System Engineering

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Background and experience

- Antenna experience
  - CSO (Caltech)
    - modeling and surface adjustment
  - OVRO millimeter array (Caltech)
    - production of second run of antennas
    - surface measurement and setting
  - ALMA (NRAO and ESO)
    - design concepts
    - analysis and review of prototype antennas
  - SZA (U. Chicago and Caltech)
    - conceptual design
    - responsible for construction (Vertex)
  - Consulted on several other antennas
    - SMA, SPT, ACT
- Extensive experience in radio astronomy instrumentation and system design

Scope and Approach

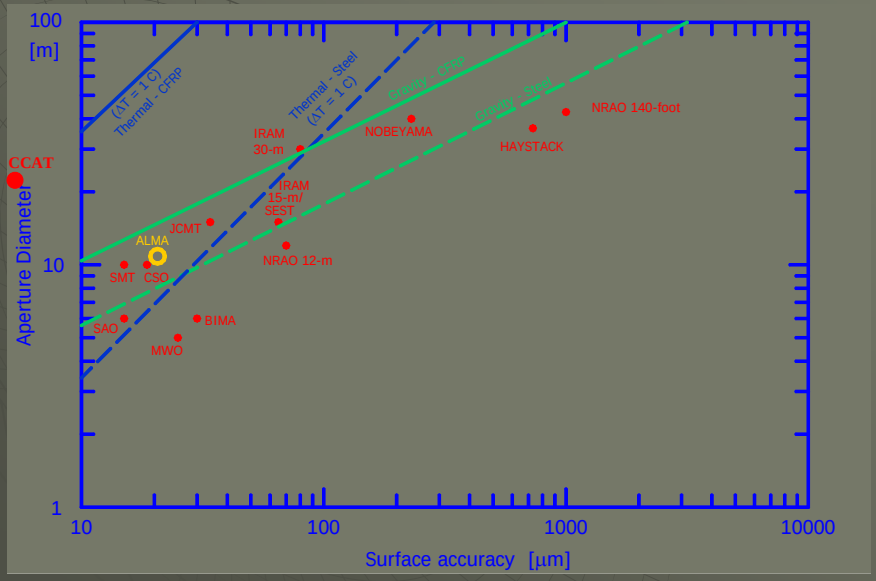
- Interaction of components and systems
- Input: carefully defined
  - requirements
  - specifications
  - design goals
  - environment parameters
- Analyze design concepts
- Output: error budgets
- Want measurable engineering specifications in next phase

Major Issues

- Wave Front Error (surface errors)
  - Primary, secondary and tertiary
    - Fabrication (panels)
    - Setting (measurement)
    - Maintenance (active control)
- Pointing and tracking errors
    - Mount distortions
    - Drive servo system
    - Atmosphere
- Image quality
    - Most image issues are encapsulated in the ½ WFE
    - Diffraction effects

Updated von Hoerner Plot

(Lamb ALMA memo)



Context for CCAT

- Physical limits shown in updated Von Hoerner plot
  - CFRP, etc.
  - Homology
  - Dome
    - No solar heating
    - Minimal wind
- CCAT will have an active surface
  - Passive would represent large risk at this point
    - Telescopes close to the limits on the plot already employ CFRP and high degree of homology
  - Active surface reduces risk and increases complexity
  - Can use steel support structure

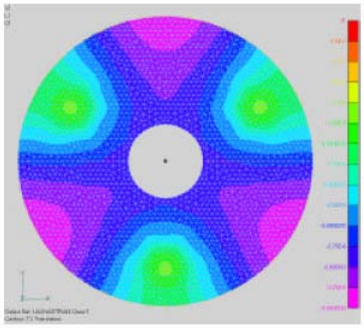
Top-Down error budget

1/2 Wavefront Error Budget			
	ALMA RFP	CCAT	
Panels	[microns]	[microns]	
Total Panel (RSS)	11.8	5.0	
Backing Structure			
Total Backing Structure	7.5	4.0	
Panel Mounting			
Total Panel Mounting (RSS)	5.4	4.0	Total Active Surface Control
Secondary Mirror			
Total Secondary Mirror (RSS)	8.4	3.5	
Total Tertiary Mirror (RSS)	0.0	3.5	
Total Measurement and Setting (RSS)	10.0	4.0	Astro. WFE & Holography
Other Errors not Included Above	2.0	1.5	
TOTAL (RSS)	20.0	10.0	

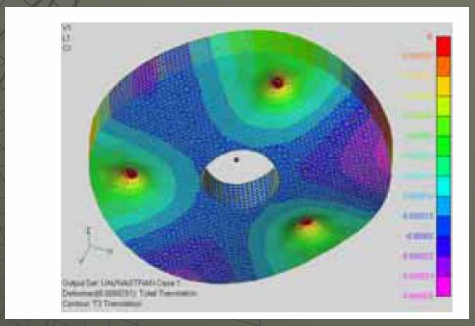
Panel analysis

- Generic parametric model
  - Plate-core-plate laminate
  - Materials
    - Al, CFRP high strength, CFRP low CTE, Ni, steel, Invar, Beryllium, Borosilicate glass, ULE glass, SiC
  - Geometry
    - Diameter
      - Round disk supported at optimal three points
    - Plate thickness
    - Core thickness and density

Three point support, fig. from SNAP 2m



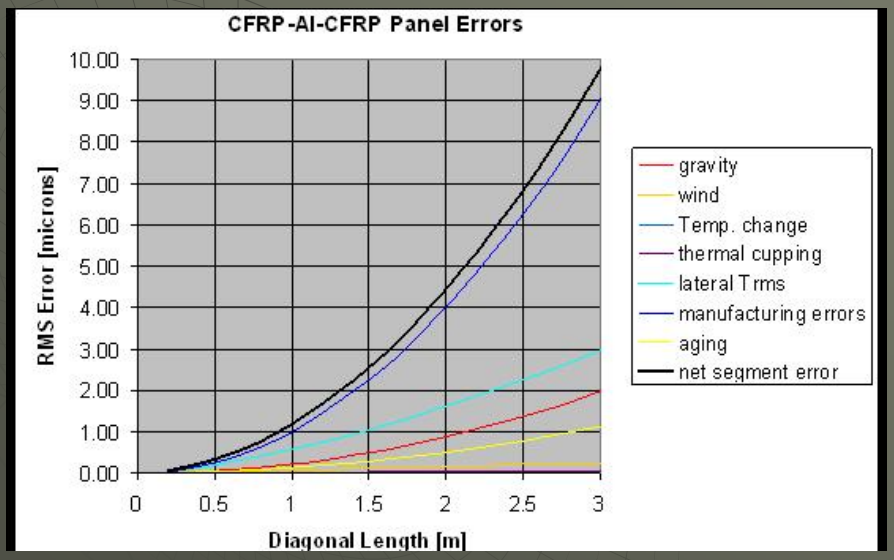
1g sag on 3pt support
vertical axis
P-P Z deflection = 2.3 μm



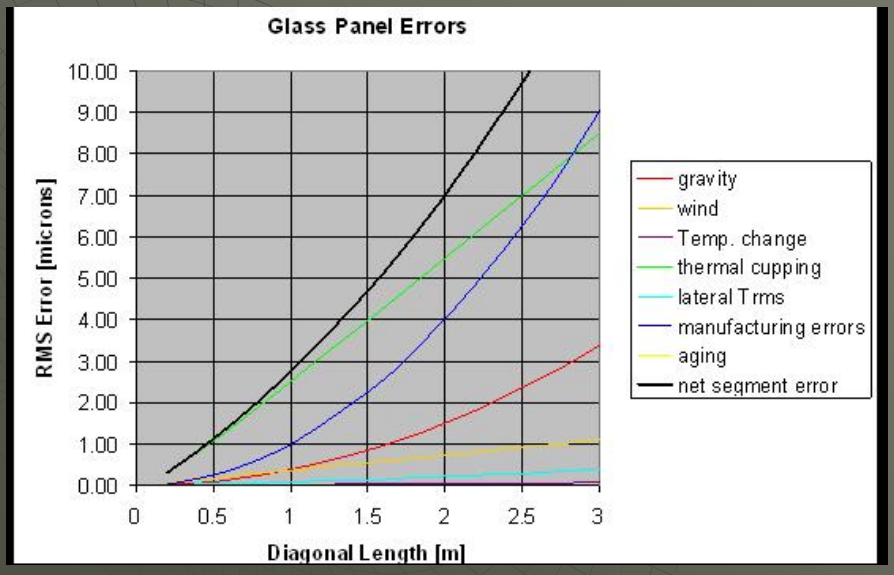
Panel errors

- Loads
  - Thermal: ΔT CTE
    - Uniform: D^2
    - lateral RMS: h
    - axial through segment: D^2/h
      - Radiative
      - Air and insulation
  - Gravity: $\rho\, t\, D^4 / Y\, h^2$
  - Wind: $v^2\, D^4 / Y\, h^2$
- Other errors
  - Fabrication: D^2
  - Aging: D^2
- Comparable to other detailed designs

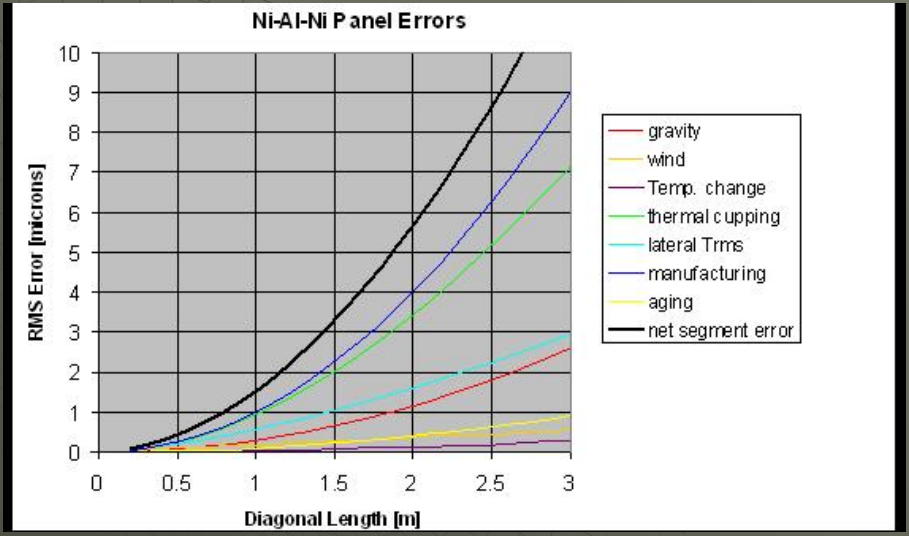
RMS surface error vs. effective diameter



RMS surface error vs. effective diameter



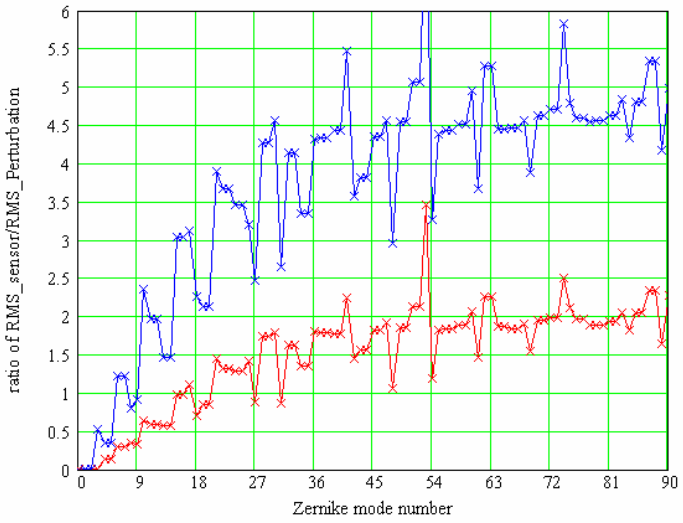
RMS surface error vs. effective diameter



Surface maintenance system

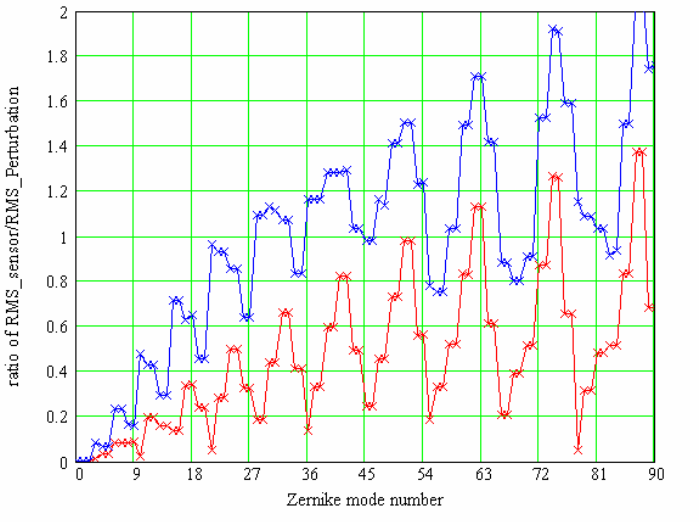
- Edge sensors
  - Continuity between panels
  - Dihedral angle between panels
- Large scale measurement
  - Absolute distance measurement from some panels to secondary
- Servo algorithm is critical
  - Can dampen or accentuate errors
- Have MathCad model of sensor reading for first 100 Zernike distortions
  - Explore configurations and number of panels
  - Use ratio of RMS_sensor/RMS_distortion

Edge sensor sensitivity, Keck



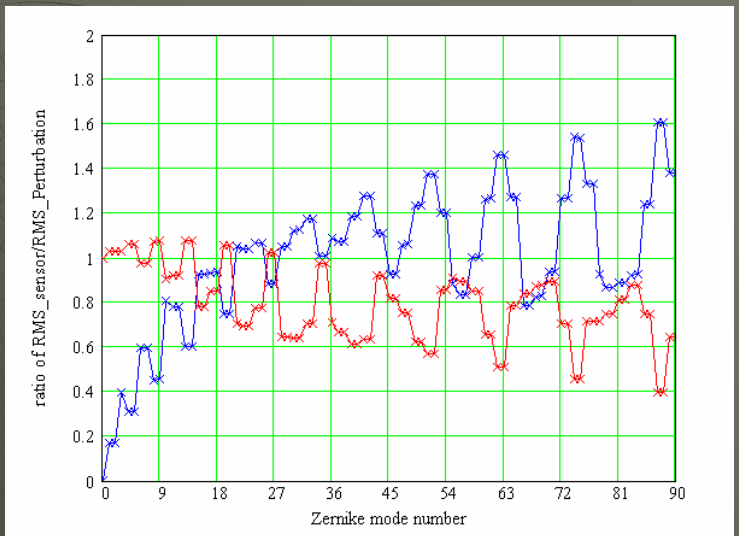
Sensitivity of edge sensors (red) and diahedral angle (blue) for a 36 hex segment surface. The diahedral sensitivity is in microradians_RMS/micron_RMS.

Edge sensor sensitivity, CCAT



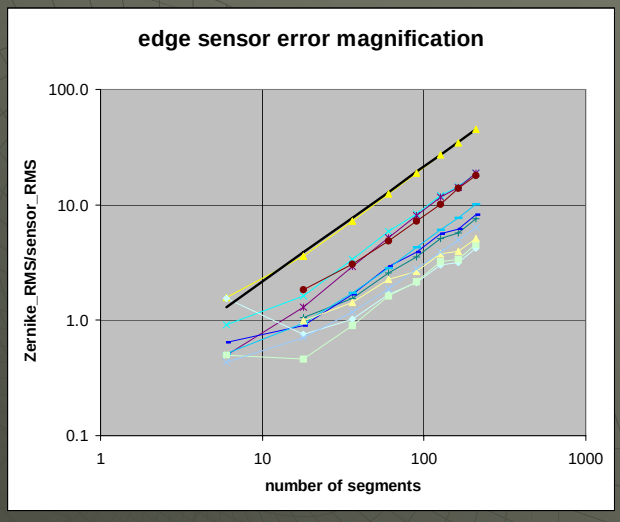
Sensitivity of edge sensors (red) and diahedral angle (blue) for a 162 pie segment surface. The diahedral sensitivity is in microradians_RMS/micron_RMS.

Distance & tip-tilt sensor sensitivity, CCAT



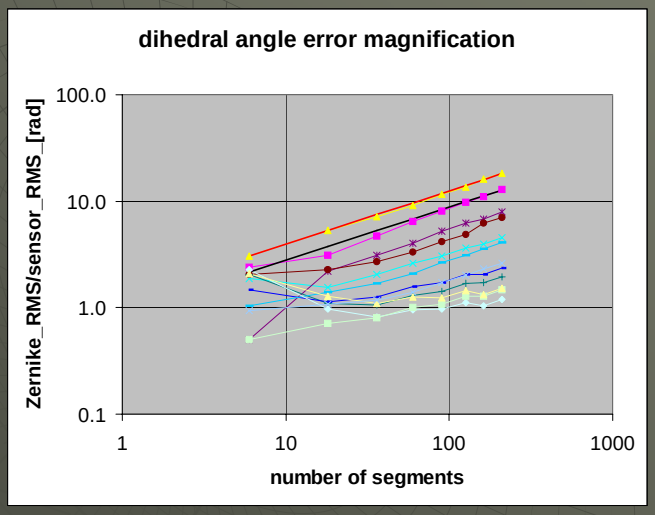
Sensitivity of distance sensors (red) and tip-tilt sensors (blue) for a 162 pie segment surface. The tip-tilt sensitivity is in microradians_RMS/micron_RMS.

Sensitivity vs. number of segments for low order Zernike modes



Mag ~ 0.2 N

Sensitivity vs. number of segments for low order Zernike modes



Mag ~ 1.3 $N^{1/2}$

Error budget input parameters

- Panel design
  - dimensions: d, t, h, f
  - Materials
  - Fabrication errors for 1 m dia panel, typical value 1 micron
- Panel thermal environment
  - Change in average temperature
  - RMS air temperature over 1 m, $d^{1/2}$
  - Dome temperature
  - Insulation thickness
  - Thermal emissivity
  - Cold sky coverage
  - Boundary layer thickness
- Sensor configuration
  - Number of distance measuring devices and noise
  - Sensor noise
  - Number of panels (from panel dia)
  - (Panel errors feed into sensor errors)
- Misc. error sources
  - Panel location
  - Wind
  - Surface measurement map resolution
  - Vibration

Typical thermal environment parameters

thermal surroundings	
average segment temperature [K]	273
temp. difference BUS to dome air [K]	5
foam thickness [m]	0.05
foam surface emissivity	1.00
effective air boundary thickness back [m]	0.05
thermal emissivity of back of segment	0.07
thermal emissivity of front of segment	0.07
effective air boundary thickness front [m]	0.05
fraction of cold sky seen by segments	0.50

CCAT 1/2 WFE from parameterized model				
segments	CFRP-Al-CFRP	Ni-Al-Ni	borosilicate	Aluminum
size, diagonal [m]	2.07	1.82	1.30	1.07
number of segments	147	190	370	542
areal density [km/m^2]	8.94	18.45	8.41	13.10
errors [microns]				
gravity	0.93	0.95	0.63	0.60
wind	0.16	0.32	0.48	0.29
thermal cupping	0.03	2.87	3.39	0.64
lateral Trms	1.68	1.39	0.11	0.63
manufacturing errors	4.26	3.29	1.69	4.61
aging	0.53	0.33	0.00	0.58
net segment error	4.71	4.70	3.87	4.78
primary figure maintence				
number of distance measurements	6	36	58	36
distance measuring error	1.00	1.00	1.00	1.00
surface error from edge sensors	10.32	3.80	4.89	4.46
surface error from angle sensors	3.48	10.46	14.91	6.78
net surface maintenance error	3.45	3.71	4.75	3.86
total primary 1/2WFE	5.84	5.99	6.13	6.14
other non-primary surface 1/2WFE				
primary support	4.91	4.72	4.50	4.46
secondary	3.49	3.49	3.49	3.49
tertiary	3.49	3.49	3.49	3.49
wavefront measurement	4.18	4.19	4.22	4.26
total other contrib. 1/2WFE	8.12	8.0	7.90	7.90
total telescope 1/2WFE	10.00	10.00	10.00	10.00

Feasible pointing error budget

Nonrepeatable Pointing and Tracking Errors			
	ALAM RFP template		CCAT
	day	night	
	[arcsec]	[arcsec]	[arcsec]
wind, steady component	0.20	0.45	0.04
wind, gusty component	0.10	0.10	0.02
structure temperature gradients	0.35	0.00	0.05
ambient temperature changes	0.20	0.00	0.05
inertial forces	0.15	0.15	0.10
encoder errors	0.20	0.20	0.10
servo error	0.10	0.10	0.10
bearing errors	0.20	0.20	0.05
other errors	0.19	0.19	0.05
Total RSS error	**0.60**	**0.60**	**0.20**

Risk assessment

- Large panels are the highest risk
  - Scaling processes to larger sizes
  - Achieving manufacturing tolerance
  - Thermal environment
  - Cost
  - Mitigation/Alternatives
    - Early prototype and full scale test production run
    - Smaller panels on CFRP sub-frames
- Active surface maintenance is a moderate risk
  - More complex than previous systems
  - Components must be much cheaper than previous systems
  - Mitigation/Alternatives
    - Accurate detailed simulation of the full system
    - Prototype large part of the system
    - Add more distance measuring devices
- Pointing accuracy is a moderate risk
  - Well beyond current performance for radio telescopes
  - Drive servo system is larger and more precise than existing systems
  - New sources of small pointing errors will be exposed
  - Mitigation/Alternatives
    - Optical offset guiding when possible
    - Fast tip-tilt corrector
    - Direct drive servo system

Raft concept

- Risk mitigation
- Large CFRP sub-frames with many smaller panels
  - Better manufacturing and performance of small panels
  - Exploit excellent properties of CFRP
  - Fewer actuators
  - Panels have to be preset to high accuracy on sub-frames
  - Extra layer of structure
    - Weight
    - complexity

CCAT 1/2 WFE from parameterized model with rafts

twice the panel manufacturing error

segments	CFRP-Al-CFRP	Ni-Al-Ni	borosilicate	Aluminum
size, diagonal [m]	**0.67**	**0.67**	**0.67**	**0.67**
number of segments	**1406**	**1406**	**1406**	**1406**
areal density [km/m^2]	2.89	6.78	4.31	8.13
errors [microns]				
manufacturing errors	**0.89**	**0.89**	**0.89**	**1.78**
net segment error	**0.95**	**1.05**	**1.80**	**1.86**
sub-frames				
dia [m]	**2.00**	**2.00**	**2.00**	**2.00**
number of sub-frames	**156**	**156**	**156**	**156**
number of segments per sub-frames	**9**	**9**	**9**	**9**
areal density	16.20	16.20	16.20	16.20
errors [microns]				
gravity, including segment wt.	**1.14**	**1.37**	**1.22**	**1.45**
wind	**0.09**	**0.37**	**0.37**	**0.37**
Temp. change	**0.00**	**0.00**	**0.00**	**0.00**
thermal cupping	**0.11**	**0.11**	**0.11**	**0.11**
lateral Trms	**0.01**	**0.01**	**0.01**	**0.01**
adjuster temp & gravity	**0.18**	**0.18**	**0.18**	**0.18**
segment setting errors	**1.20**	**1.20**	**1.20**	**1.20**
aging	**0.40**	**0.40**	**0.40**	**0.40**
net subframe error	**1.72**	**1.91**	**1.81**	**1.97**
primary figure maintence				
number of distance measurements	**6**	**6**	**6**	**6**
net surface maintenance error	**3.26**	**3.46**	**3.63**	**3.46**
total primary 1/2WFE	**3.80**	**4.09**	**4.44**	**4.39**
total other contrib. 1/2WFE	**8.08**	**8.08**	**8.08**	**8.08**
total telescope 1/2WFE	**8.93**	**9.05**	**9.22**	**9.20**