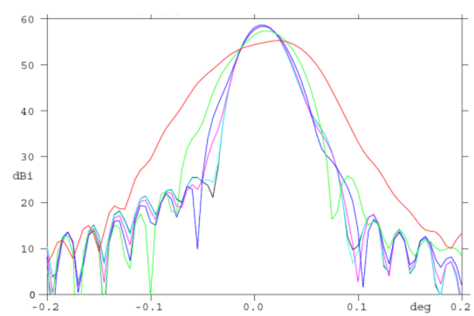
•Apply systematic errors to geophysical parameter retrievals



Effect of Beamwidth error on retrieval



Vertical profile of CO. The precision from a single SMLS vertical scan is shown in orange, indicating a useful S/N throughout ~10-18 km. The brown line indicates the systematic error associated with a putative 10% error in the measured SMLS FOV width.

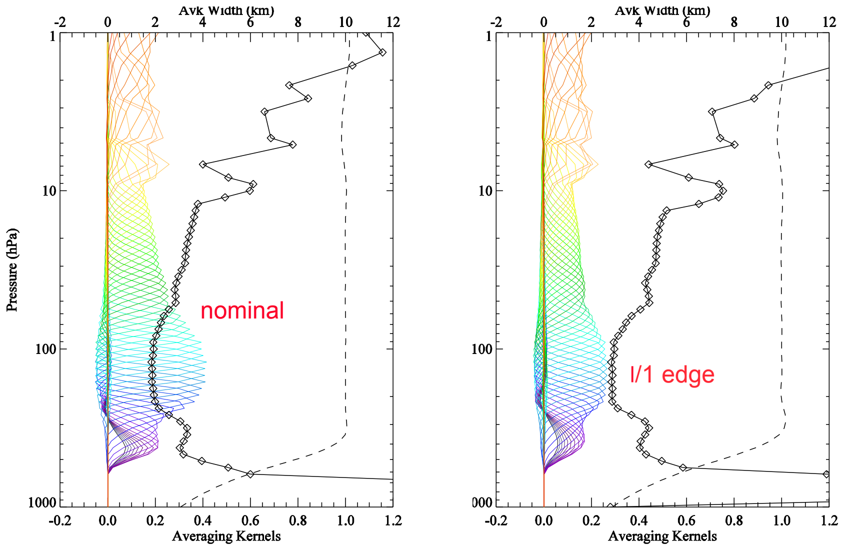


Phase errors in the long (vertical) axis of the aperture dominate retrieval errors

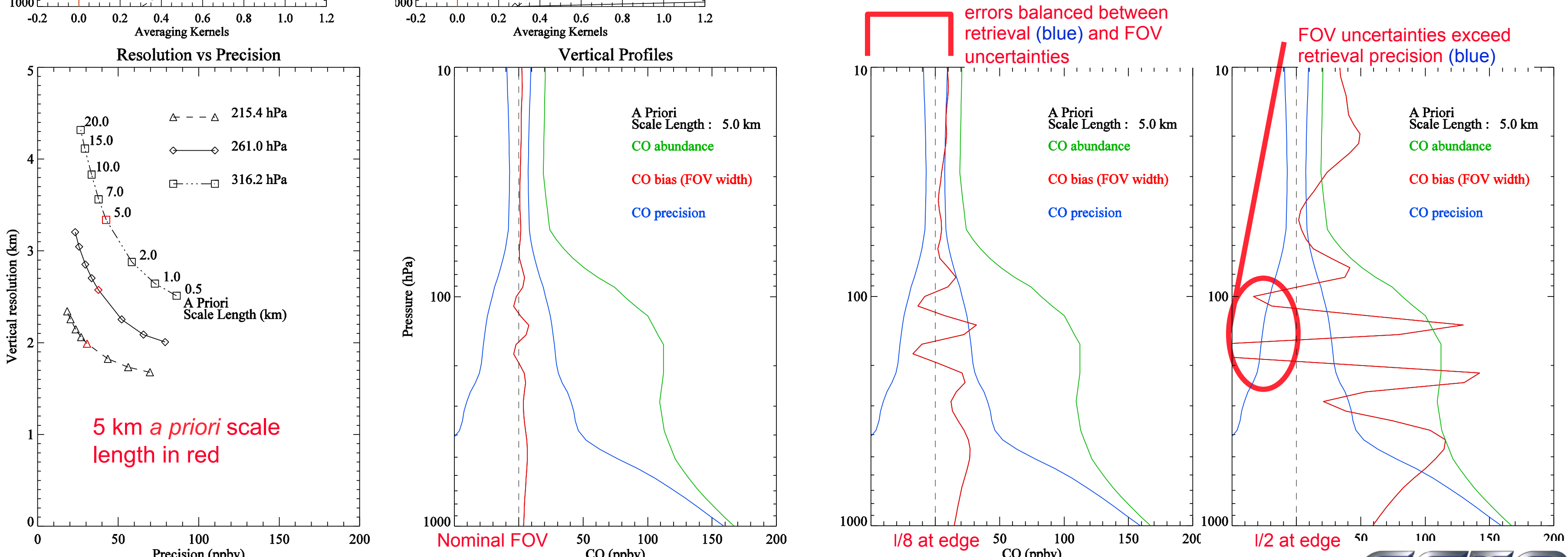
Parameterize vertical plane surface errors, then complete end-to-end model

Max. quad. phase error	G_0 / dB	Run time (8 cores) / hh:mm
0	58.12	1:47
l/32	58.1	1:48
l/8	58.0	1:48
l/4	57.6	1:48
l/2		1:56
l/1	54.3	3:11

Effect of quadratic surface distortion on error contributions in simulated CO retrieval



- Retrievals were simulated with current nominal and parameterized error patterns
    - 230 GHz Physical Optics patterns, applied for both CO and O3
    - Predicted deformations to be mapped within this range of phase error
- I/1 errors (huge, expect much smaller from orbital performance models) are visible in error contributions and averaging kernel functions.



Summary and acknowledgements

- With the near field scans measured, we have completed the set of measurements for this SMLS antenna IIP
- Measurements and analysis to date support advancement to Technology Readiness Level (TRL) of 5
  - Demonstrated ability to control composite CTE to 0.05 ppm/deg.C
  - Reconciled Thermal soak, gradient tests with math models
  - Measured Near Field patterns and evaluated effect of beam pattern variations (measured and modeled, and projected for a future flight instrument) on geophysical retrievals

- Research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Earth Sciences Technology Office IIP-10 program

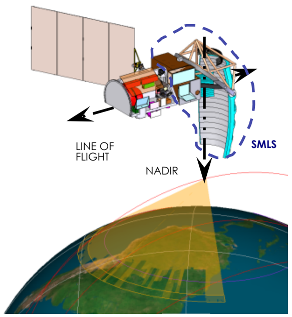
We thank ESTO for supporting these tasks and for patience as we completed them to achieve the desired exit TRL

A 4 Meter 180 to 680 GHz antenna for the Scanning Microwave Limb Sounder

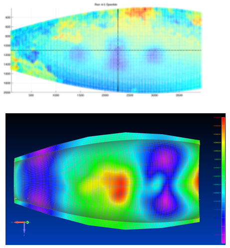
PI: Richard Cofield, JPL

Objective

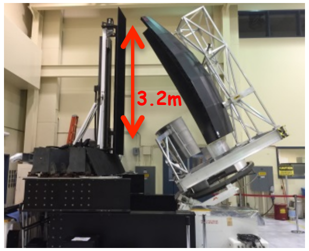
- Demonstrate fabrication and performance of the azimuth- and elevation-scanning antenna for the Scanning Microwave Limb Sounder (SMLS) on the Global Atmospheric Composition Mission (GACM).
  - Fabricate a Graphite Fiber Reinforced Composite (GFRC) reflector using a graphite mold.
  - Verify reflector performance in flight-like thermal environments using JPL's Large Aperture facility.
  - Demonstrate critical GACM requirements are met by SMLS antenna design.
  - Verify antenna performance using SMLS breadboard components.



(a) SMLS measurement Concept



(b) Primary Reflector thermal gradient tests: above, measured; below, structural math model



(c) Breadboard antenna in Near-Field Range for beam pattern measurements

Accomplishments

- Simulated geophysical retrievals for the SMLS antenna, including expected thermal deformations
- Fabricated a composite SMLS Primary reflector 4x1.8 m having thermal stability of 8 micron in the expected orbital thermal environment of GACM
- Tested thermal stability of an precursor SBIR and the SMLS composite Primary in a temperature-controlled facility at JPL, using a speckle interferometer to detect relative surface deformations at visible light wavelengths, with heat loads applied to the back side of the reflector. Developed a structural/optics model to correlate deformations with skin temperatures measured using IR cameras. The level of correlation was ~7%
- Fabricated and aligned breadboard antenna combining composite Primary with aluminum reflectors and structure.
- Measured near-field patterns at 120 GHz of 3 Azimuth pixels (+30, 0 and -45°) within the ±65°design range of SMLS and showed good comparison with a Physical Optics model

Co-Is/Partners: Paul Stek, Nathaniel Livesey, Bill Read, Greg Agnes, Mark Thomson, JPL; Eldon Kasl, Vanguard Space Technologies

$TRL_{in}=3$ $TRL_{out}=5$