



Metrology of Radio Reflector Antennas

A historical introduction and summary of methods

Jacob Baars - MPI for Radio Astronomy, Bonn
RadioNet Workshop ERATec
Göteborg, 1-2 September 2014



Introduction

When Grote Reber designed his 10 m diameter parabolic reflector in 1935 his plan was to observe at a wavelength of 10 cm, about the limit where electronic components were available at the time. How precise should his reflector represent a paraboloid? He applied the criterion used in optics, due to Rayleigh, that the maximum deviation of a mirror should be less than one-quarter of the wavelength. If we assume these errors to be randomly distributed with a Gaussian distribution, the rms error would have to be less than about one-twentieth of the wavelength. In 1952 John Ruze published his "tolerance theory" of random errors in the reflector profile and there we find that a $\lambda/20$ rms error leads to a loss of efficiency of 33 percent. Most observers consider this an acceptable situation. If you want to observe at the submillimeter wavelength of 0.35 mm, a surface rms error of $\lambda/20$ means a surface accuracy of 17 μm ! This is close to the ALMA specification goal of 20 μm . It not only requires fabrication capabilities of such quality but also measuring methods to demonstrate both the manufacturing precision and the setting of the reflector panels on the telescope structure to the required precision. This means metrology methods and instruments with an accuracy of better than 10 μm in the "field".

While the measurement and setting of reflector surfaces is the main subject of this Workshop, other aspects of the construction and operation of large and accurate reflector antennas can be discussed under the general designation of metrology. An obvious example is the pointing and tracking precision under operational conditions. Temperature variations and wind influence can cause deformations in the structure, which lead to pointing errors that cannot be sensed by the encoders. In order to correct for these in real time one has to install a sensor system with accompanying algorithms which measures the structural deformation and provides correcting data to the pointing control system. Such systems are known under the name Flexible Body Compensation (FBC). They include the use of Finite Element Analysis (FEA) in correcting deformation due to measured temperature differences in the structure.

In this talk I shall present a historical review of reflector metrology and mention some of the recent developments in FBC.

J. Ruze, *The effect of aperture errors on the antenna radiation pattern*, 1952, Suppl. al Nuovo Cimento **9**,364-380

J. Ruze, *Antenna Tolerance Theory - A Review*, 1966, Proc IEEE **54**, 633-640

Metrology of reflector antennas

What must be measured and how?

- surface panels - intrinsic manufacturing
- intermediate support frames with several panels
- total reflector surface
 - rarely continuous surface (one big panel)
 - usually a set of panels or panels frames, supported by adjusters on the backup structure
- pointing and pathlength (interferometers)
 - errors caused by wind and temperature
 - Flexible Body Compensation (FBC)
 - temperature, displacement sensors, FEM

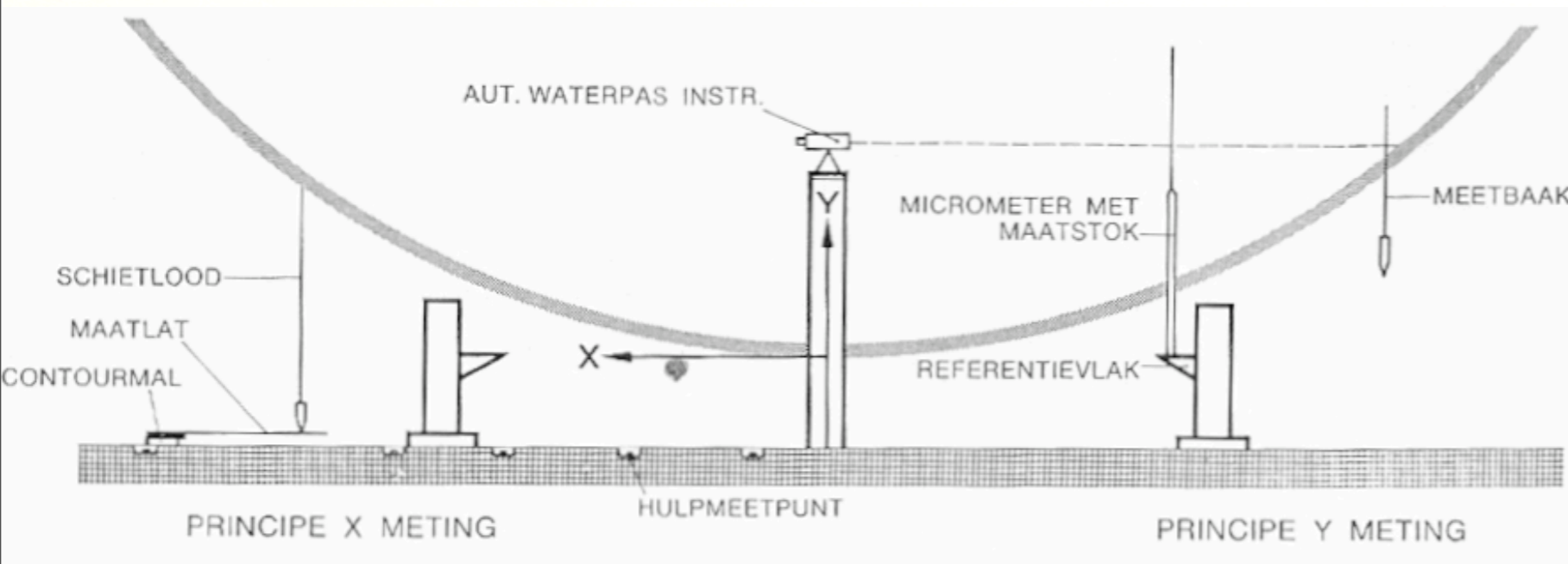
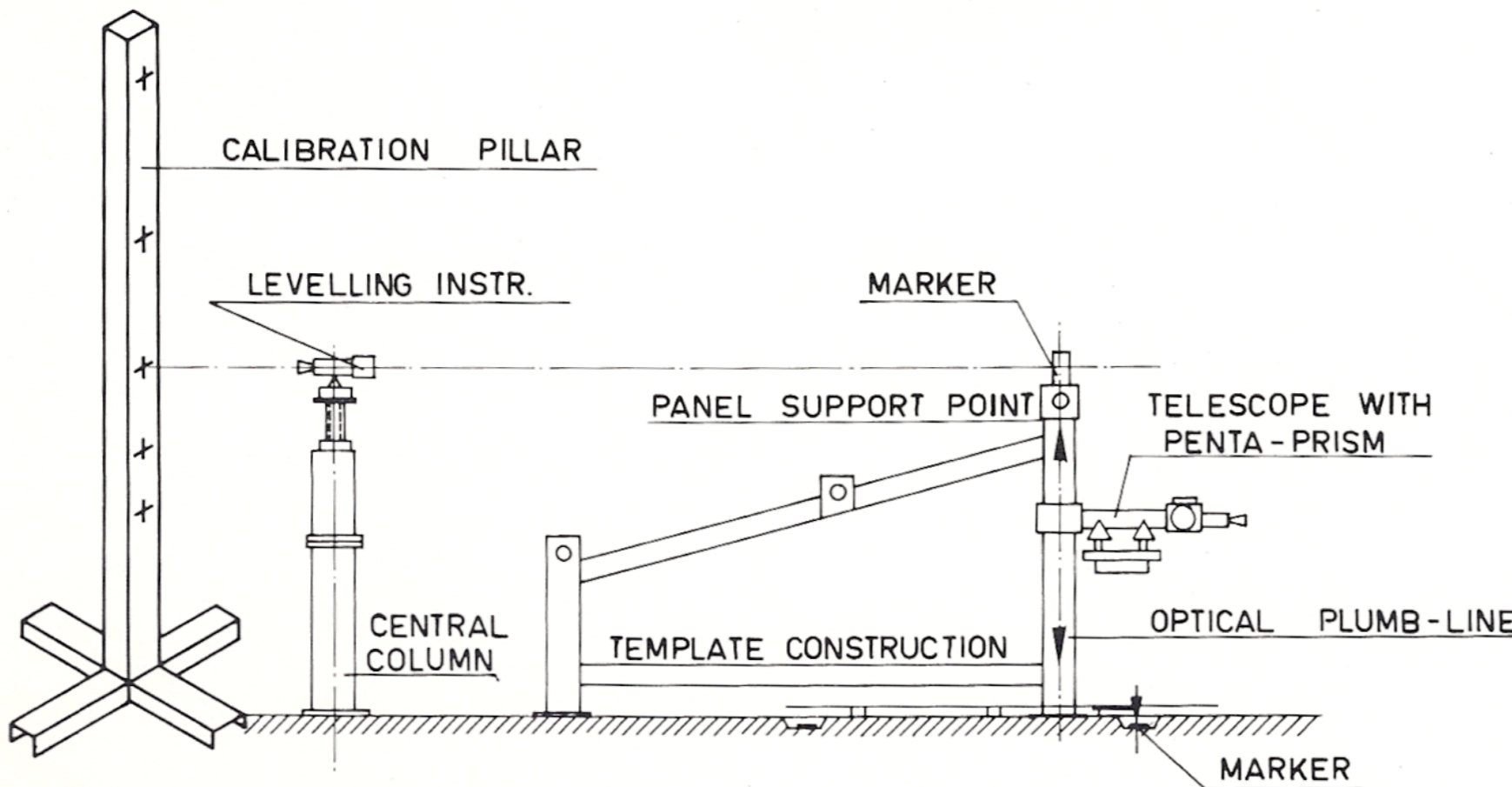
Methods of reflector metrology

- Geodetic - theodolite or level and tape, pentaprism, modern laser-tracker, laser interferometer
- Geometric - curvature, pathlength, CMM
- Photogrammetry
- Radio holography - phase: full / retrieval, farfield / nearfield

WSRT - X-Y measurement of template and panel

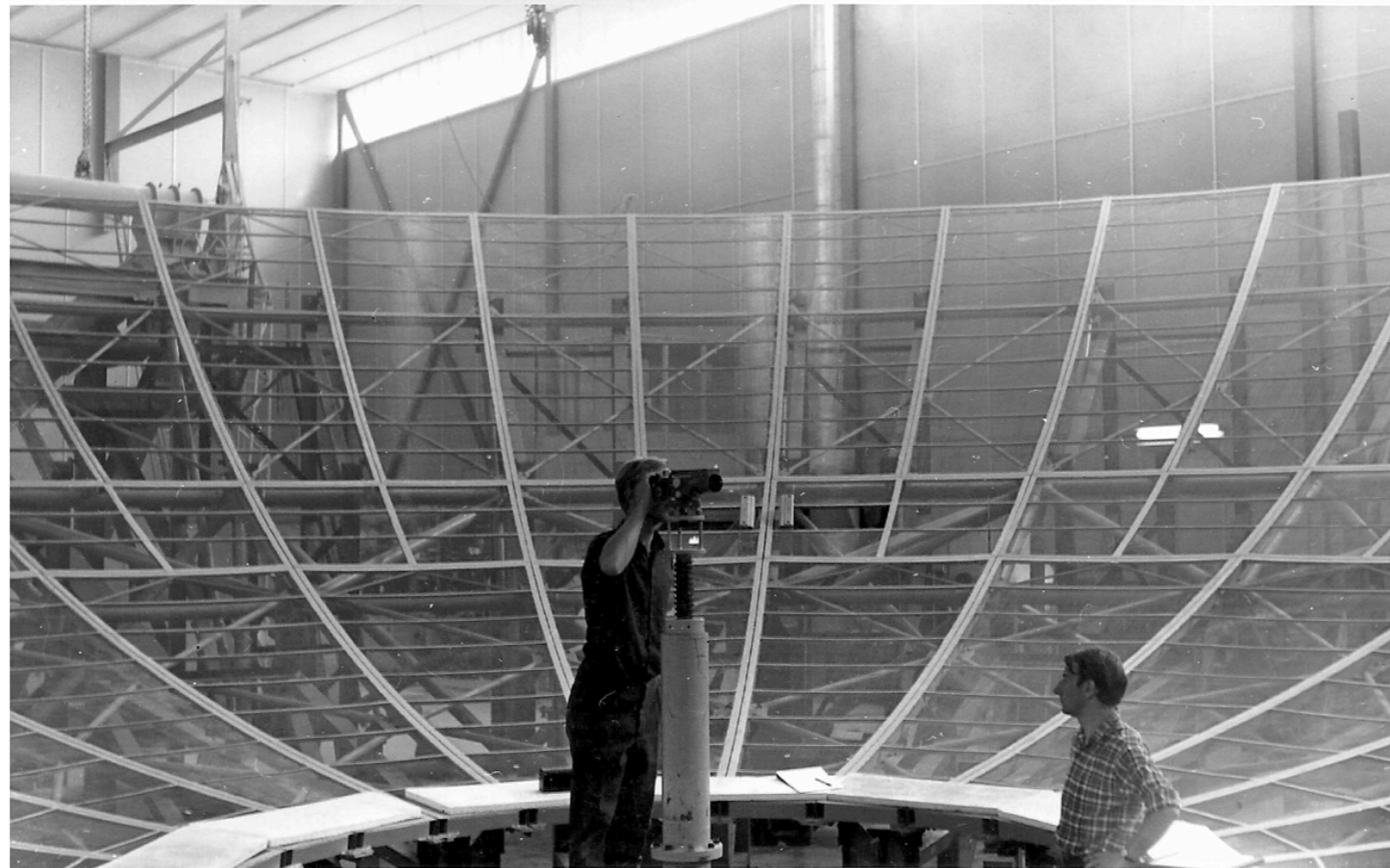
Temperature controlled assembly hall

Setup of the assembly template for the reflector. Panel supports are set in y by automatic level w.r.t. to calibration bar and in x by optical plumb line w.r.t. markers on the floor.



Measurement of reflector with level, movable target with plumb w.r.t calibrated height bar and markers on the floor. Achieved measuring accuracy 0.1 mm

measurement of the WSRT dish



*The author as a young man, witnessing and logging
a measurement of a WSRT reflector.*

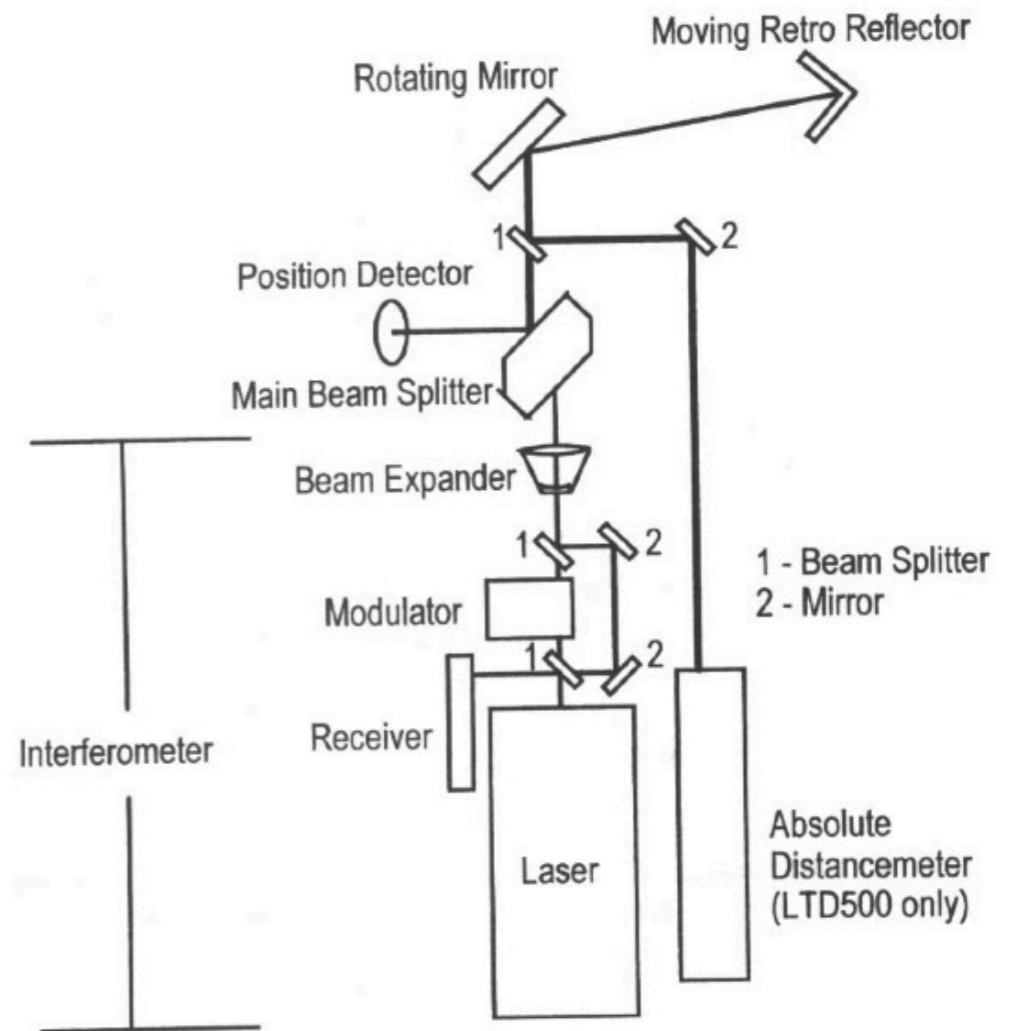
J.W.M. Baars and B.G. Hooghoudt, *The Synthesis Radio Telescope at Westerbork. General lay-out and mechanical aspects*, 1974, *Astron.Astrophys.* **31**, 323-331.

Theodolite/Tape - Laser tracker

The “classical” method is the theodolite and tape arrangement. Targets are placed on the surface, at or near the adjusters. The theodolite is placed in the center on the reflector axis and the angle to the targets is measured. A measuring metal tape with gradation is laid along the surface to measure the length of the curve.

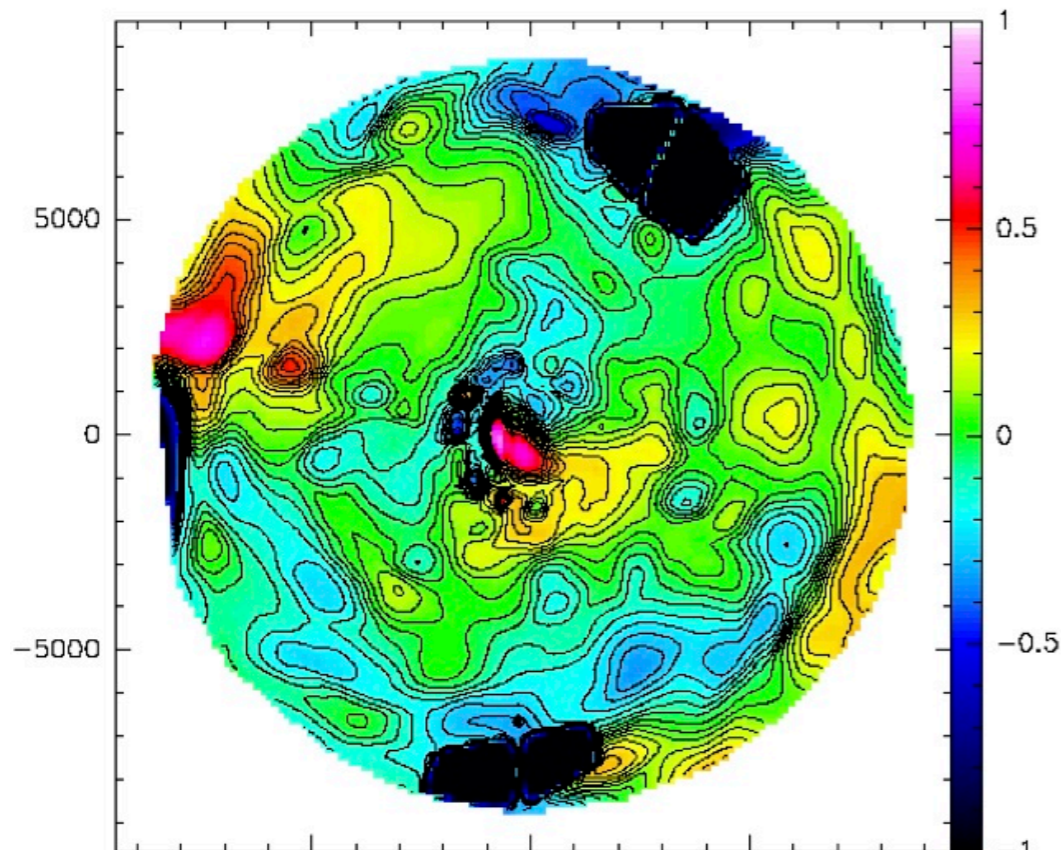
With great care and patience and under well controlled circumstances an accuracy of about 10^{-5} D can be reached.

A. Greve, *Reflector surface measurements of the IRAM 30-m radio telescope*, 1986, *Int. J. Infrared and Millimeter Waves* **7**, 121-135

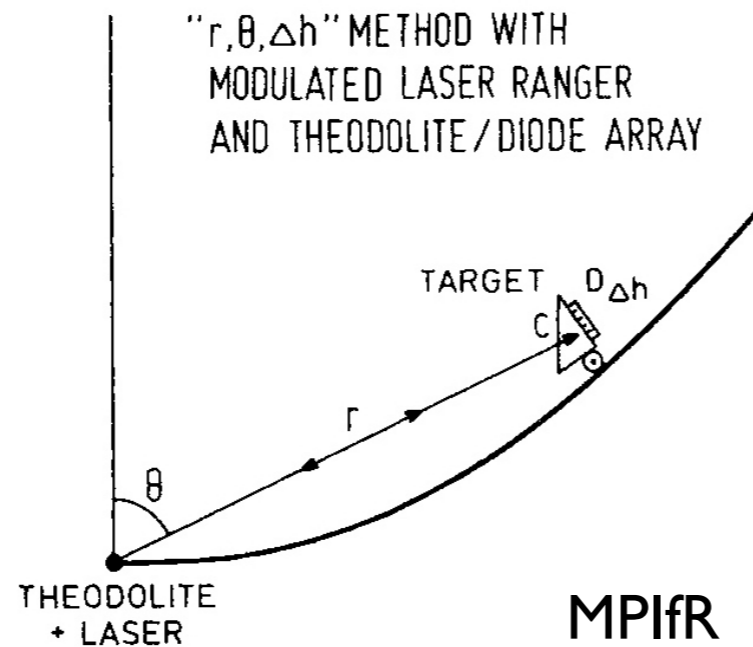
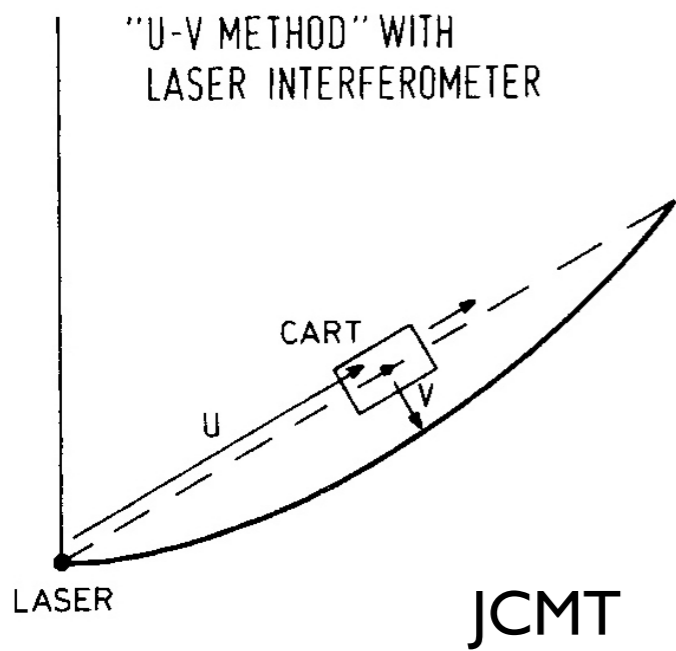


The current laser rangefinders combine angle and distance measurement into one theodolite-like instrument. The target is a corner reflector and can be moved over the surface with the instrument tracking its position. On the 12 m ALMA antennas a measuring accuracy of about $30 \mu\text{m}$ has been demonstrated.

Onsala dish measured with laser-tracker

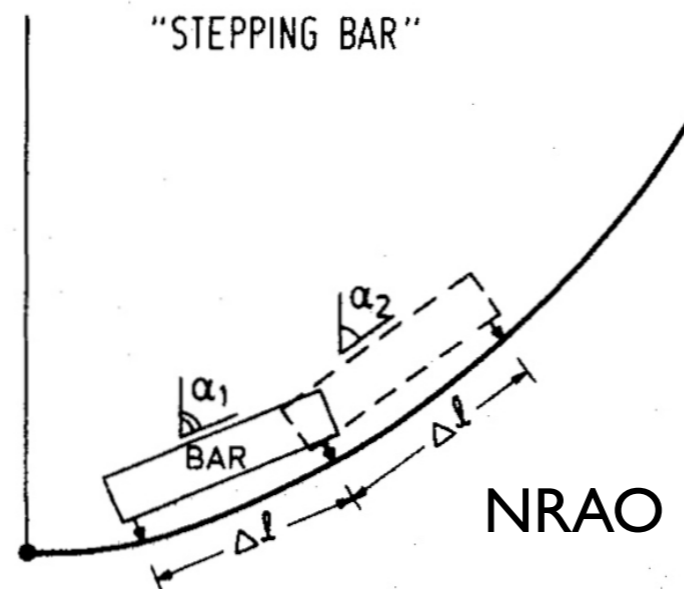
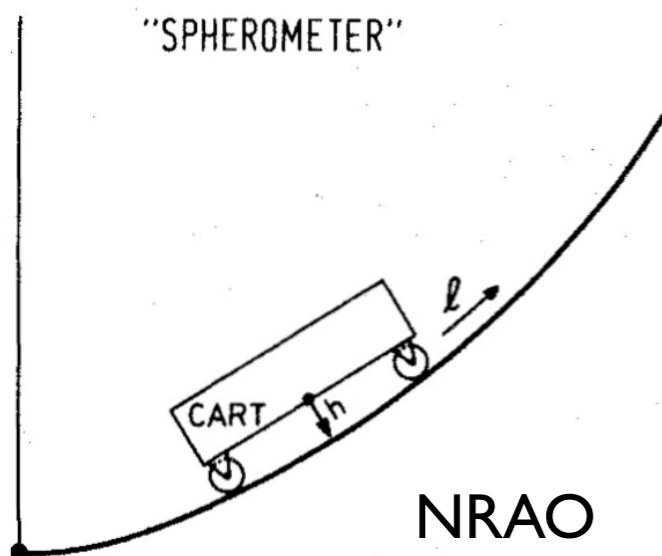


Alternatives: laser based ranging - measurement of depth or curvature



(a): the laser-interferometer and cart with depth sensor of the JCMT system. Coordinates (u,v) are measured while the cart moves outward along a radial.

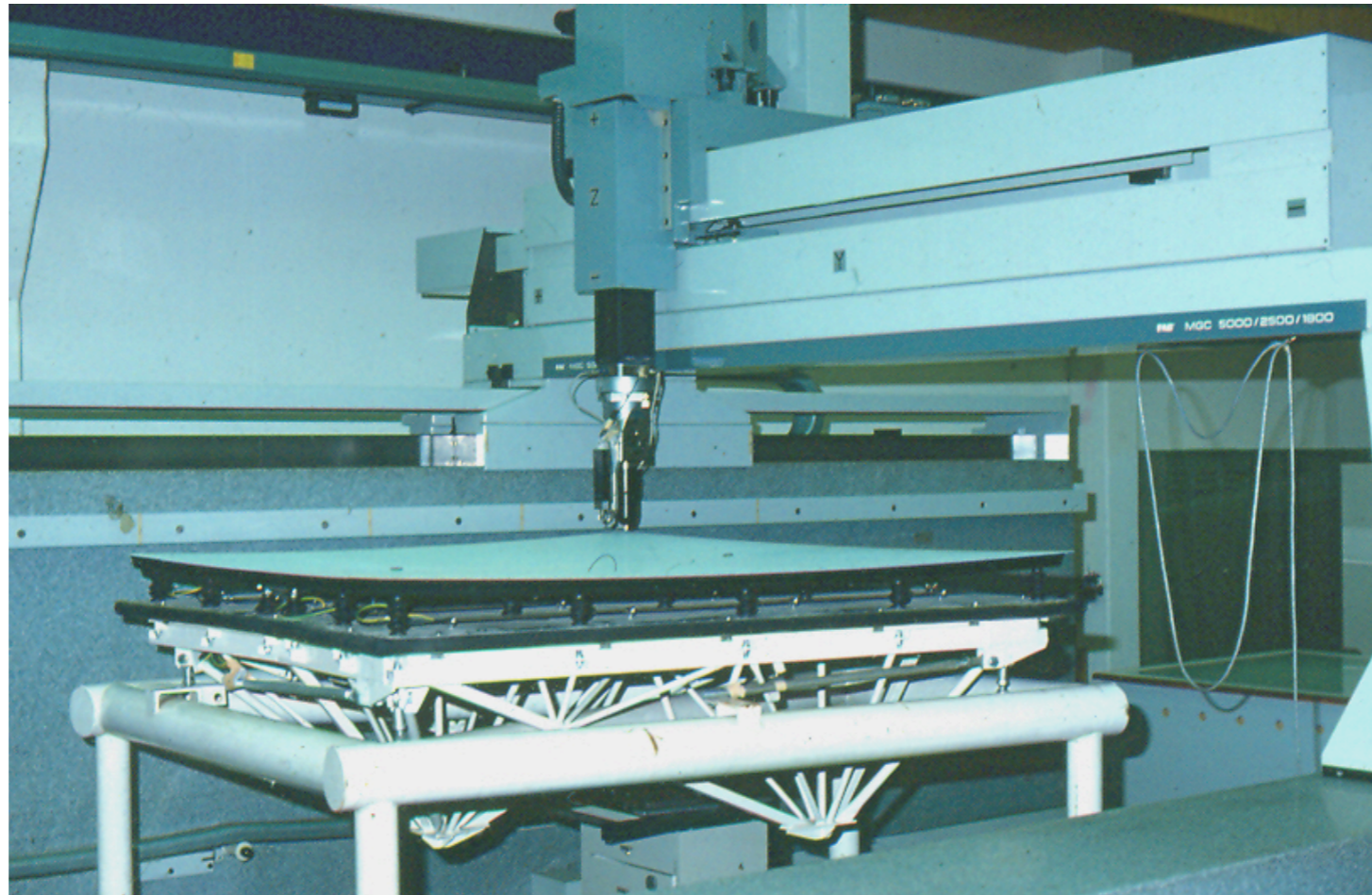
(b): the theodolite-modulated laser system of MPIfR. Distance r and height variation Δh are measured while the arm moves tangentially. Angle θ is set once with theodolite.



Two methods used by Findlay. (a): spherometer measures l along radius and depth h . Double integration delivers the shape.

(b): stepping bar of length Δl with inclinometer measures angles α . NRAO 140-ft telescope was measured with this method.

Measurement of MRT panel-frame unit in CMM



Measurement and adjustment of the two surface panels each supported by 15 adjusters on the frame of size 2x2 m, which is connected to the backup structure by four adjusters. The large CMM at the Karmann-Ghia auto-works is normally used to check molds and prototypes of cars. Measuring accuracy is better than 5 μm rms. The average frame surface precision is 27 μm .

the need for non-contacting measurements

All methods described up to this point require either the placement of markers on the surface and/or the movement of devices by hand over the surface. This essentially limits the application to the zenith position of the telescope. Because the bulk of observations is done at intermediate elevation angles there is a pressing desire to have a measuring method of sufficient accuracy that can be applied on the reflector in an "out of the zenith" position. Two of such non-contacting methods are available:

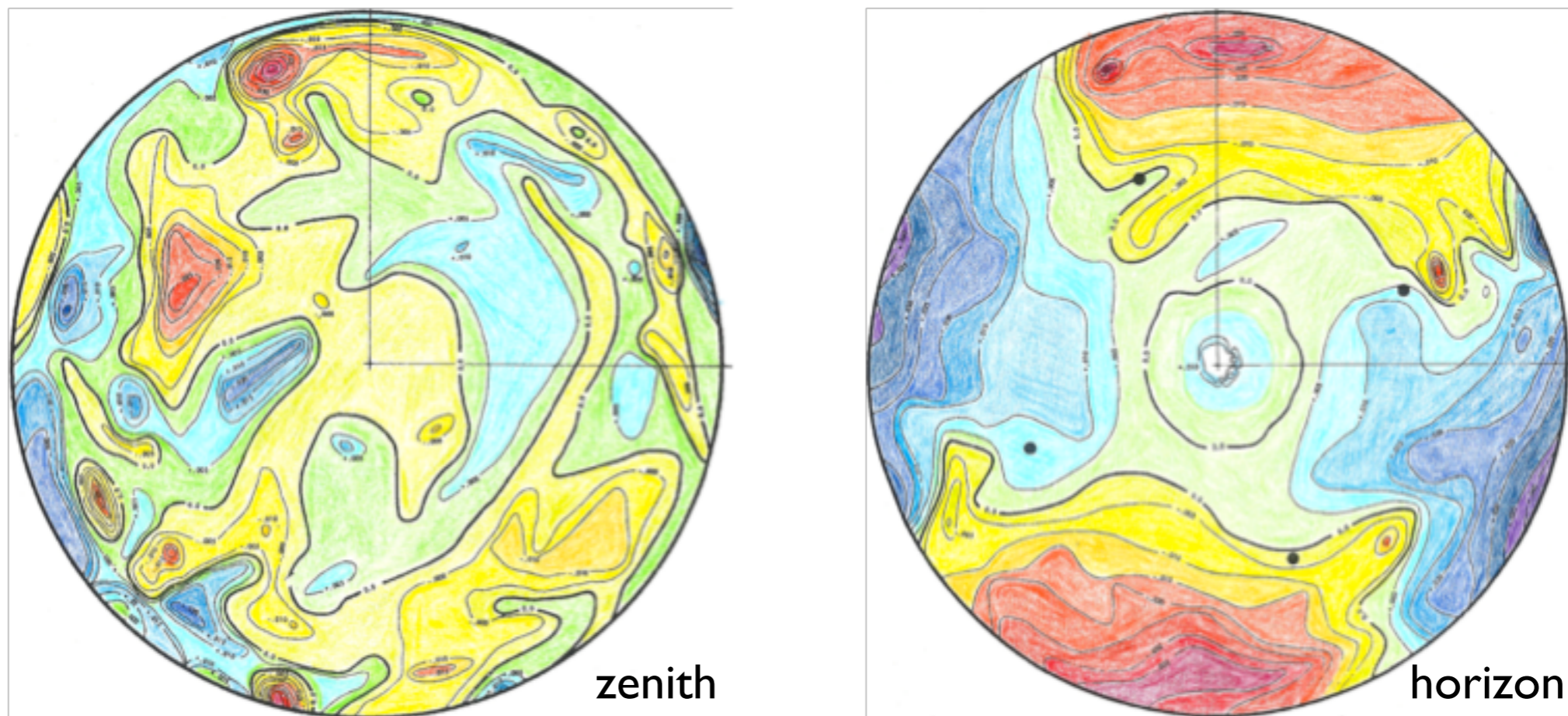
photogrammetry and **radio-holography**.

photogrammetry of the NRAO 85-ft in 1962

At NRAO the 300-ft and 85-ft telescopes were measured by photogrammetry.

Cameras placed on a helicopter hovering over the antennas.

Measurements at 2-3 elevation angles, estimated accuracy 1.5 mm rms.

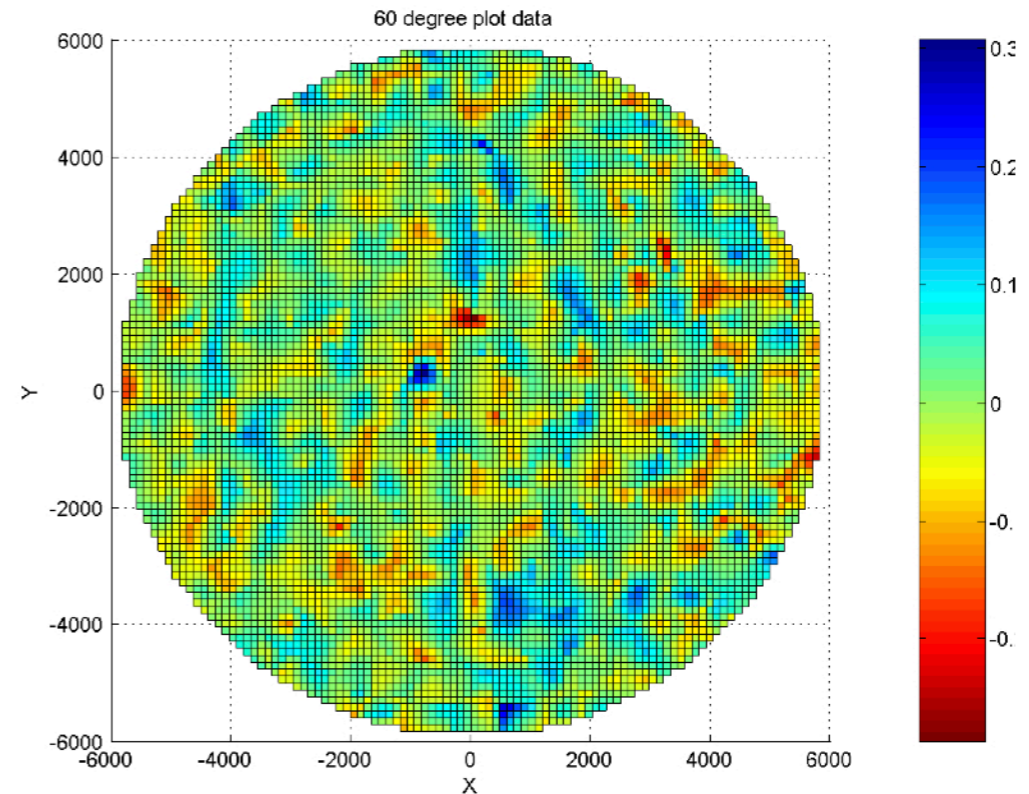
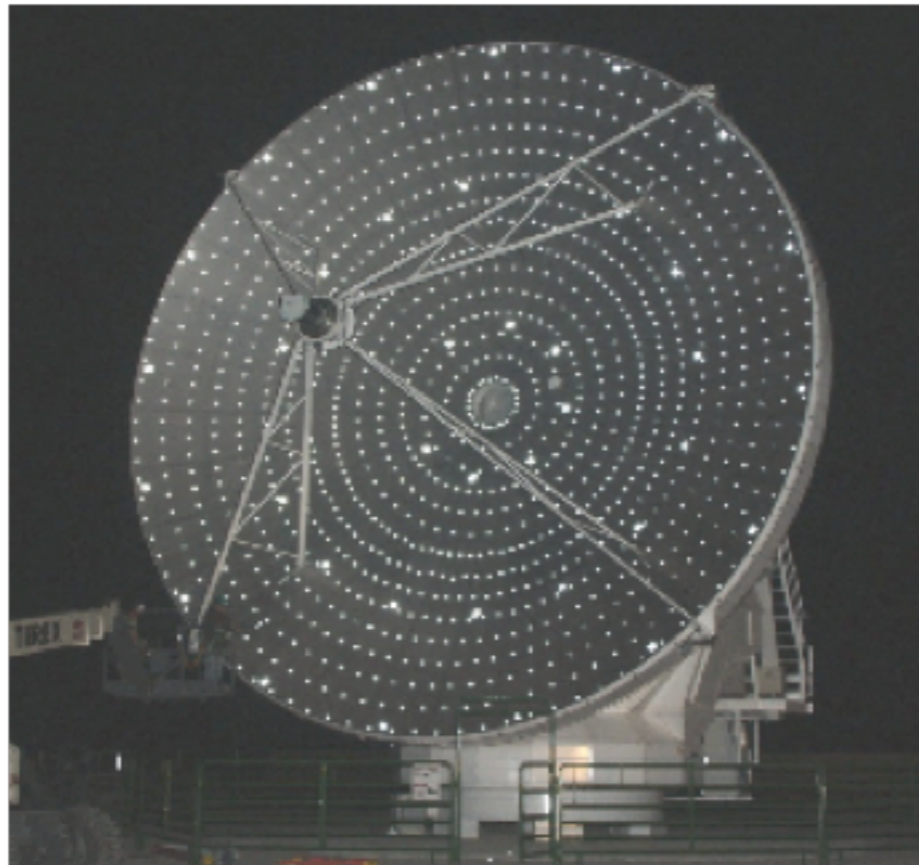


85-ft results. Zenith on left, Horizon on right. Strong astigmatism at horizon. Derived rms surface error: 3.2 mm and 5.7 mm in zenith and horizon, resp. But best-fit paraboloid has 41 mm shorter focal length at horizon! Aperture efficiency measurements confirmed Ruze's Tolerance Theory.

modern photogrammetry with digital cameras

Photogrammetry was used as a start to characterize the ALMA prototype antennas in 2002 and again at the end of the evaluation in early 2005.

Digital cameras placed on a cherry picker allowed measurements at different elevation angles. The best results indicated a measuring accuracy of the order of 30 - 40 μm . The setup is laborious with the need to place targets at each adjustment screw, but the measurement is relatively fast.



Surface accuracy RMS: 0.079mm

The AEC antenna with targets (small dots) and a set of calibration targets (bright). On the right a typical result, color coded deviations of measurements made at an elevation angle of 60° .

radio-holography

In the classic text "Microwave Antenna Theory and Design", published in 1949 in the MIT Radiation Lab Series, the author, S. Silver, demonstrates the Fourier Transform relationship between the aperture field distribution in amplitude and phase, and the farfield radiation pattern, also in amplitude and phase. The relation is reversible and hence the aperture field distribution could be recovered if one had a complete knowledge of the radiation field, both in amplitude and phase. Silver then notes: "in practice, the radiation pattern is only known in power and the aperture distribution cannot be determined uniquely".

In 1966 Roger Jennison published a pocket book "An Introduction to Radio Astronomy" and in an appendix he points to the same FT relation and mentions: "this relation may be reversed to give the field in the aperture plane in terms of the directivity pattern (in amplitude and phase)". Remarkably, although interferometry is extensively discussed in the book, he does not mention the use of an interferometer to preserve the phase of the radiation pattern.

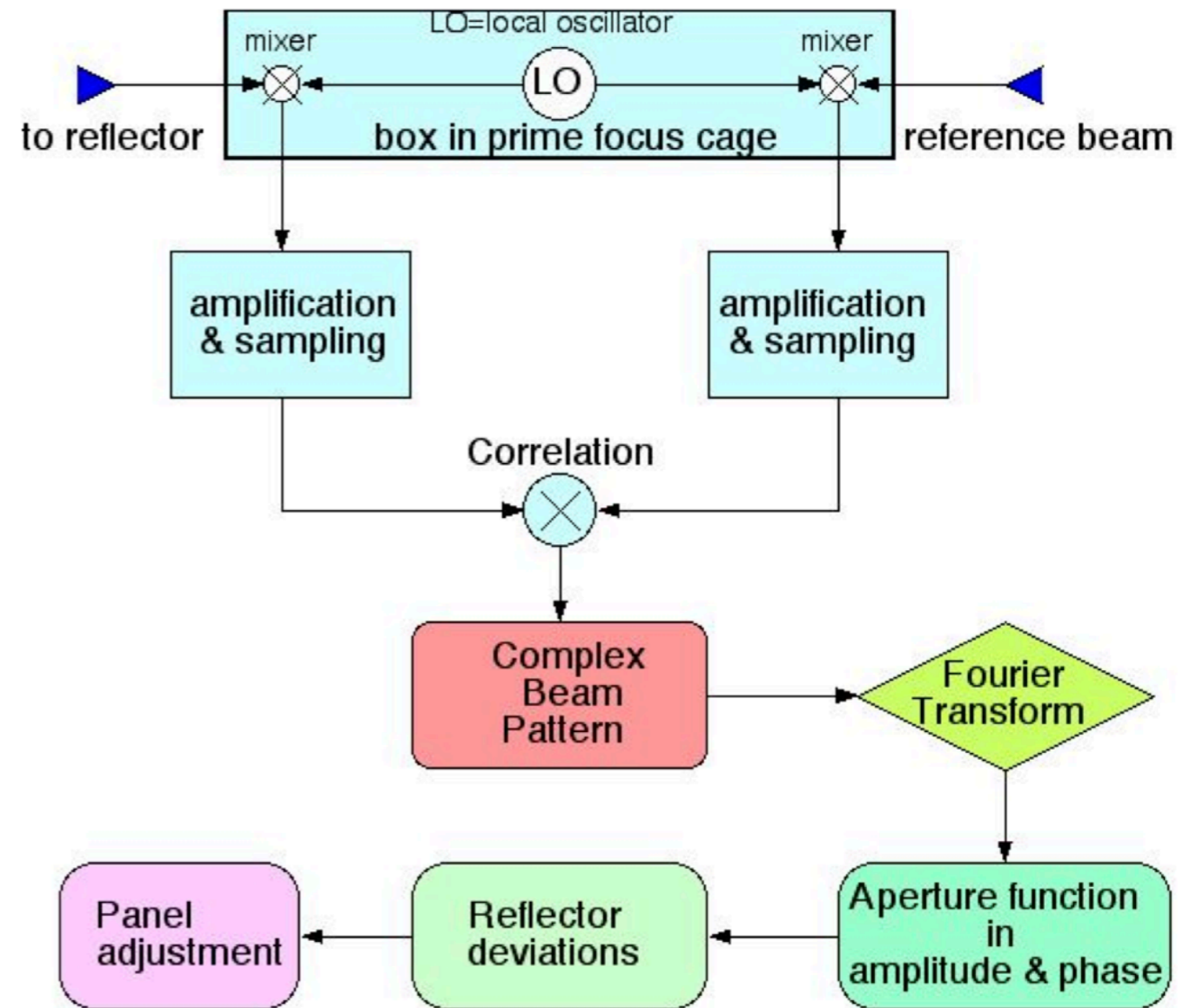
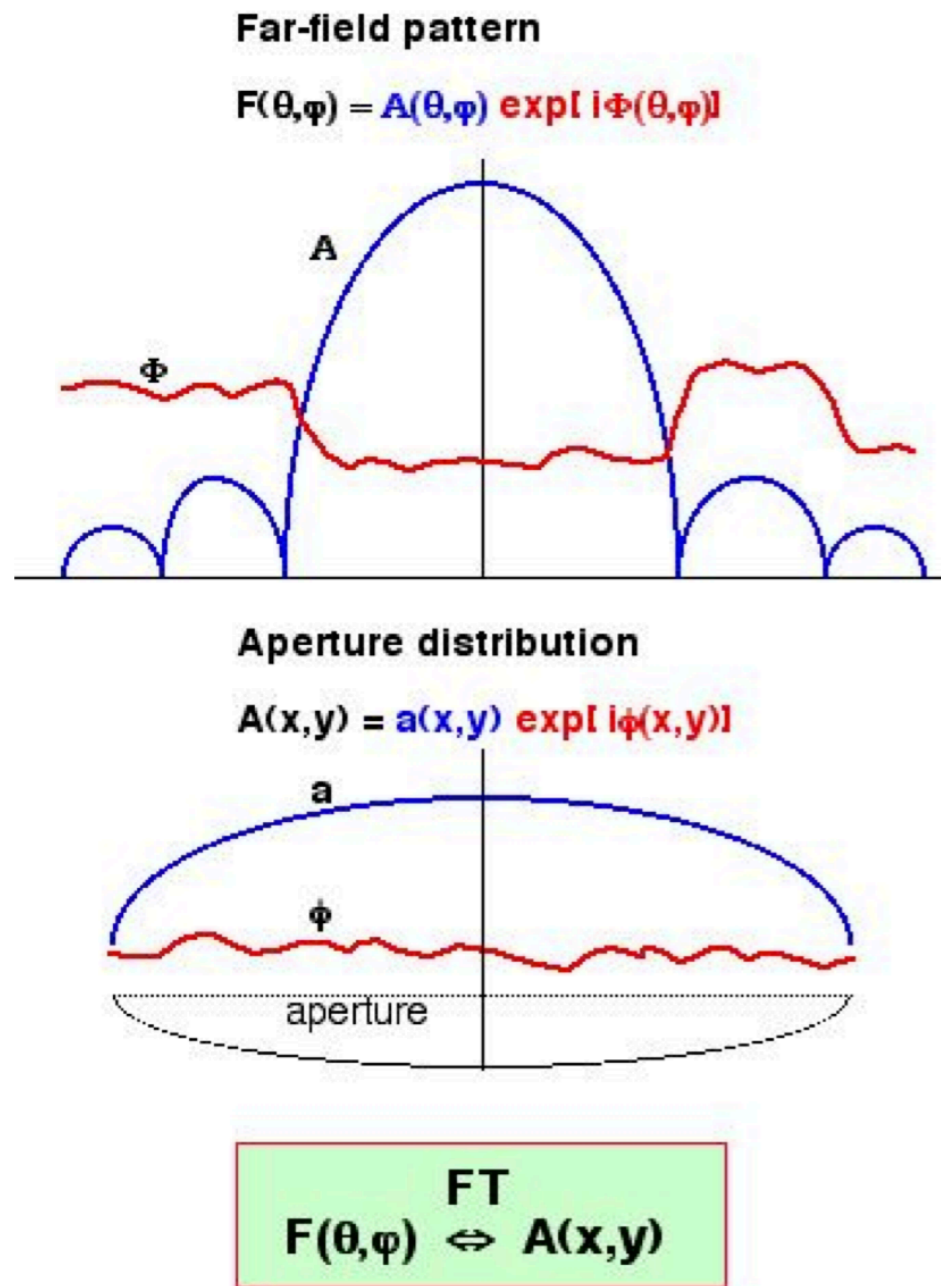
In 1976 Bennett and colleagues at the University of Sheffield published a ground-braking paper entitled "Microwave holographic metrology of large reflector antennas". Although they use the terminology of "holography", the method basically applies an interferometer with a reference signal of constant phase. After Scott and Ryle used the one-mile-synthesis telescope to measure the pattern of one of the antennas, while using another array element as reference source and demonstrated the practical feasibility of the method, it quickly grew to the favorite method to measure the shape of a reflector.

The term Radio Holography is generally used for any method to measure the phase distribution of the reflector aperture field and to identify deviations from the expected function with local distortions in the prescribed profile shape of the reflector. Over the years the method has been improved and several variations have been introduced. We summarise these by showing examples of measurements on several radio telescopes.

Bennett, J.C., Anderson, A.P., McInnes, P., Whitaker, A.J.T., *Microwave holographic metrology of large reflector antennas*, 1976, IEEE Trans. Ant. Prop. **24**, 295-303.

Scott, P. F. and Ryle, M., *A rapid method for measuring the figure of a radio telescope reflector*, 1977, Mon. Not. Royal Astron. Soc. **178**, 539-545.

the principle and practice of radio-holography



Blue - hardware, red to green - calculations, pink - human activity

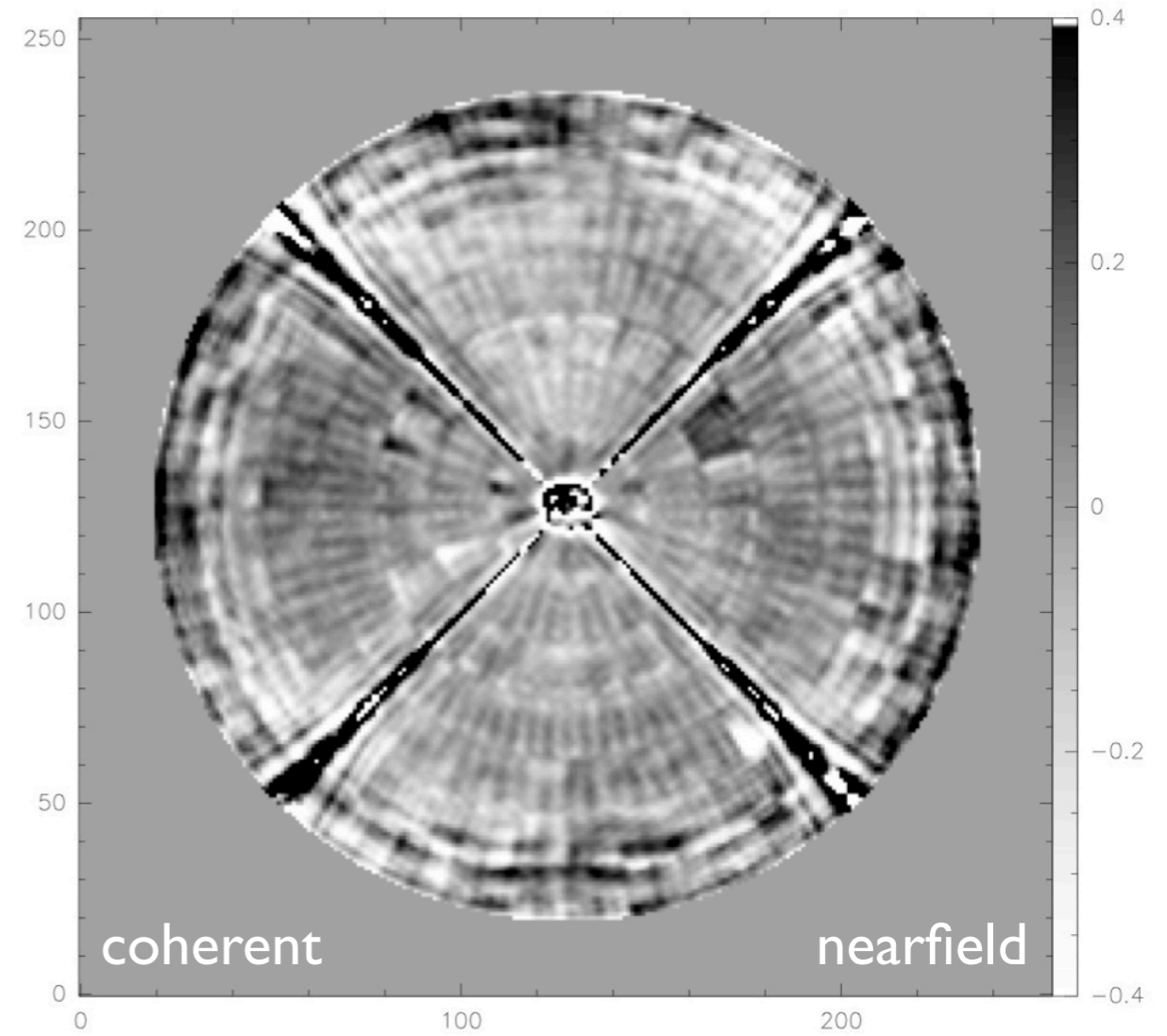
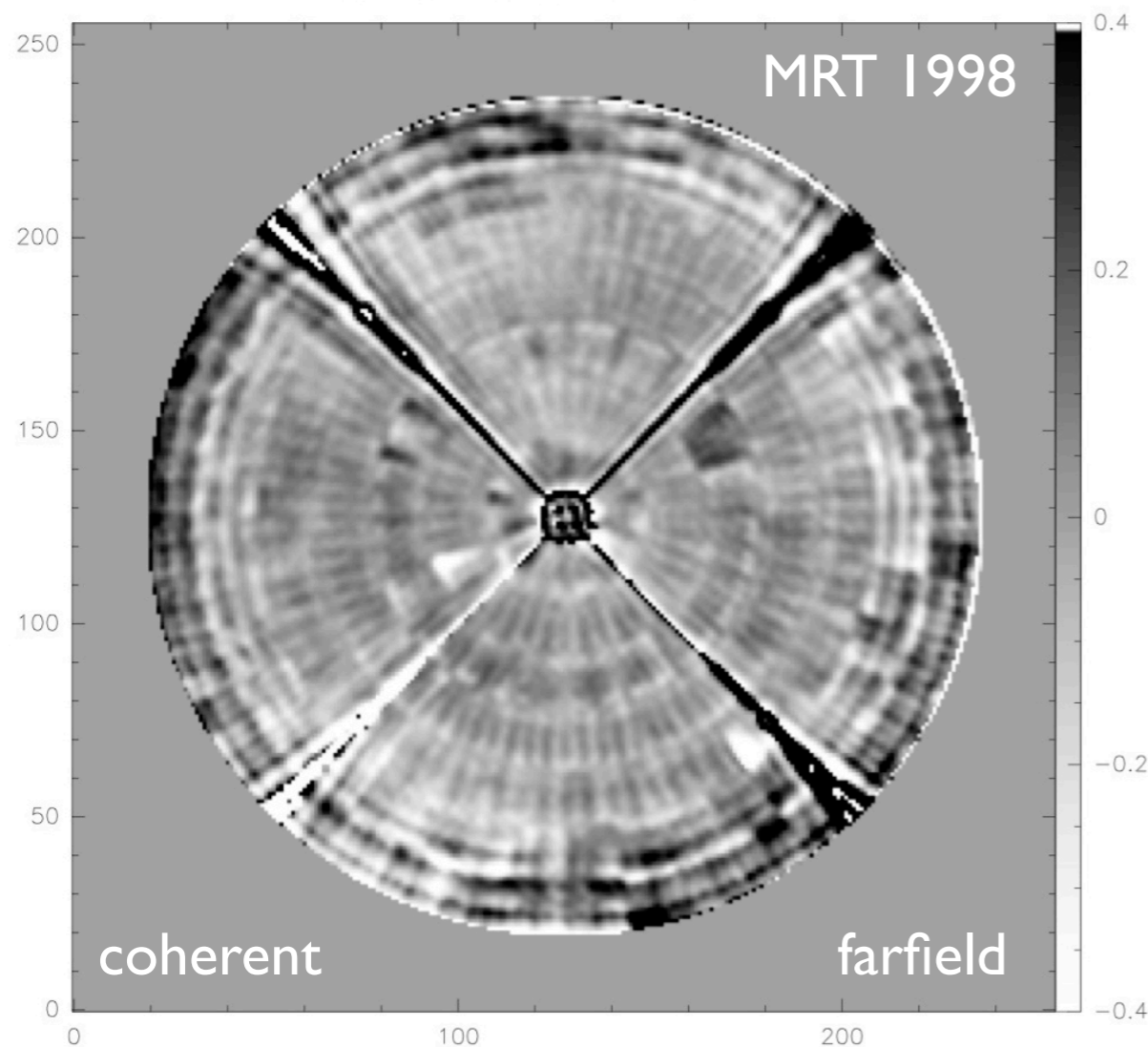
Illustration of the Fourier Transformation relationship between farfield pattern and aperture field distribution.

Basic block diagram of the holography method. The main beam and reference beam are correlated to form the complex beam pattern. After Fourier Transformation we obtain the aperture phase function, which is translated to reflector deviations. These are then adjusted.

the “57 varieties” of holography

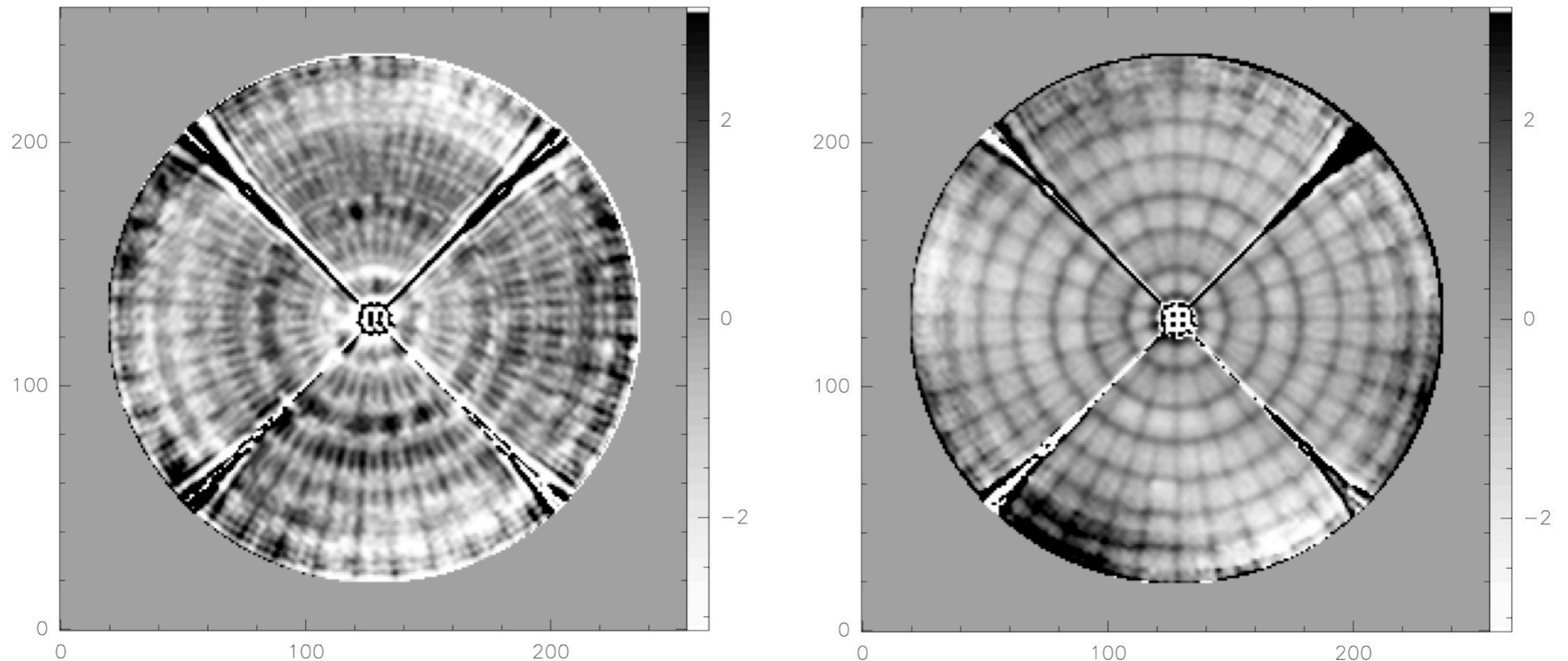
- phase coherent (full phase) with reference antenna
- phase retrieval (out-of-focus (OOF)) - no reference signal needed
 - advantageous for measurement with RA receiver but need strong source
 - required SNR order of magnitude larger than with phase coherence
- farfield range - cosmic source (H₂O maser, planet, quasar)
 - satellite beacon, stationary or moving (LES)
- nearfield range - “nearby” earthbound transmitter (300 m to several km)
 - intricate, distance and geometry dependent corrections necessary.
 - current status well developed, allows accuracies of better than 10 μm.
- any possible combination has been used.
 - depends also on the goal of the measurement:
 - initial setting of panels: high accuracy and sufficient spatial resolution.
 - “real-time” correction of large scale deformations: fast measurement.

a comparative example - 30-m mm-telescope



The 30-m millimeter telescope on Pico Veleta in September 1998.
Left: full phase measurement in farfield; source ITALSAT at 39 GHz.
Right: full phase map in nearfield; source transmitter on top of PV at 3 km.
The similarity is good. Range of phase plotted is 0.8 rad pp; the rms of the surface is about 70 μm . (work by Dave Morris et al. at IRAM)

map of 30-m telescope in 2000

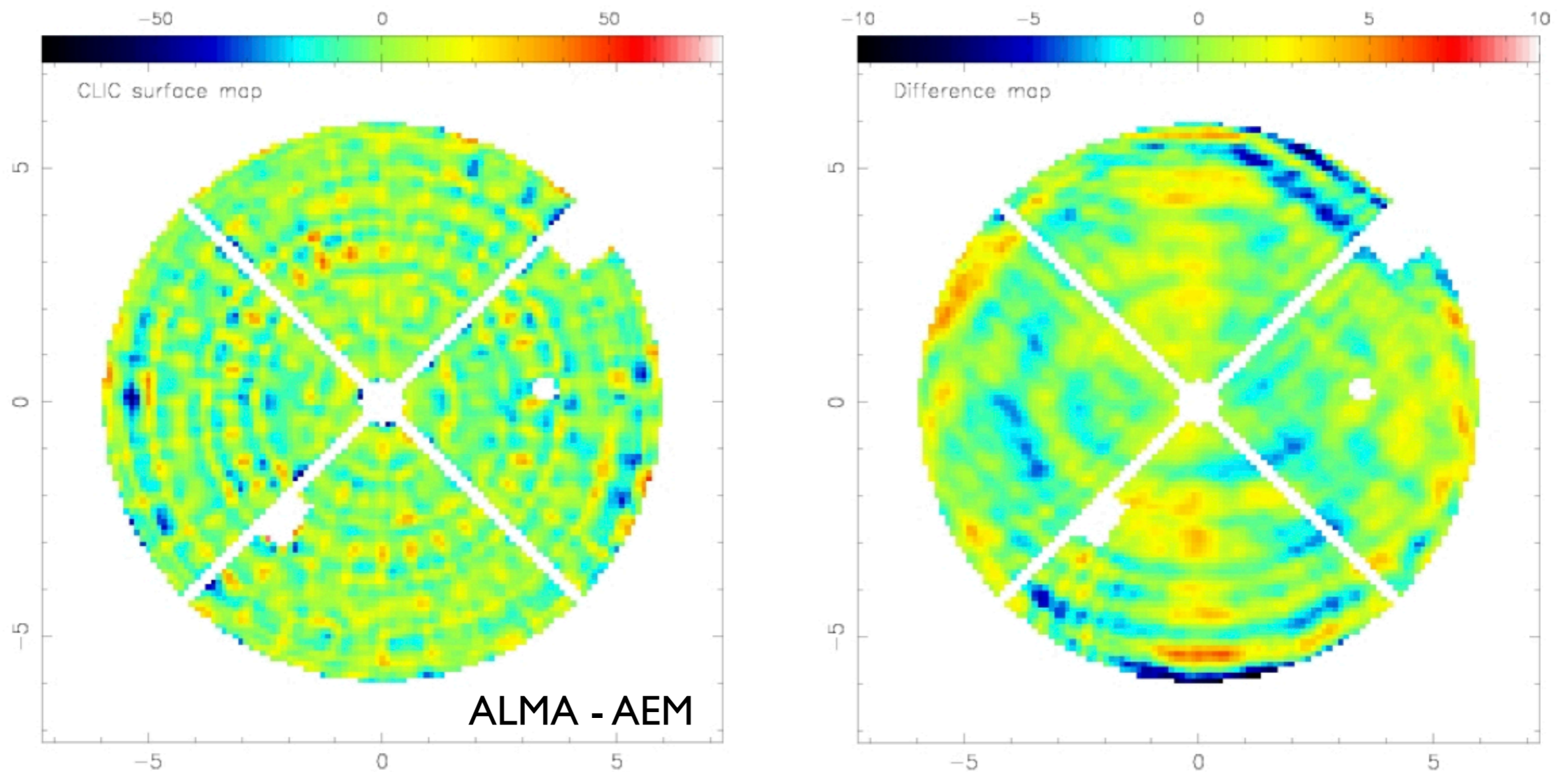


Left: the surface in Sep. 2000 with an rms of 56 μm with an error of less than 10 μm , measured with ITALSAT. Resolution 14 cm, intensity scale 240 μm pp.

A systematic “buckling” of the panel frames is visible along with small-scale internal panel errors. The panel-frames, as fabricated, have an rms error of 27 μm on average.

Right: the surface change between midnight and noon with the Sun at about 35° from boresight. The panel buckling is pronounced due to frame deformation. The small-scale panel errors are subtracted rather well and obviously not very sensitive to temperature change.

ALMA nearfield holography at 3 mm



Full phase system at 100 GHz with transmitter on 50 m high tower at 400 m distance.

Prime focus system with on-axis reference horn.

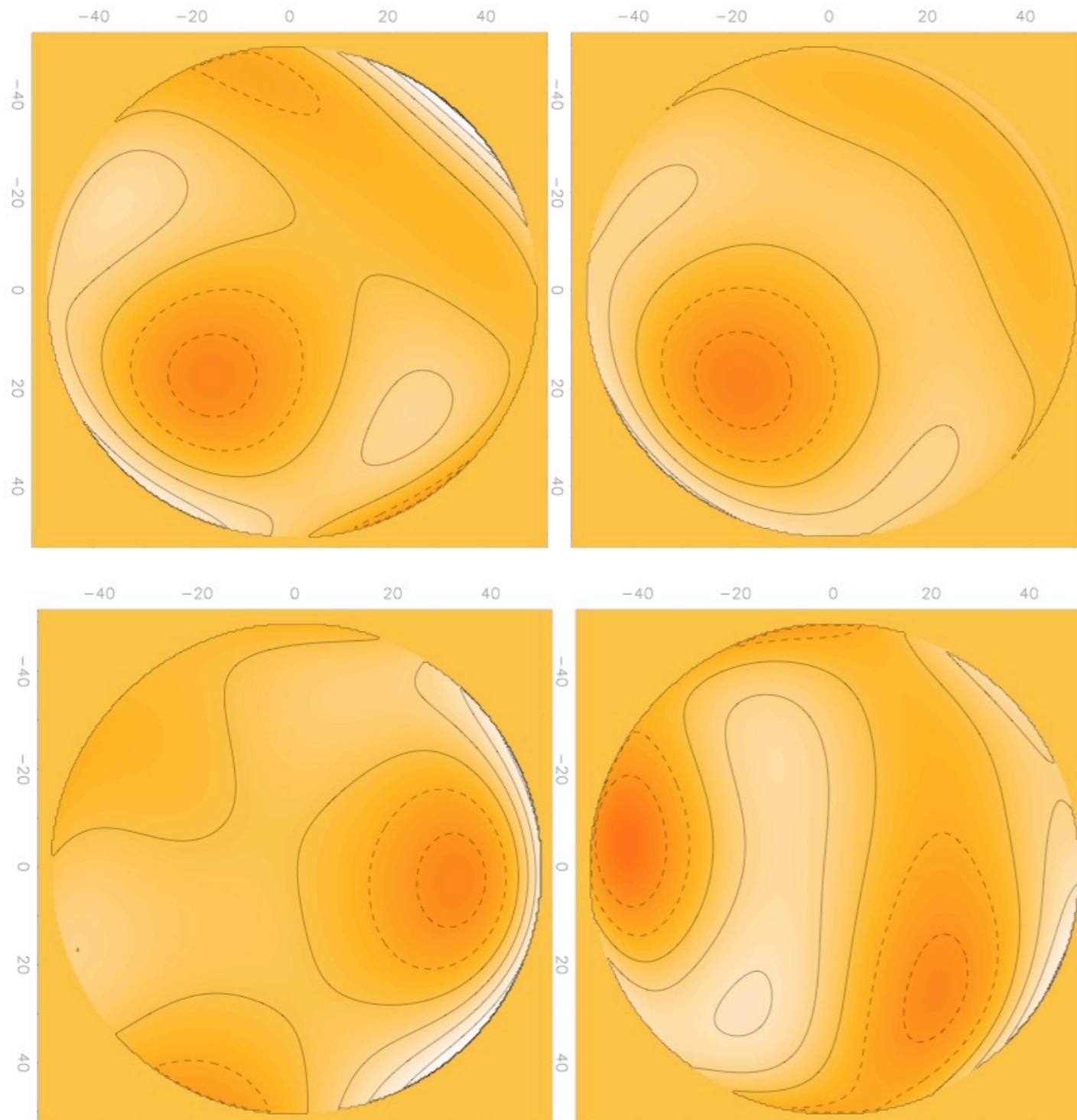
Results of the first AEM production antenna of 12 m diameter.

Left: the map after final setting of surface; surface rms is 11 μm .

Right: difference map of two consecutive measurements; the rms is only 1.6 μm .

phase retrieval (OOF) measurement at GBT

Astronomical signal source, measurement at 7 mm wavelength



Test of OOF at GBT.

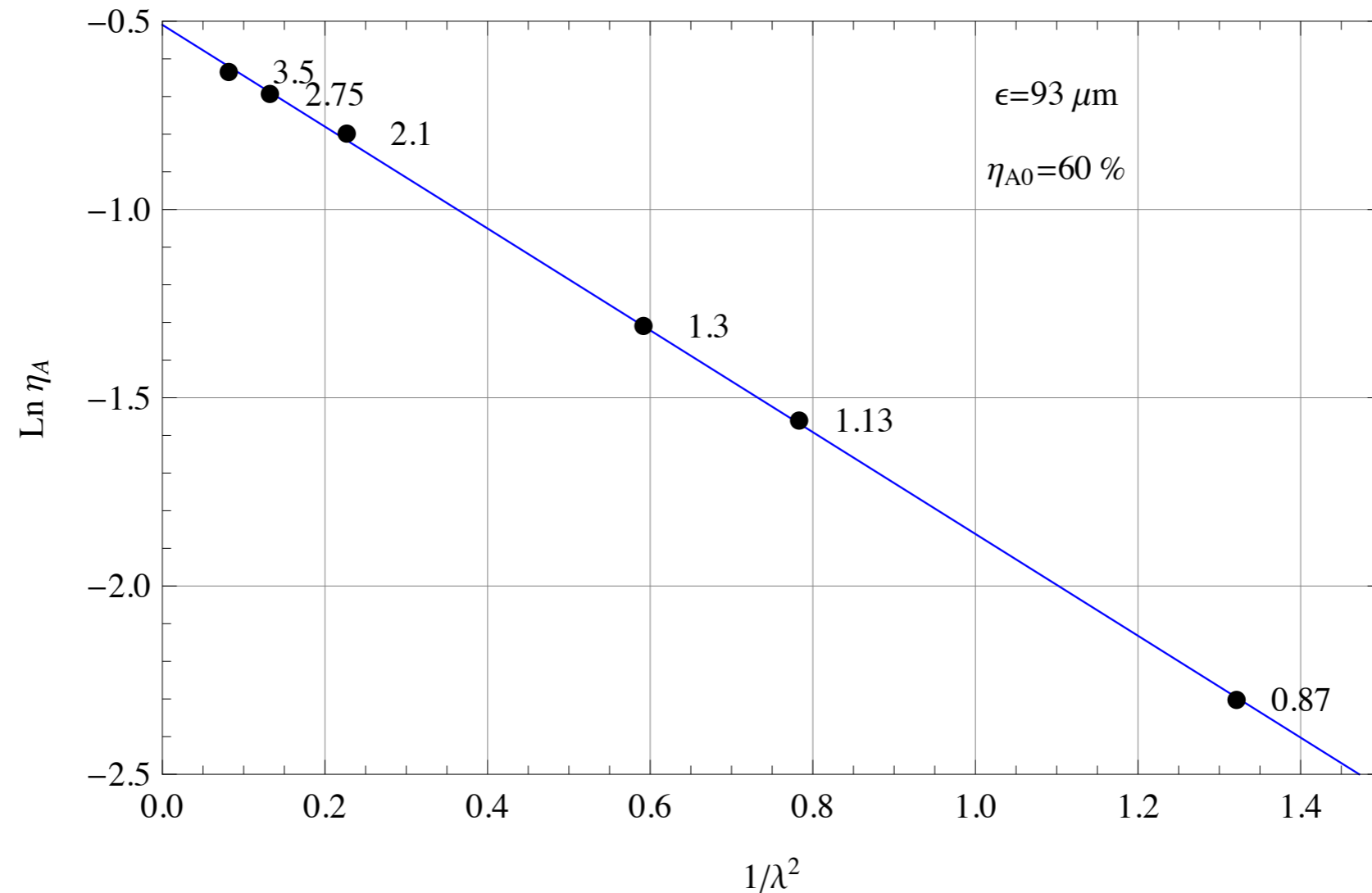
Right: error introduced in the reflector.
Left: measurement of error with OOF
contour interval 225 μm . Main feature
OK, but problems at the edges of dish.

Right: OOF measurement of GBT, rms
surface error 330 μm .

Left: after surface correction in 1 hour a
new measurement shows rms 220 μm .
Contour interval is 225 μm .

work by Nikolic, Prestage et al.

derive surface error from efficiency measurements



Application of the “Ruze-formula”. Plotted is the logarithm of measured aperture efficiency at 6 wavelengths against the reverse square of the wavelength. Data from the IRAM 30-m telescope. The slope of the best fit line delivers the rms reflector error of 93 μm . A holography measurement during this period gave 85 μm . This is consistent with flux calibrator and measurement uncertainty.

dynamical aspects: pointing and pathlength

We now move to the problem of pointing and pathlength variations. These can be at least as serious as reflector errors. Take, for instance, the GBT at 3 mm wavelength or ALMA at 0.3 mm and you work with a beamwidth of about 7 arcseconds. This requires a pointing precision and stability to better than 1 arcsecond.

Now, let us assume a differential warming by the Sun and a temperature difference between the two yoke arms of the ALMA antenna of 1 degree Celsius. This results in a yoke arm length difference of about 0.4 mm and a tilt of the elevation axis and hence a pointing error of about 1.5 arcsecond, which is outside the specification.

Both wind and temperature changes are time dependent and relatively fast measuring devices are needed to sample their effects and perform corrections. It is a dynamic feature, which requires a good knowledge of the structural dynamics of the antenna for any correction to succeed.

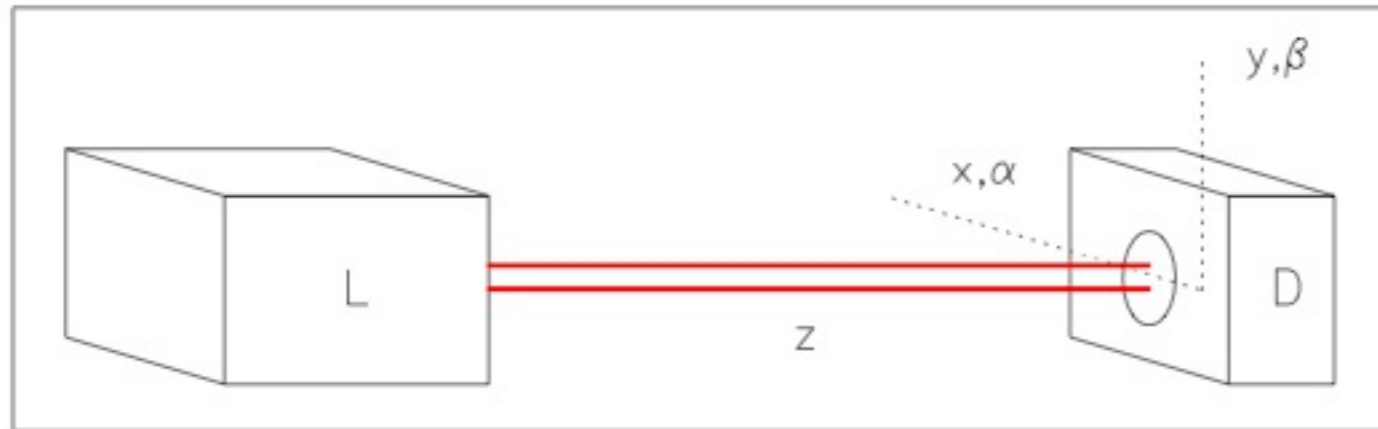
There are a number of sensors and instruments which can help in this area. Several of them have been applied for the evaluation of the ALMA antennas and I present some examples of that work to illustrate what is possible.

pointing and path length corrections

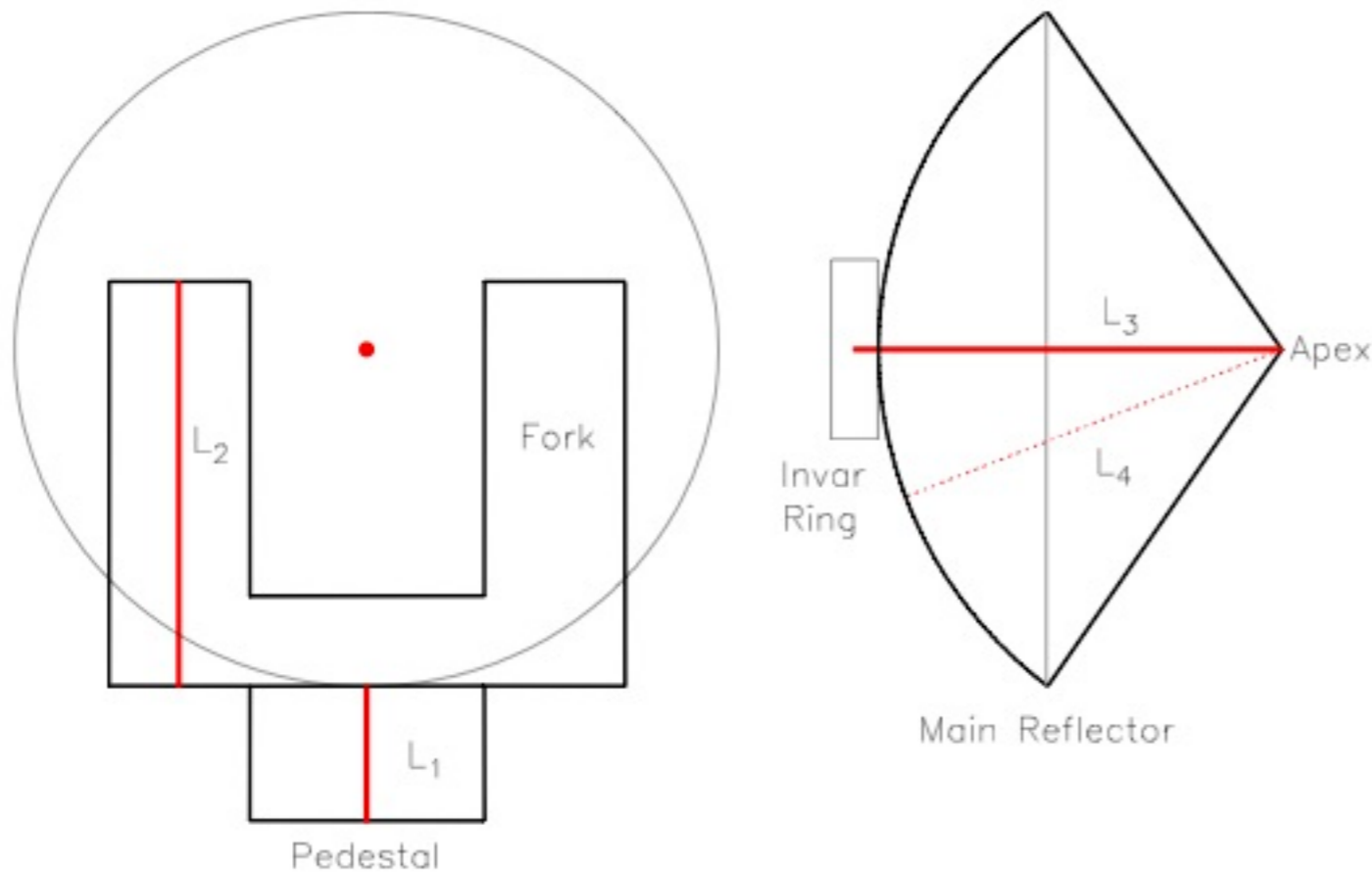
- ***Pointing precision and stability is as essential as a good reflector surface!***
- Time invariant structural effects are captured in the **pointing model**.
- Temperature variations and wind forces cause time variable pointing errors, which are not detected by the encoders. They must be determined in real time from in situ measurements to yield corrections, often via a structural model.
- ***Interferometers require constant/known pathlength in the structure.***
- Inclinator (tilt meter) measures bending, for instance due to wind
- Laser ranger - AIP 5D measures length and angle changes
- CFRP metering rod with displacement sensor measures length changes
- Accelerometer and strain gauges on relevant structural elements provides info on dynamic effects. With structural model corrections can be determined
- ***Most of these have been tried at ALMA antennas and several are routinely used.***

pathlength measurements with api-5d

The Automated Precision Inc. 5 DOF instrument was used for pathlength measurements within the structure of the ALMA antenna.

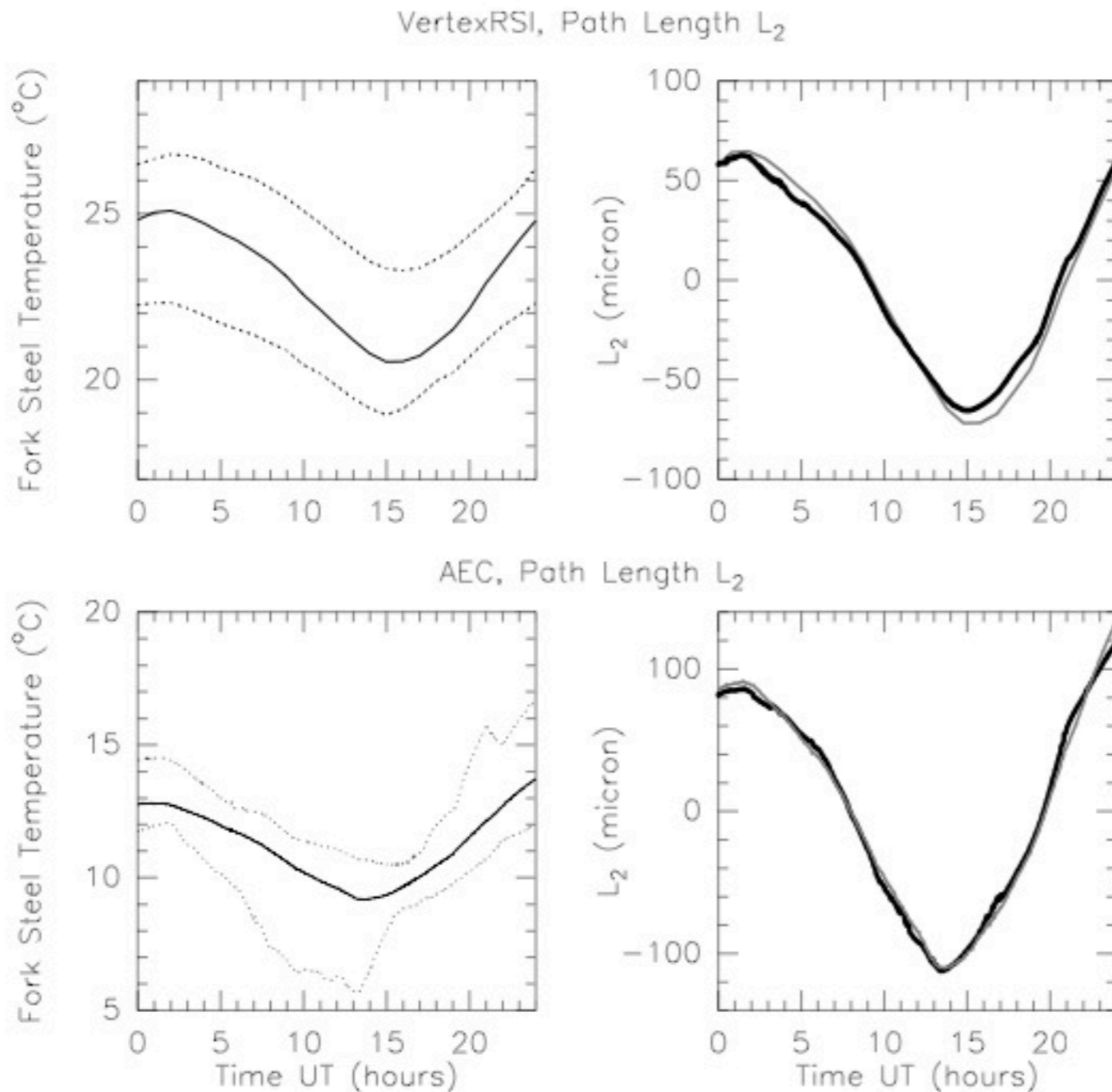


Capabilities of the API 5D machine:
distance z (laser interferometer), x, y - lateral shift, α, β - rotation



Measured parameter changes:
 L_1 - height of the antenna pedestal
 L_2 - length and angle of fork arm
 L_3 - Apex position w.r.t. reflector base

pathlength change in yoke arm with temperature



L₂ measurements on two ALMA prototype antennas.
upper frames Vertex antenna,
lower frames - Alcatel-EIE antenna

Left: yoke arm temperature with time measured at 14 points; average is thick line, thin lines show extremes.

Right: thick line - measured pathlength change with API.

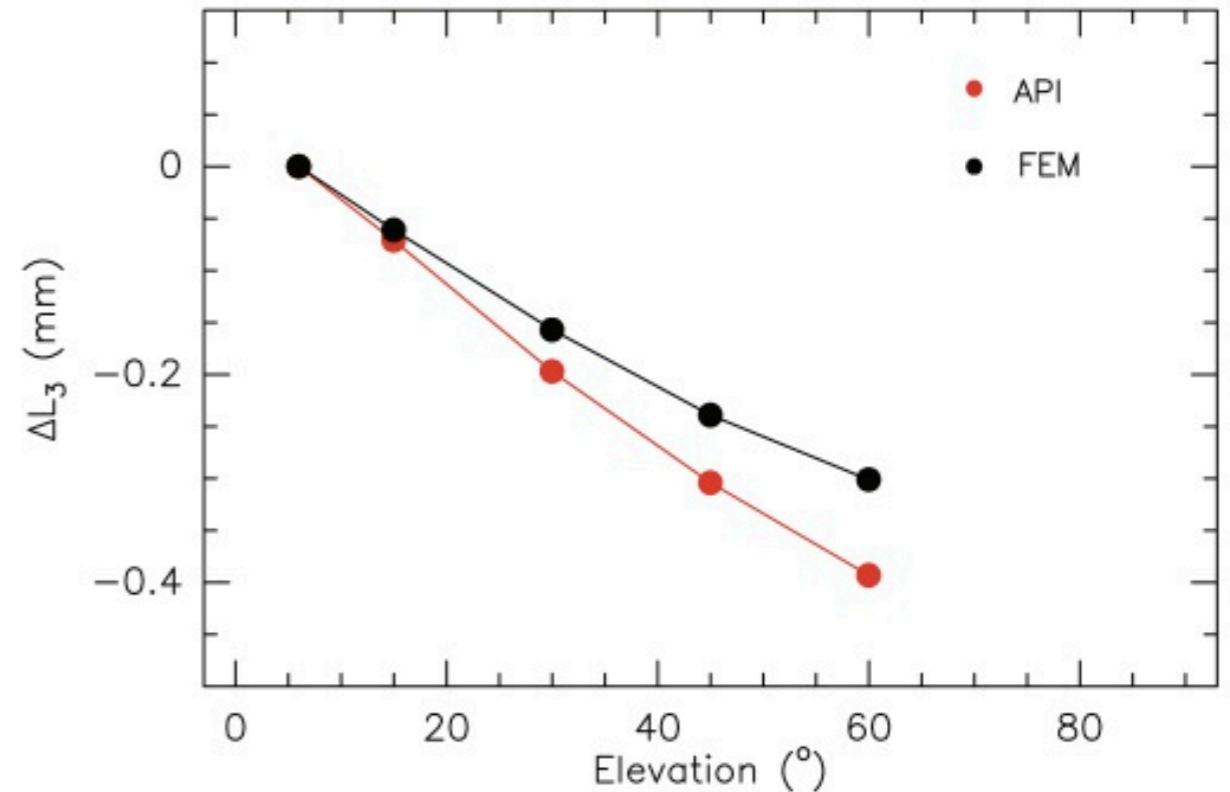
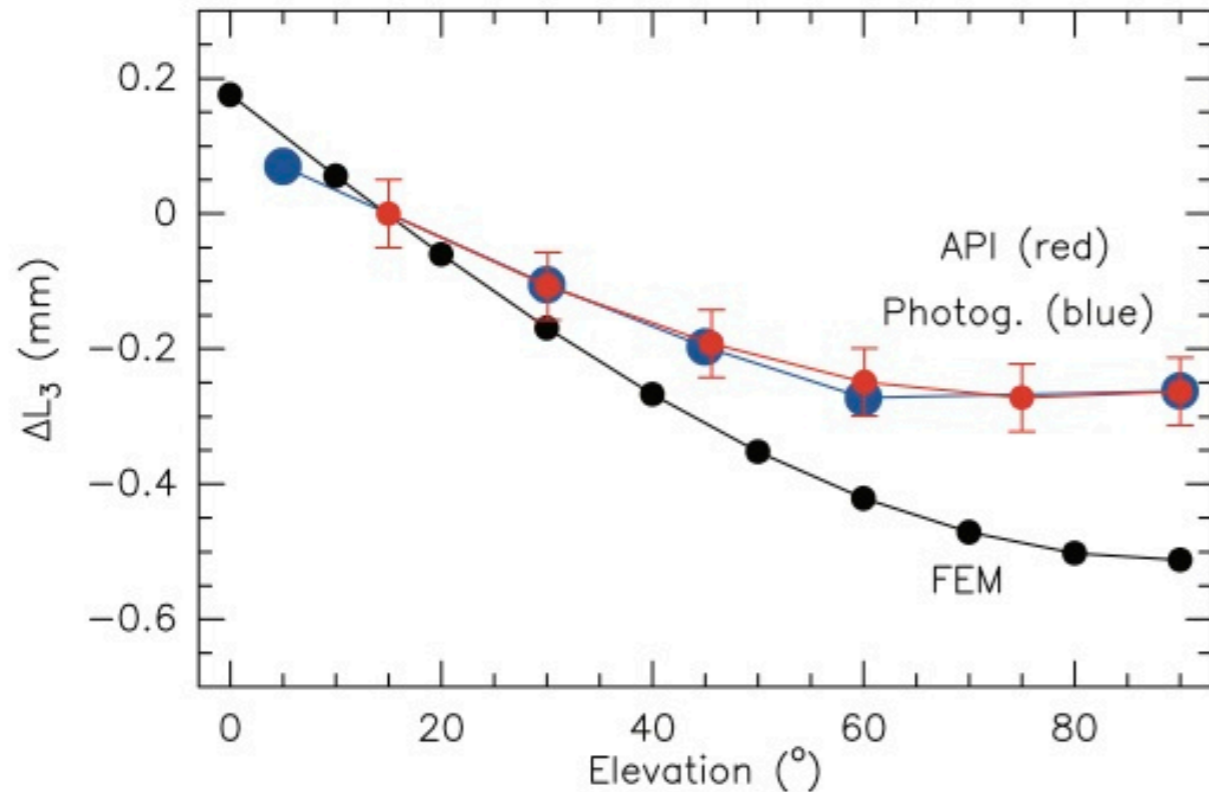
thin line - path change computed from FEM due to temperature change.

Conclusion: temperature measurement allows for good correction of pathlength

Work by Greve and Mangum

Data from a strategically placed network of temperature sensors in the backup structure can be input to the FEM and deliver the corrections to the panel adjustors in real time. This is routinely done at the GBT and the LMT in Mexico.

Change in L3 (“focal length”) for ALMA antennas

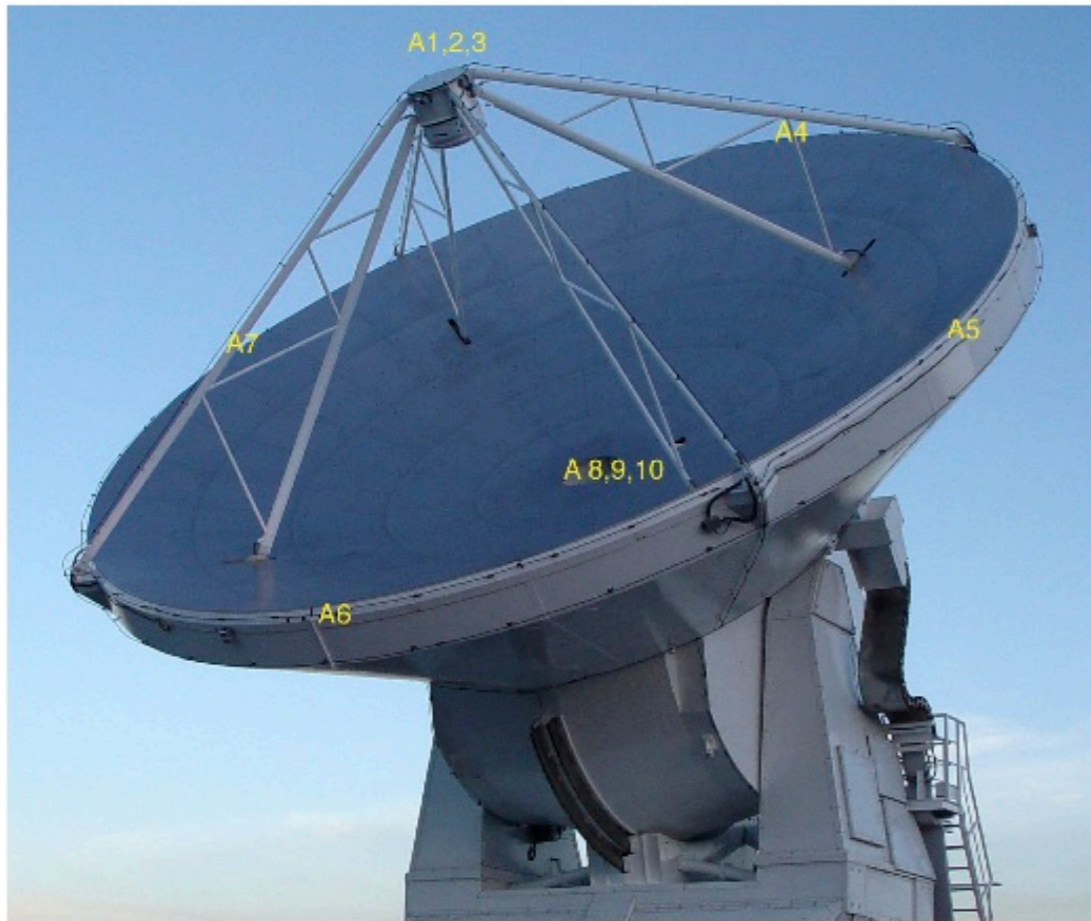


Measured change in L3 as function of elevation for both ALMA prototype antennas.
left: Vertex antenna: red dots - API direct measurement, blue dots - derived from photogrammetry measurements, black dots - FEM prediction.
right: AEC antenna: same color code (no photogrammetry data).

Observations:

1. Vertex appears somewhat “stiffer” than FEM predicts
2. AEC seems a bit “weaker” than its FEM prediction
3. From the measurements both reflector structures appear roughly equally stiff

accelerometers for study of dynamics

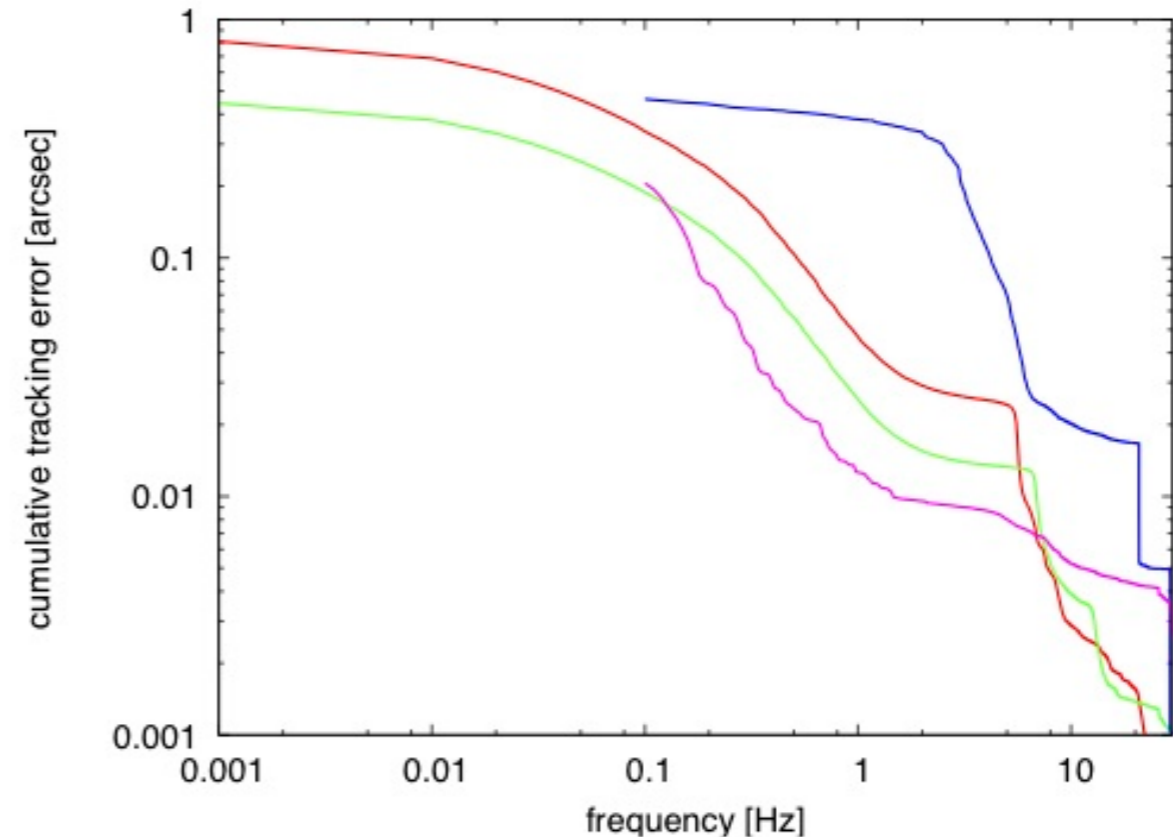


Placement of accelerometers on ALMA antenna. Three axes set in vertex and on apex structure, four on reflector rim at 90 degrees distance.

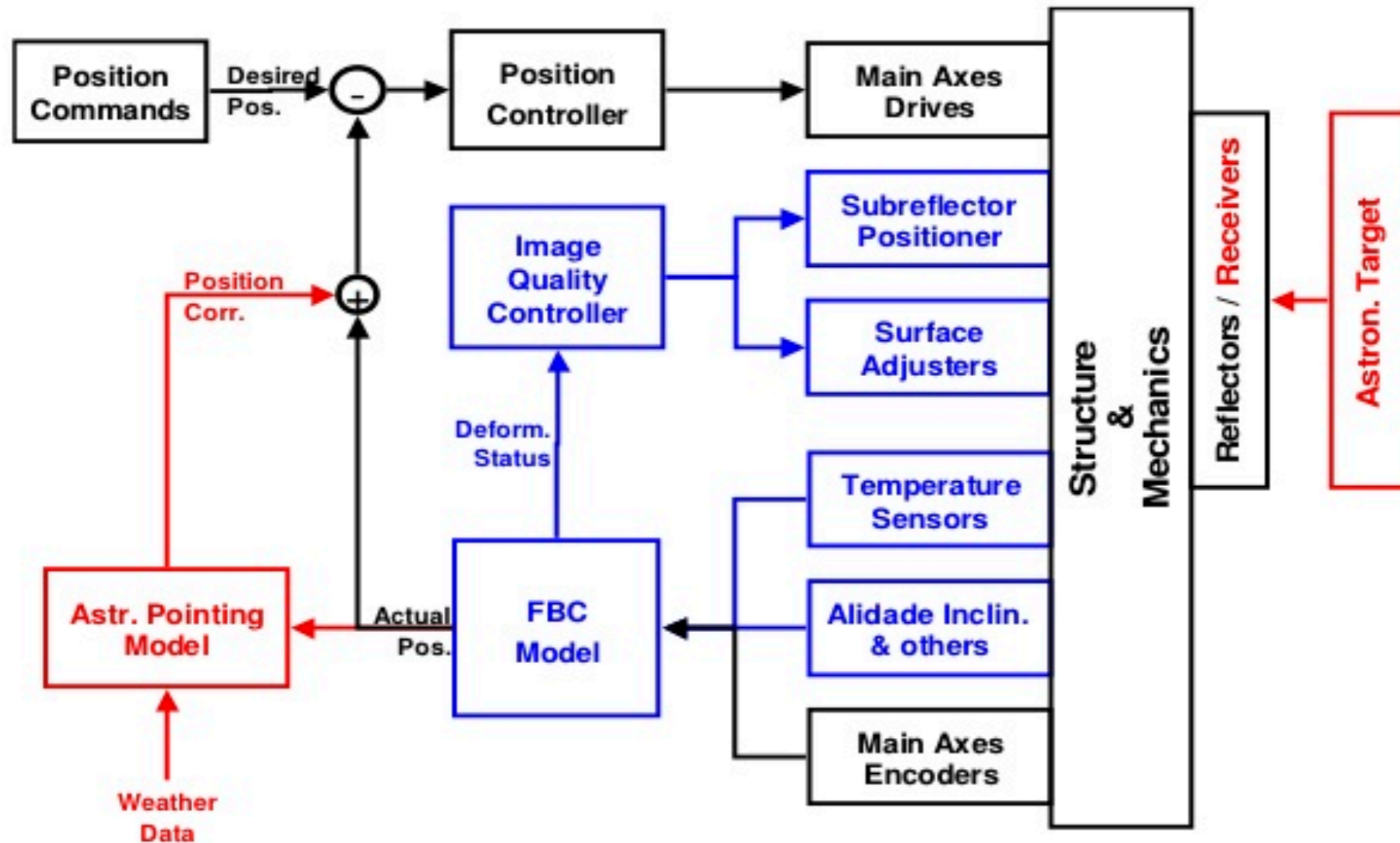
Data on dynamical behavior of pointing in elevation and cross-elevation and on defocus, pathlength and astigmatism.

Work by Ralph Snel

Wind induced pointing jitter (red-Vertex, green-AEC) and tracking jitter (blue-Vertex, magenta-AEC). Difference between blue and magenta mainly due to drive system: Vertex-gear/pinion, AEC-direct drive.



Principle of Flexible Body Compensation (FBC)



Active Optics through Flexible Body Compensation.

The FBC Model receives data from sensors on the structure (temperature, inclination or deformation) and delivers corrections to subreflector position and surface adjusters, as well as to the pointing module. (H. J. Kärcher)

Sensors and Tools for control metrology

	Sensor Type	Kind of Information	Main Application
a	Angular encoders	Relative angular position of adjacent structural components	Position control
b	Tachos	Motor velocities	
c	Current sensors	Motor torques	
d	Temperature sensors	Absolute temperature of structural components	Flexible Body Control
e	Inclinometers	Inclination of attachment flange against local gravity	
f	Laser trackers	Relative spatial position of target points	
g	Pressure sensors	Aerodynamic pressure at attachment area	
h	Strain gauges	Strain at attachment area	
i	MEMS type sensors	Any kind of available MEMS sensor technology	
j	Accelerometers	Lateral accelerations	Inertial stabilization
k	Gyroscopes	Angular accelerations	
l	Wavefront sensors	Image and position of a reference target in the focal plane	Adaptive optics
m	Weather stations	Wind speed, wind direction, mean outside temperature etc.	General

Conclusion

- Metrology is here to stay!
- “Semi-static”, slowly varying situation and environment:
- Reflector surface: holography provides accuracy of order 10 micrometer.
Thermal deformation from FEM enables real-time adjuster control.
- Pointing: basic pointing model based on “star” measurements is adequate.
Some “steady wind” pointing errors might be correctable at 10 sec interval.
ALMA uses dense net of quasars for quick “nearby” pointing checks.
- “Dynamic”, time dependent effects - temperature, wind, atmosphere
- Reflector surface: no routine correction at present. Need for fast measuring of deformation and servo-controlled actuator system. Challenging.
- Pointing, tracking, pathlength: large telescopes (in wavelengths) cannot do without. Promising developments, but routine use in earliest stages.
FBC requires a reliable, complete dynamic model of the structure.
Several types of sensors are available. [Expect more in near future.](#)