Holographic Measurements of the AEM ALMA Antennas

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[on behalf of many people at at ESO, JAO and NRAO,
particularly Pascal Martinez, Jaap Baars,
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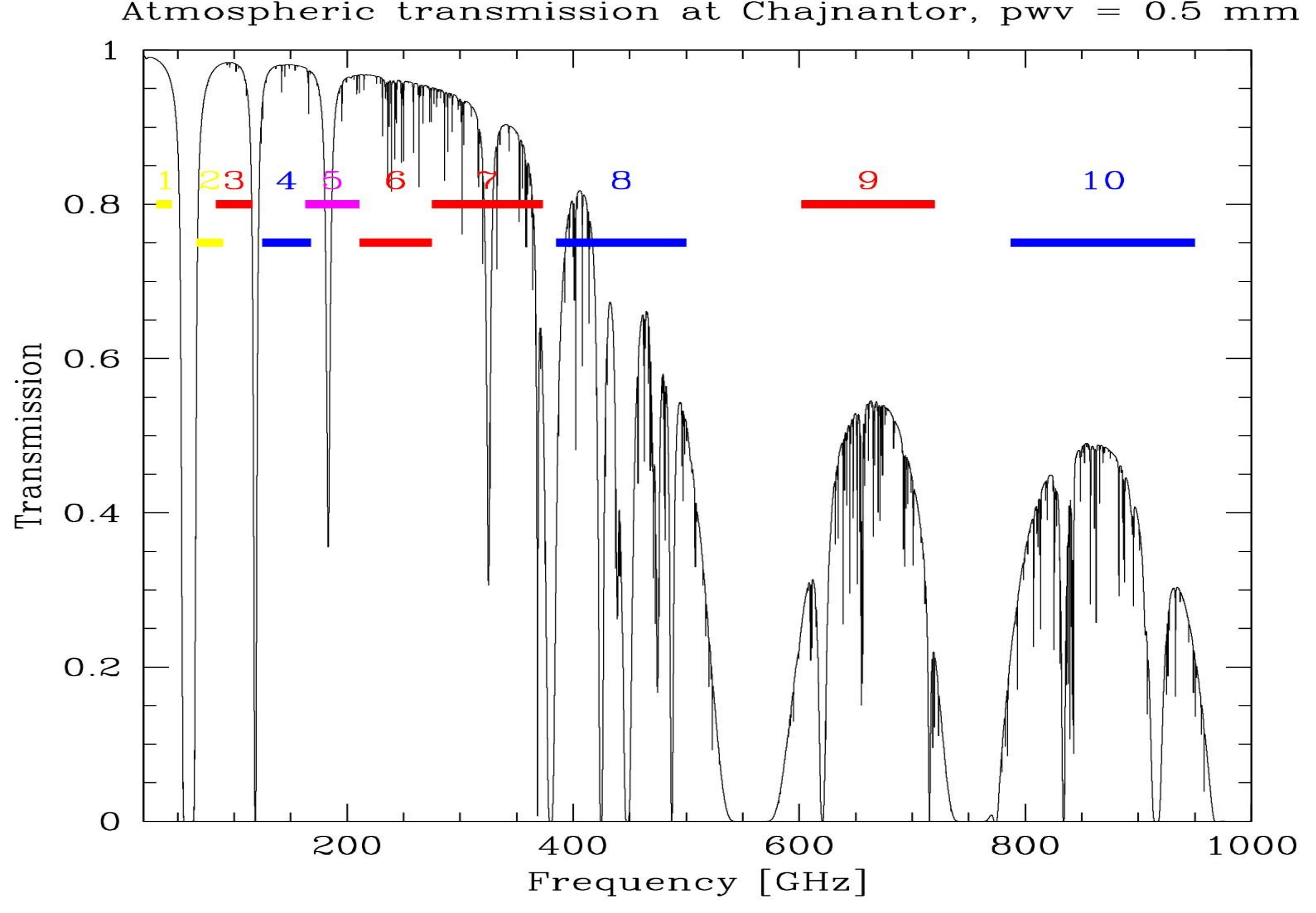
ALMA

ALMA Numbers

- Aperture synthesis array optimised for wavelengths of 1cm – 0.3mm (35 – 950 GHz)
- **High, dry site**, Chajnantor Plateau, Chile (5000m)
- 54 12m + 12 7m antennas
- Baselines from ~15m to 16km.
- **Resolution**/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

  5 mas for highest frequency/longest baseline
- Field of view / arcsec ≈ 17 (λ/mm) [12m dish]
- **Sensitive**, wide-band (8 GHz) receivers; full polarization
- **Flexible** digital correlator giving wide range of spectral resolutions.
- **Software**

Receiver Bands



Antenna Performance Specifications

- 12m diameter, primary F/D = 0.4, Cassegrain optics, final F/D = 8
- Frequency range 35 – 950 GHz; hence total surface accuracy <25 µm rms
- Non-repeatable residual delay <15 µm
- 2 arcsec rms absolute; 0.6 arcsec rms offset pointing
- >6 deg/s Azimuth, >3 deg/s Elevation speed
- Fast switching (1.5 deg move, 3 arcsec within 1.5 s, 0.6 arcsec within 2 s)
- On-the-fly and mosaic requirements

AEM 12m antennas

AEM Antennas

- 25 of the 54 12m antennas procured by ESO
- Designed and built by the AEM Consortium: Thales Alenia Space, European Industrial Engineering, MT Mechatronics
- First antenna provisionally accepted in April 2011; the last in September 2013
- Key design features:
  - Steel mount; insulated
  - Moving part of the elevation structure (including receiver cabin) is entirely CFRP
  - Electroformed Ni-Al panels on CFRP back-up structure
  - Direct drive motors
  - Al subreflector on 5-axis support
  - Thermal and wind metrology systems (talks tomorrow)

More on Surface Specifications

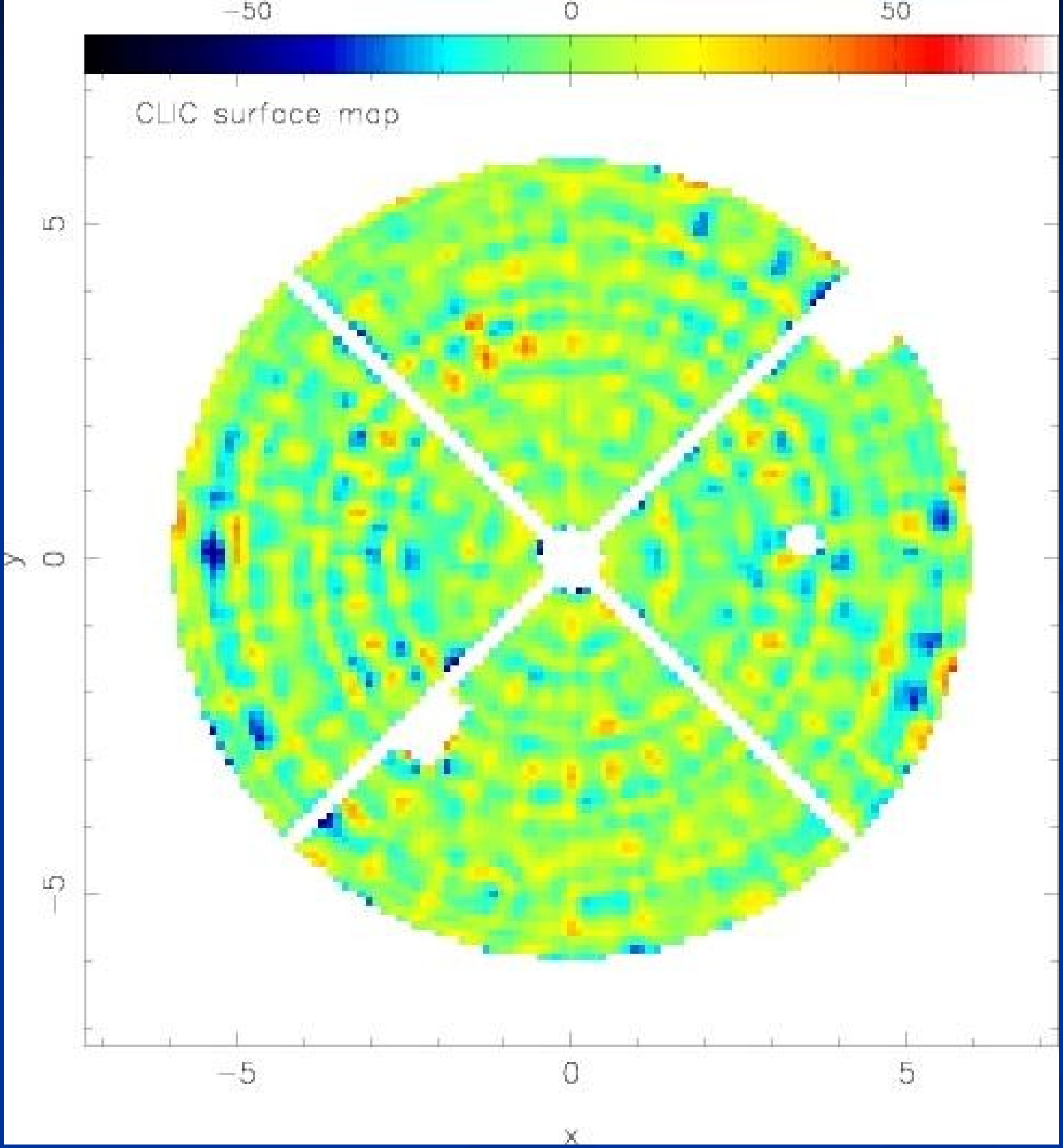
Under primary operating conditions (<10 m/s wind, ...), the rms surface accuracy must not exceed 25 μm rms

- Includes primary, secondary and any misalignments between them
- Measured normal to boresight; calculated with 12dB edge taper
- Assumes refocus every 30 min

Primary Surface Setting

- Near-field holography (Baars et al. 2007)
  - 104 (79) GHz
  - Double receiver with reference horn
  - Transmitter at 400 m distance implies fixed (low) elevation
  - Raster scan
  - Measurement error specified to be <10 μm rms; in practice, reproducibility 2-4 μm rms
- Panel setting
  - Initial setting by laser tracker: 30-40 μm rms
  - 2-3 iterations based on holography results
  - 120 panels in 3 rings

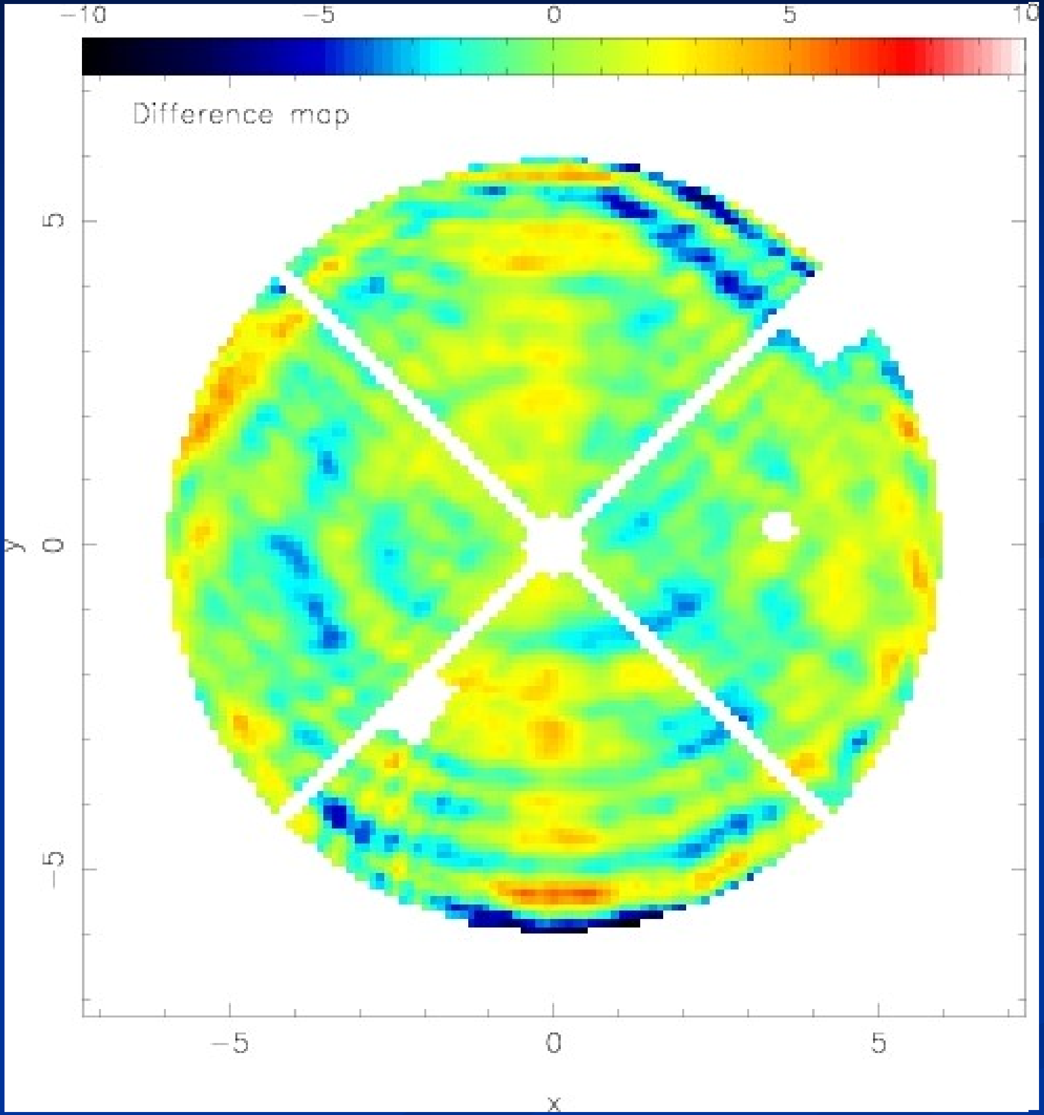
Surface measurement after final setting



Surface
rms 10.9μm

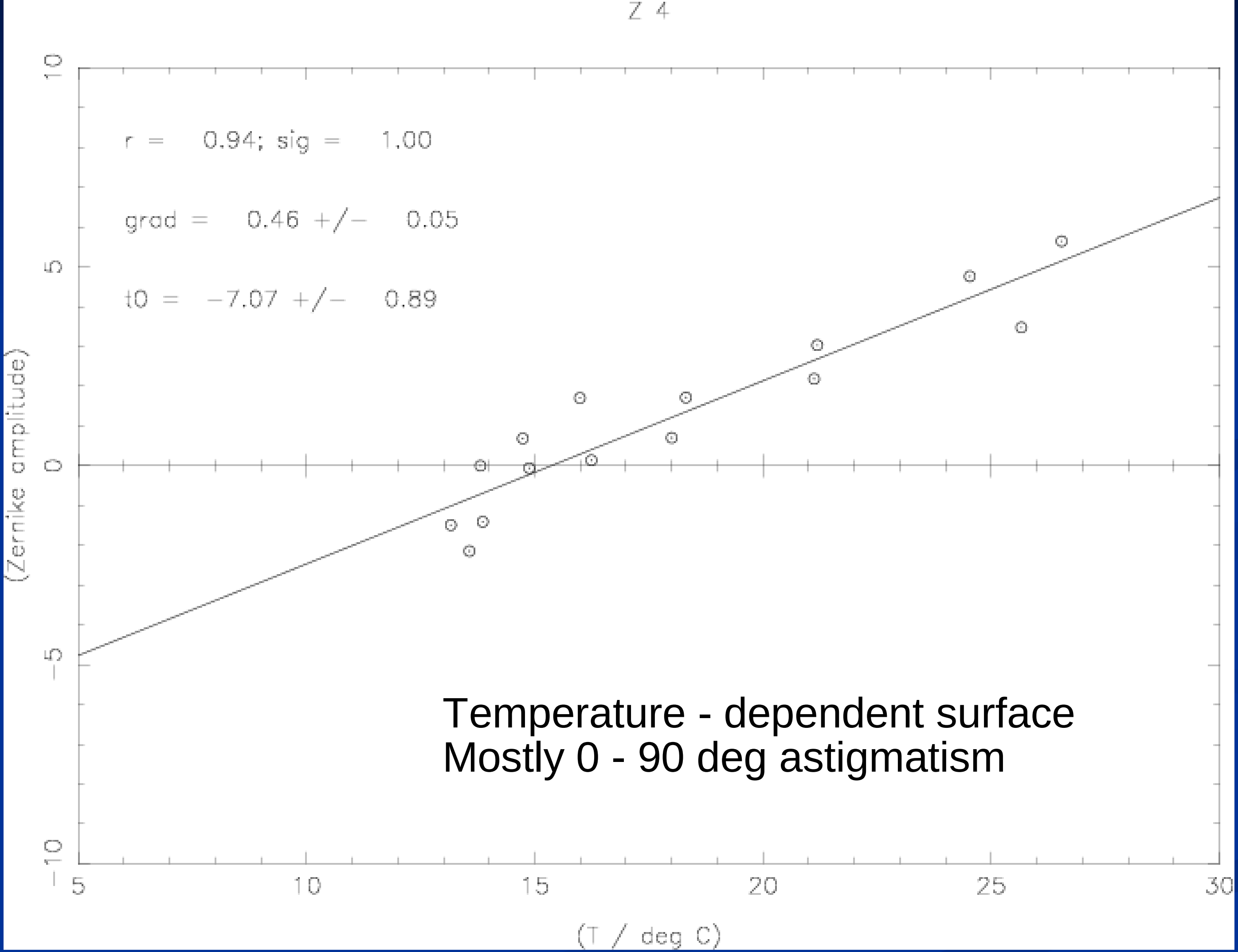
Limit at ≈10.5μm

Measurement Reproducibility



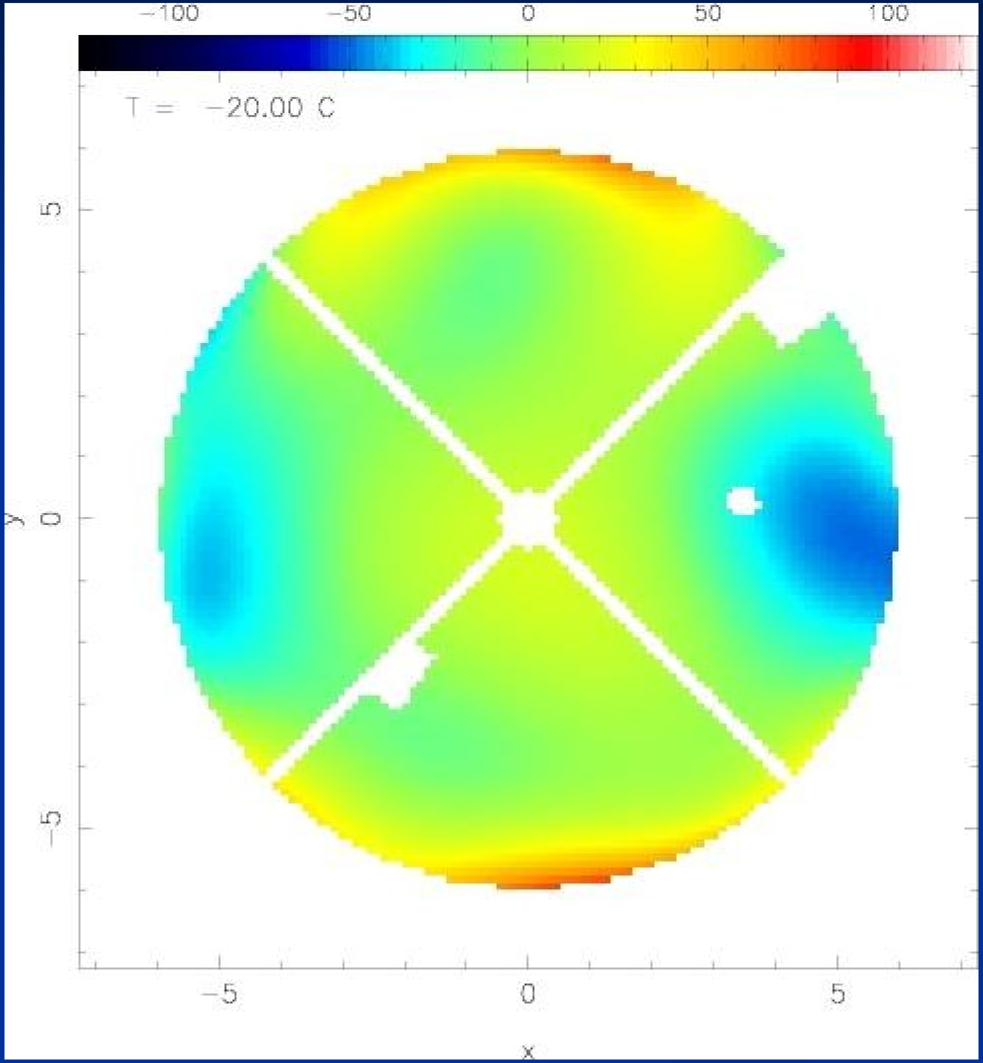
rms difference between successive maps with horizontal and vertical scan patterns = 1.6µm

Thermal effects at OSF



Temperature - dependent surface
Mostly 0 - 90 deg astigmatism

Temperature dependence: Zernike Model



Model the temperature-dependence of the surface using Zernike polynomials

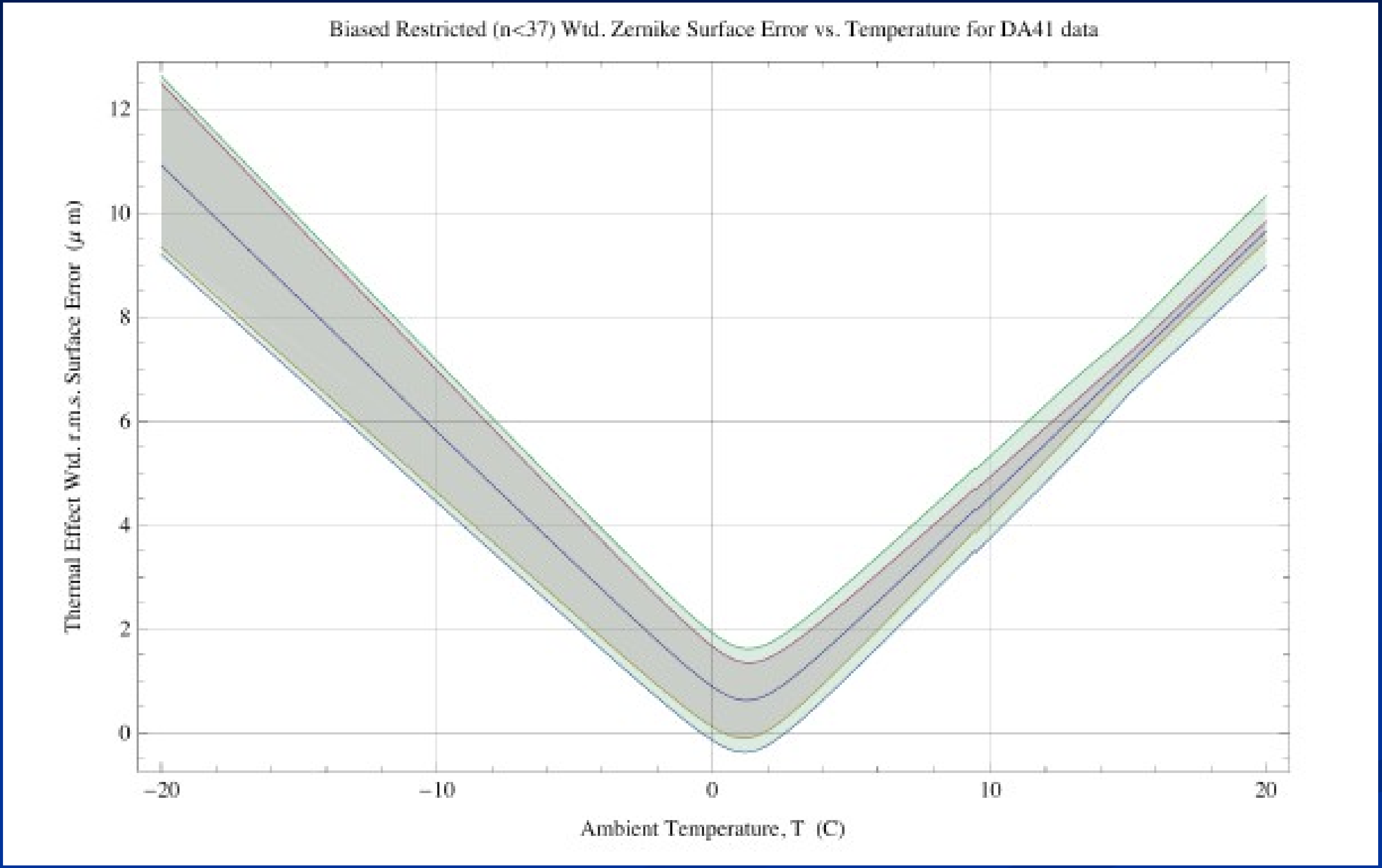
Dominant terms are 0 - 90 deg astigmatism and spherical aberration

Linear in temperature

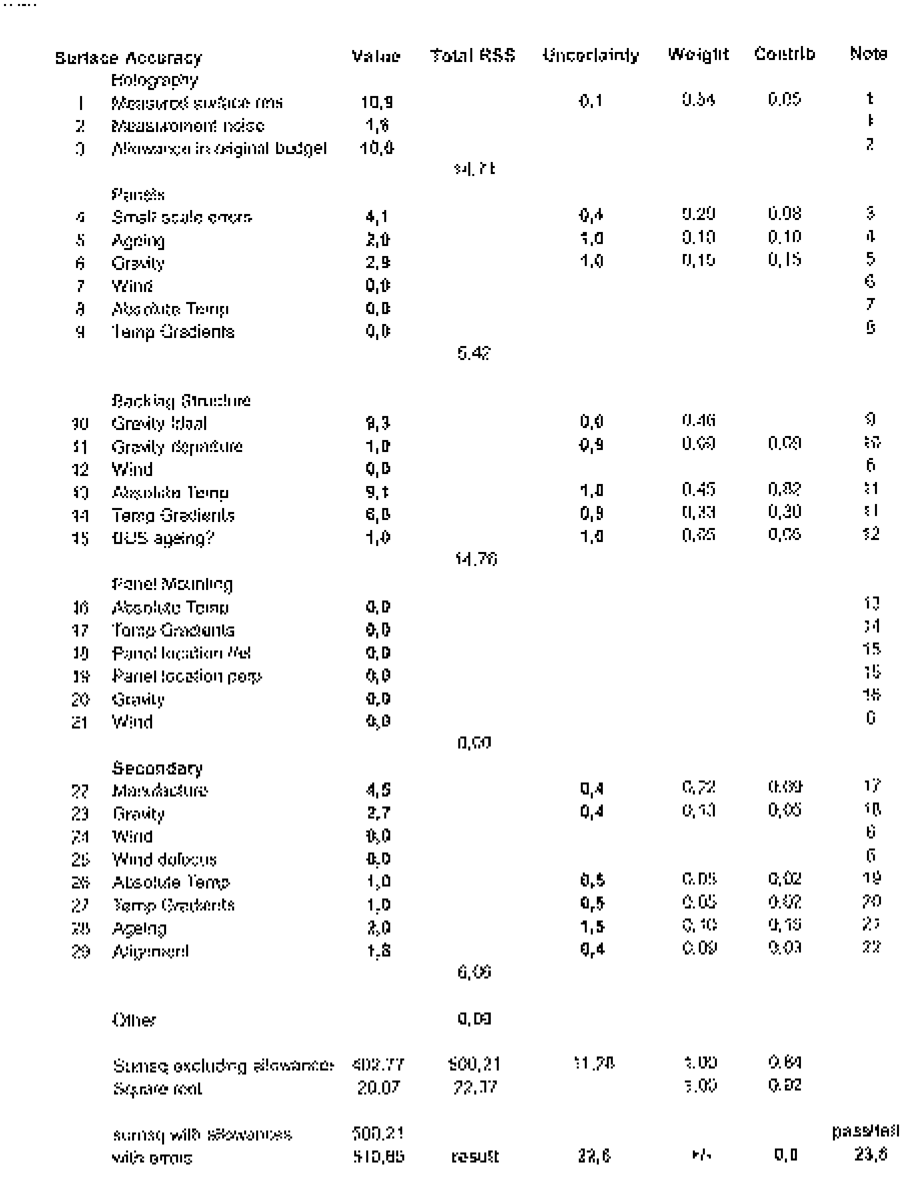
Without further adjustment, surface would be out of specification at lower end of operating temperature range

Bias the surface setting to optimise at ≈ 0 C (range is -20 to +20 C)

Surface error prediction



Error Budget



	Surface Accuracy	Value	Total RSS	Uncertainty	Weight	Contrib	Note
	Holography						
1	Measured surface rms	10,9		0,1	0,54	0,05	1
2	Measurement noise	1,6					1
3	Allowance in original budget	10,0					2
			94,71				
	Panels						
4	Small scale errors	4,1		0,4	0,20	0,08	3
5	Ageing	2,0		1,0	0,10	0,10	4
6	Gravity	2,9		1,0	0,15	0,15	5
7	Wind	0,0					6
8	Absolute Temp	0,0					7
9	Temp Gradients	0,0					8
			5.42				
	Backing Structure						
10	Gravity ideal	8,3		0,0	0,46		9
11	Gravity departure	1,0		0,9	0,09	0,09	10
12	Wind	0,0					6
13	Absolute Temp	9,1		1,0	0,45	0,82	11
14	Temp Gradients	6,0		0,9	0,33	0,30	11
15	BUS ageing?	1,0		1,0	0,05	0,05	12
			14,76				
	Panel Mounting						
16	Absolute Temp	0,0					13
17	Temp Gradients	0,0					14
18	Panel location Rel	0,0					15
19	Panel location perp	0,0					15
20	Gravity	0,0					16
21	Wind	0,0					6
			0,00				
	Secondary						
22	Manufacture	4,5		0,4	0,72	0,09	17
23	Gravity	2,7		0,4	0,13	0,05	18
24	Wind	0,0					6
25	Wind defocus	0,0					6
26	Absolute Temp	1,0		0,5	0,05	0,02	19
27	Temp Gradients	1,0		0,5	0,05	0,02	20
28	Ageing	2,0		1,5	0,10	0,15	21
29	Alignment	1,8		0,4	0,09	0,03	22
			6,06				
	Other		0,09				
	Sumsq excluding allowances	402.77	500,21	11,24	1.00	0.64	
	Square root	20.07	22.37		1.00	0.82	
	sumsq with allowances	500,21					pass/fail
	with errors	510,85	result	22,6	+/-	0,9	23,5

Overall surface error

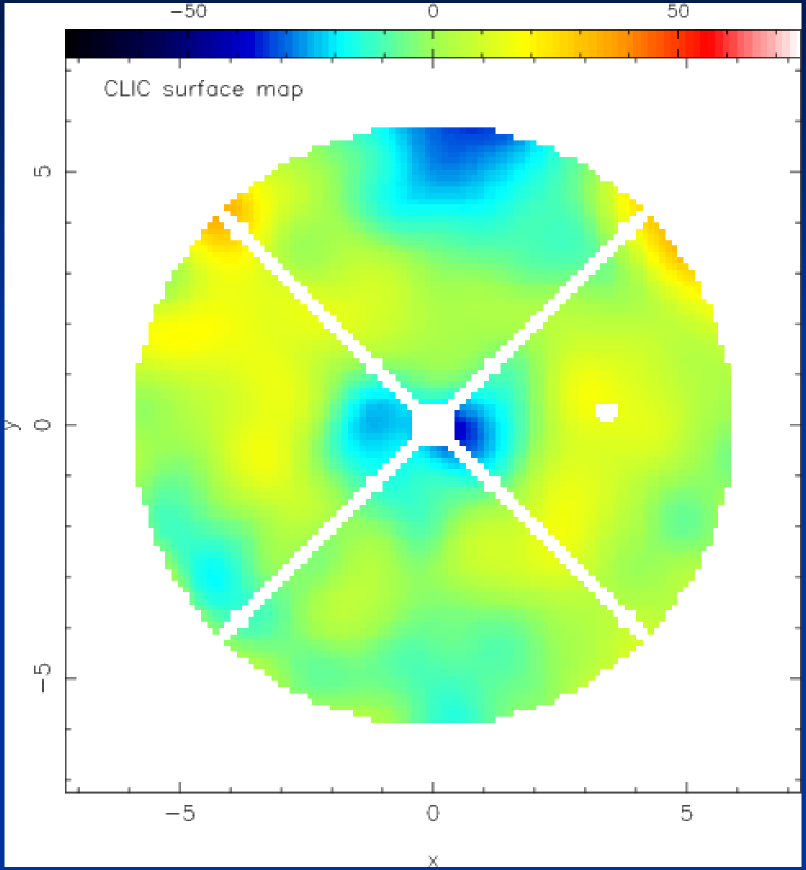
Best estimate 22.6μm
1σ upper bound 23.5μm

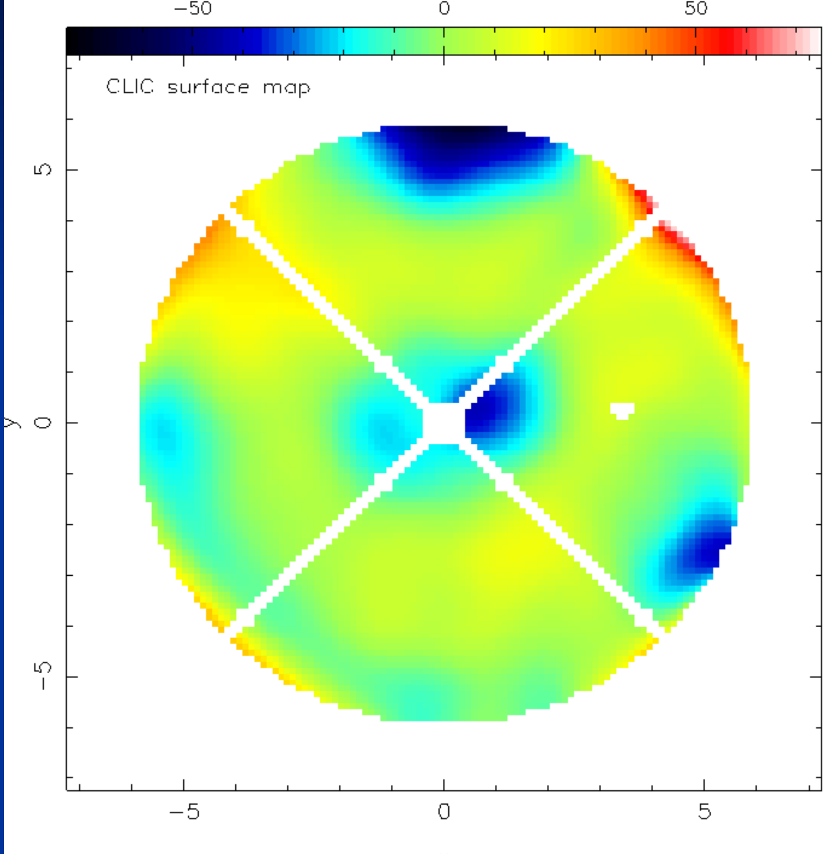
Specification 25.0μm

Interferometric Holography at AOS

- Method (Scott & Ryle 1977)
  - Scan the antennas under test across a bright quasar in a raster (or, more recently, star) pattern
  - Use a subset of antennas to provide reference amplitude and phase
  - Tests complete optics, but with limited spatial resolution (~1m on primary surface)
- Details
  - 230 and 345 GHz (problems with illumination at 90 GHz)
  - Water vapour radiometer phase corrections used
  - Frequent boresight calibrations
  - 15-20 antennas, ~5 used as references
  - Compare H and V polarizations/upper and lower sidebands to check internal accuracy (typical differences are a few µm rms)

Results (DA41 and DA43)





DA41
rms = 11.3 µm
T = -5.5C
Elevation 41 deg

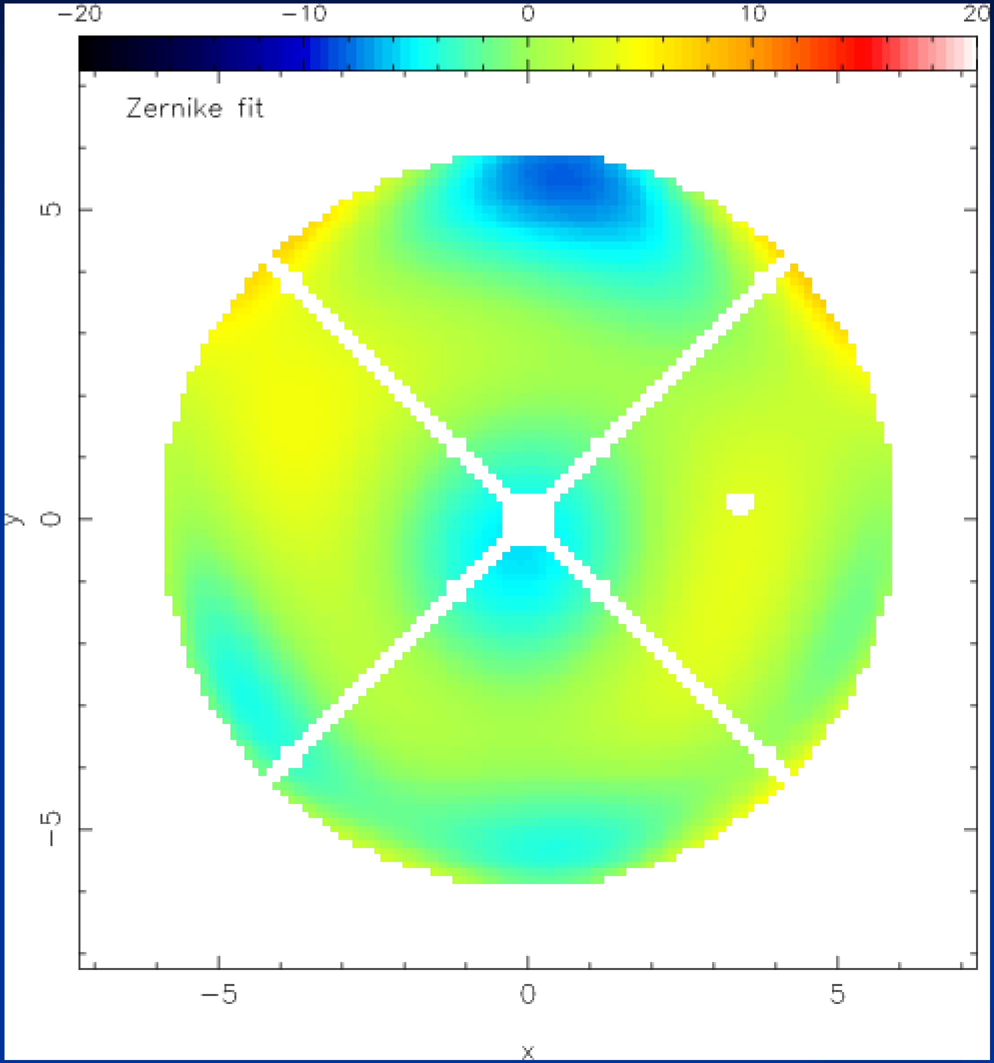
High-order Zernike modes e.g.

$Z_{10} = r^3 \sin 3\theta$

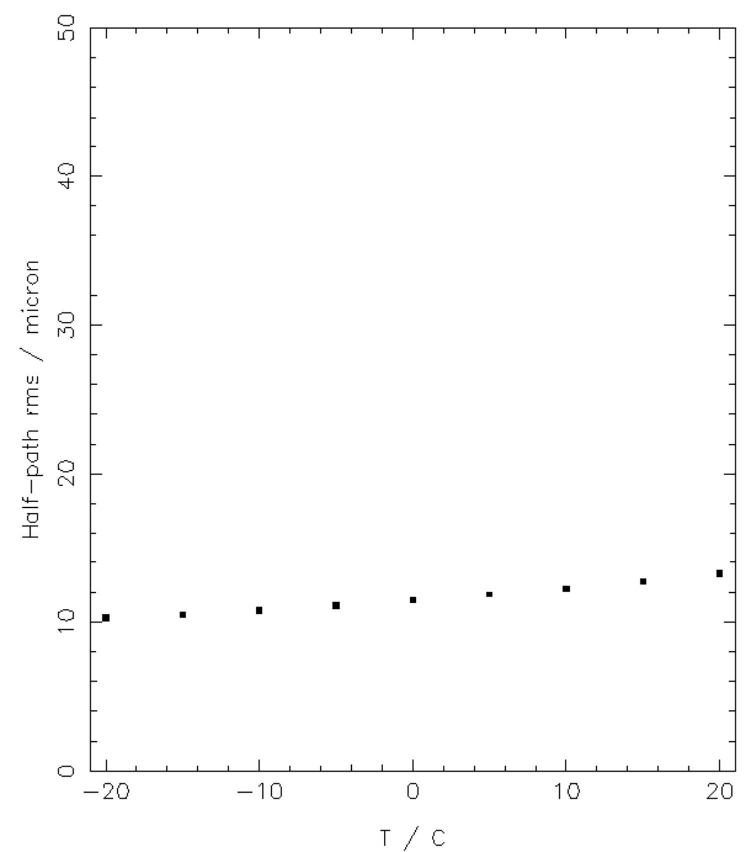
$Z_{25} = 20r^6 - 30r^4 + 12r^2 - 1$

DA43
rms = 13.1 µm
T = -3.1C
Elevation 71 deg

Little Temperature Dependence

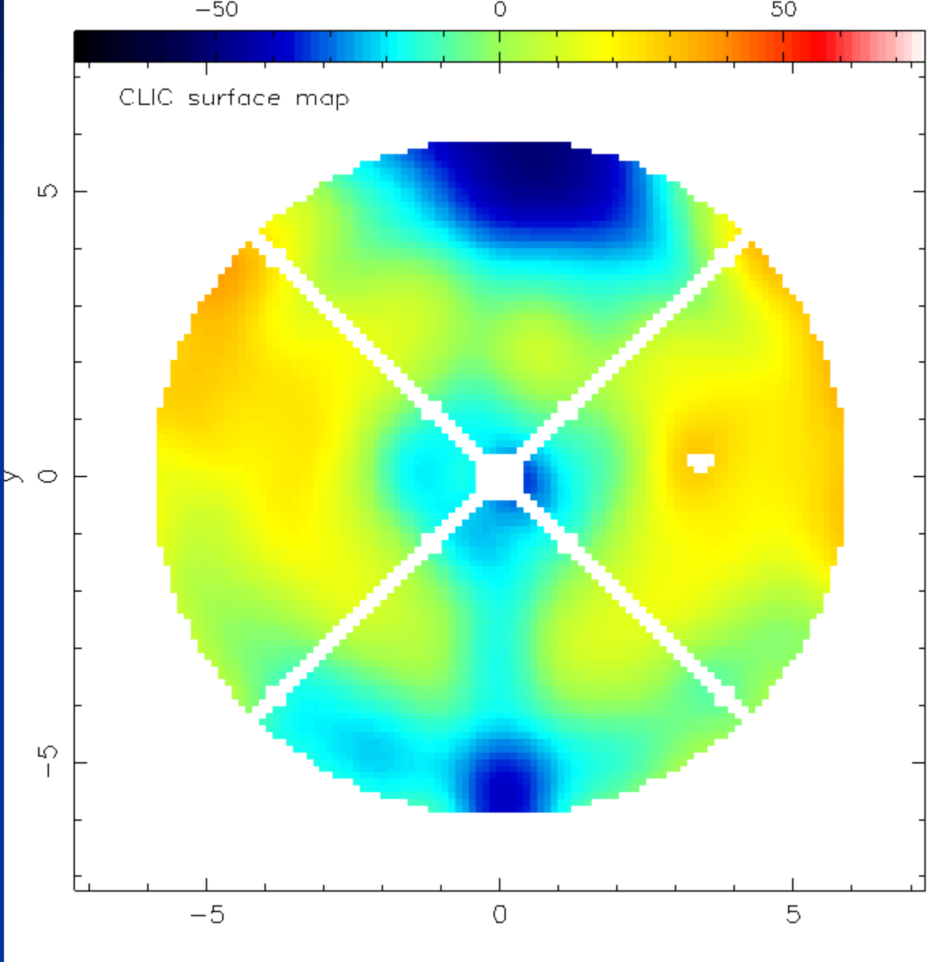


Zernike fit to surface map



Predicted temperature variation of surface rms of Zernike model

Worst case (DA45)



17.0 µm rms

Similar high-order Zernike terms to DA41 and 43

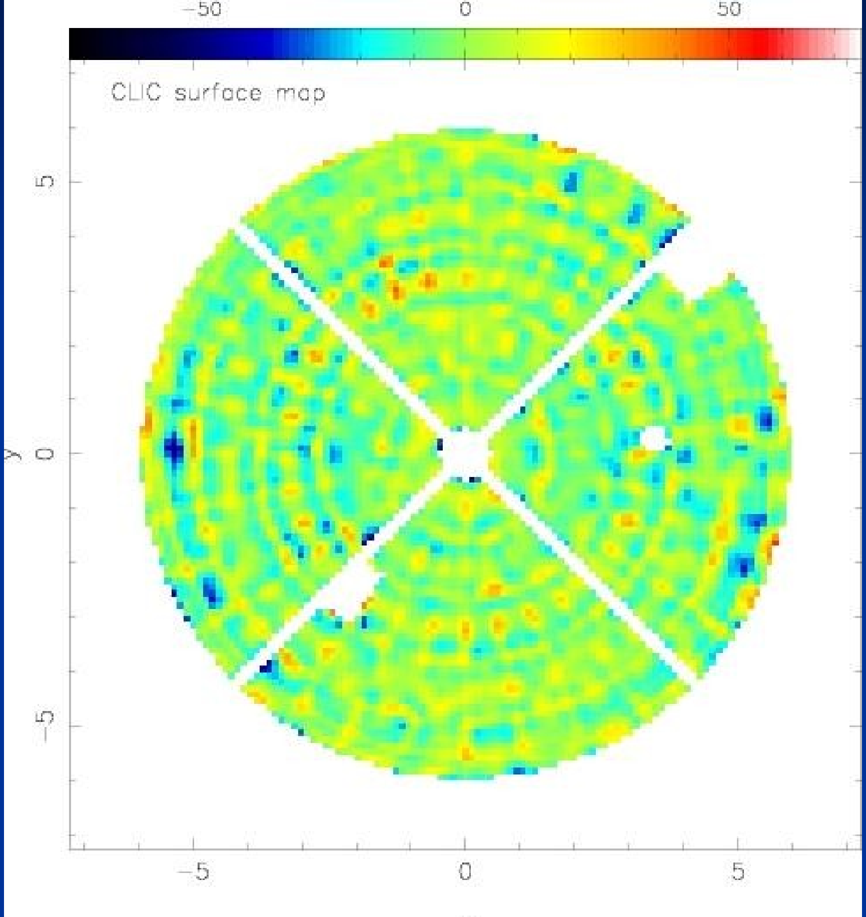
Additional large 0-90 deg astigmatism term (Z_4)

No significant dependence on temperature

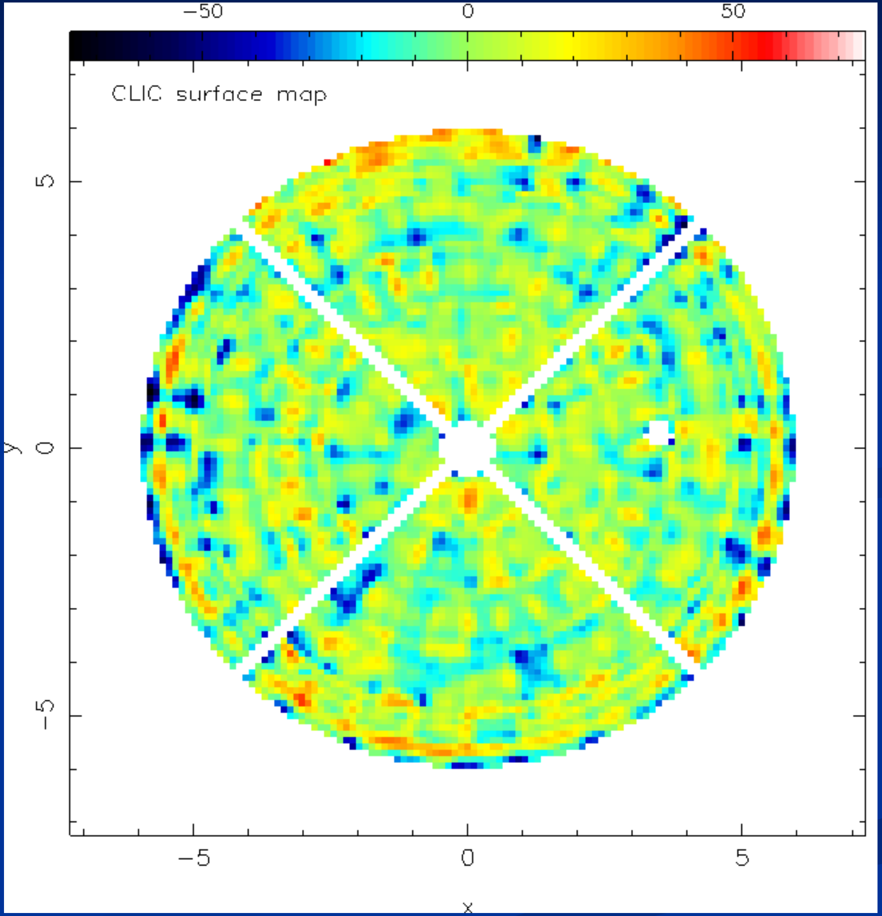
Surface accuracy from interferometric holography

- Bands 6 and 7; night-time only
- Rms
  - Best 10.5 µm; worst 20.5 µm
- Small-scale structure
  - Interferometric holography has limited resolution (approximately 1m on the primary for the current datasets)
  - Best estimate for additional rms on smaller scales is 9.9 µm (added in quadrature)
- Results
  - All antennas in specification (<25 µm)
  - Best 14.4 µm; worst 22.7 µm; mean 18.6 µm.

Surface degradation after 2 years



2011: rms 10.9 µm



2013: rms 13.7 µm

Next Steps

- What causes the (consistent) residual pattern on the best set antennas?
  - Wrong correction for holography receiver feed horn?
- Why the spread in surface accuracy?
  - Error does not depend very much on temperature or elevation
  - Dependence on receiver/feed horn used to set the primary surface?
  - Error pattern looks like the thermal model - incorrect bias?
  - Return worst affected antenna to OSF, repeat tower holography, check for changes and reset surface based on results
- Why is the thermal behaviour apparently different at OSF and AOS?
  - Thermal bias worked well for some antennas, not for others
- Incremental adjustments to the surface at AOS?
  - Done for APEX, but safety concerns
  - Test source planned to give panel-scale resolution

Lessons

- A holography system is for life, not just for Christmas
  - Engineering for reliability and repeated use
- Be very careful of components which require a software correction
  - Feed horn
  - Careful comparison of measurements from different receivers/horns
- Measure temperatures properly
  - Careful positioning of sensors
- Calibrate as often as possible

Summary

- 25 AEM 12m ALMA antennas have been set using tower holography with a typical primary surface rms of 11 μm
- Interferometric holography at the 5000m site show that all of the antennas measured so far meet the full surface accuracy specification of 25 μm rms under good night-time conditions
- The best antennas are set to ~15 μm rms; further work should allow the remainder to reach the same level
- Much more to do on day-time observations, thermal transients, ...