

Resolution on Modelling Gravity-Induced Deformations of the Radio Telescope Receiving Unit

Joint Working Group 1.2.2

Metrology of Space Geodetic Infrastructure

C. Eschelbach

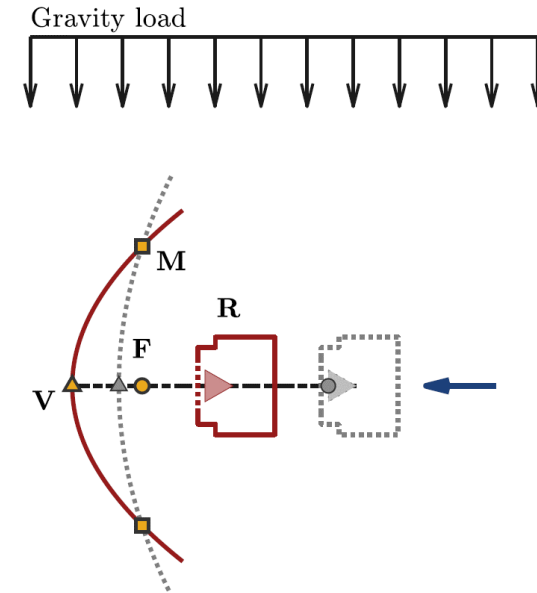
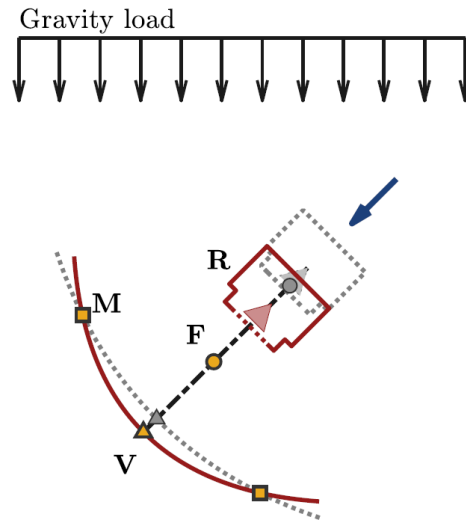
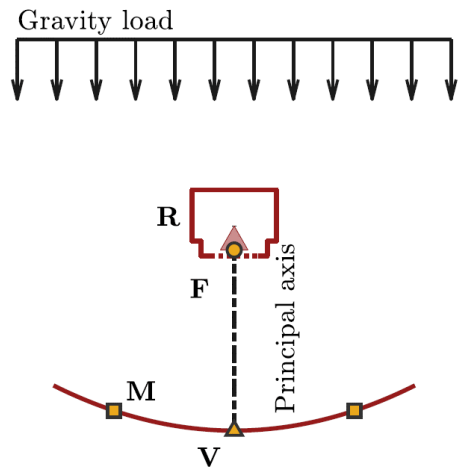
UAW | March 5th 2026



Agenda

- Introduction to Modelling Deformations of the Receiving Unit of a VLBI Radio Telescope
- State of Progress
- Discussion

Main Reflector Deformation



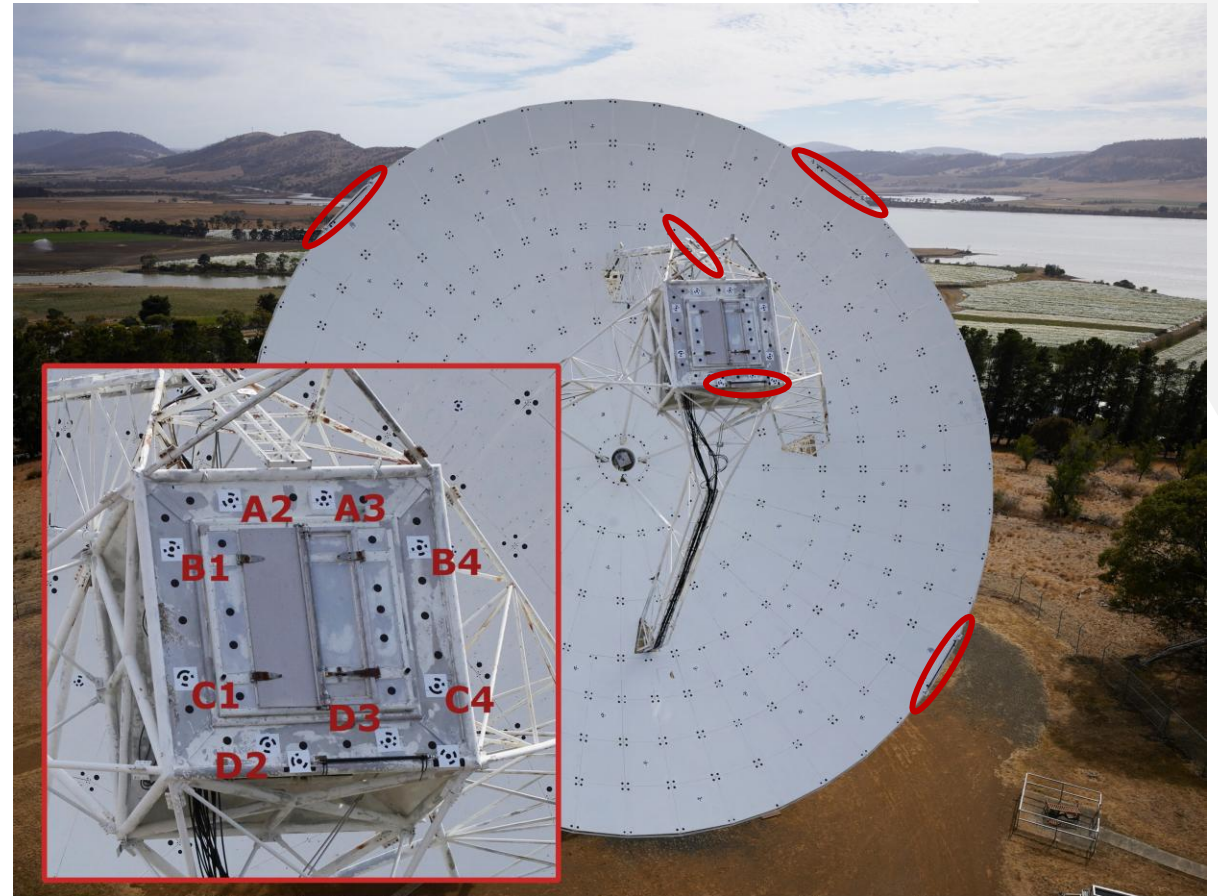
- Propagation delay by gravitational deformation of the receiving unit
- Orientation-dependent systematic deformation (**standard model 1988**)
- Consideration starts with ITRF2020
- Correction data available for **6 of approx. 150 stations**

Variations in focal length

<i>Onsala 20 m:</i>	10 mm
<i>Wettzell 20 m:</i>	10 mm
<i>Medicina 32 m:</i>	25 mm
<i>Effelsberg 100 m:</i>	15 mm

26 m Radio Telescope Hobart

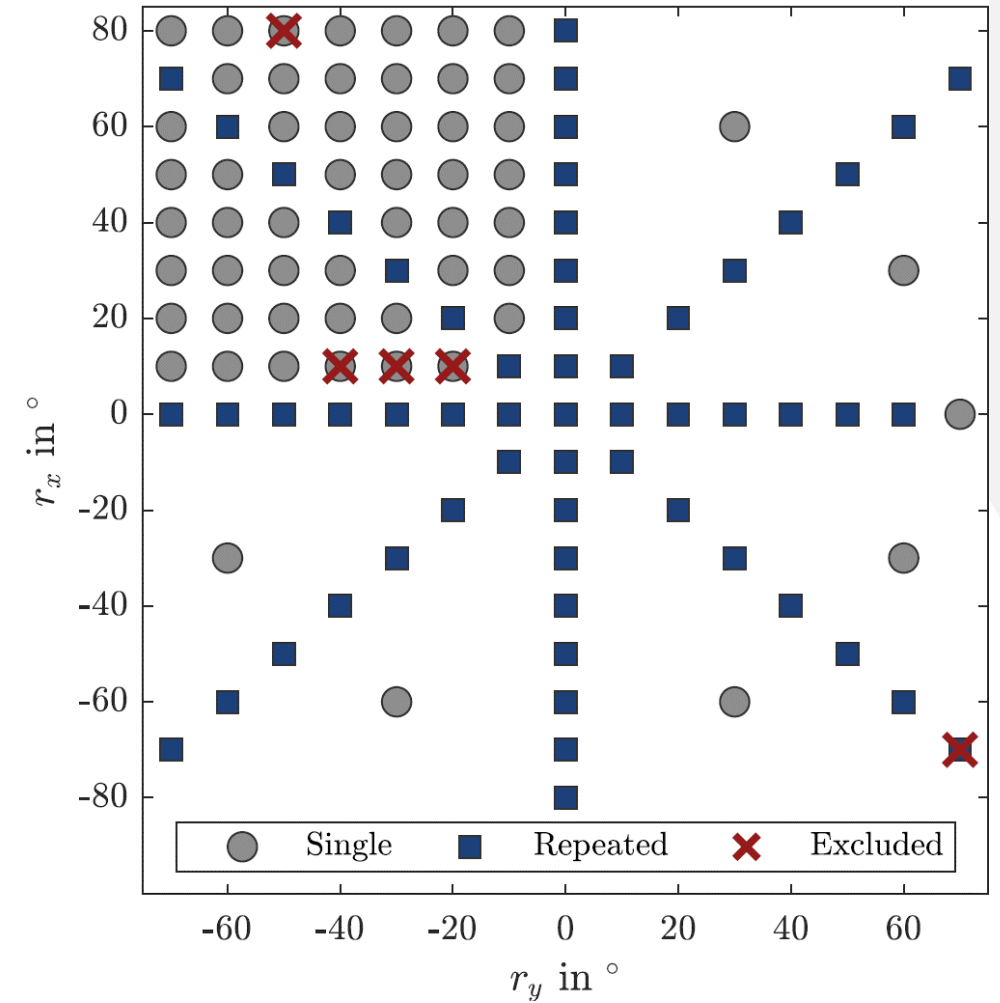
- NASA telescope from the Apollo program
- XY mount instead of azimuth/elevation
- Parabolic main reflector with 252 panels
- Each Panel with four uncoded circular markers
- Additionally, markers on the receiver box
- 60 coded photogrammetric circular markers
- Six scalebars (1.3 m and 2.3 m)



Drone flights for Data Acquisition

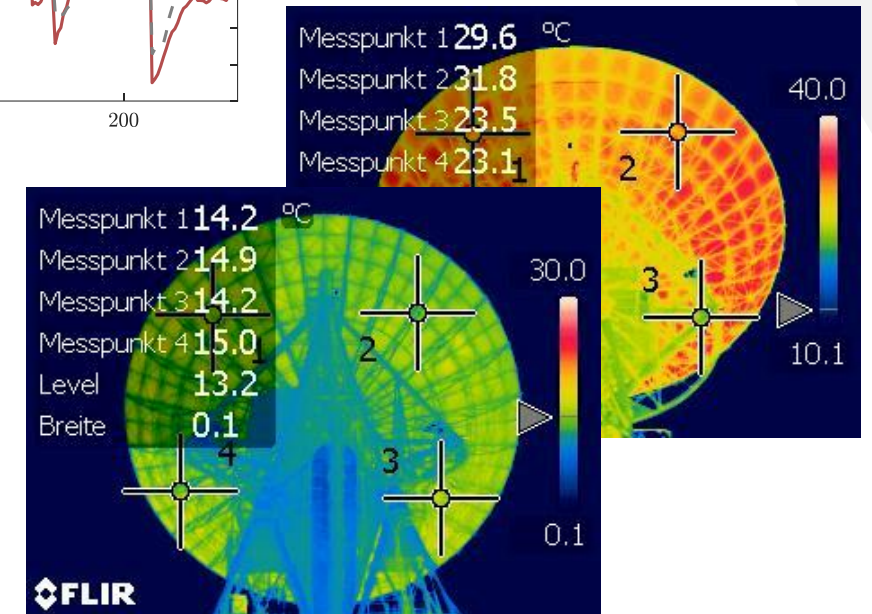
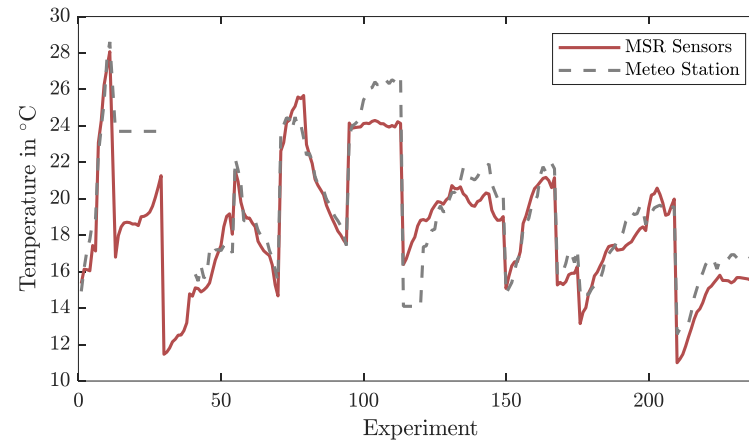


- PhaseOne iXM (35 mm lens) carried by DJI M350
- 114 configurations (230 single flights)
- Pre-analysis via AICON 3D Studio
- Bundle adjustment via in-house solution JAiCov



Temperature

- Meteorological station at the observatory
- Continuous temperature measurement at back end structure with contact temperature sensors (4 x)
- Real-time monitoring using a thermal camera
- Reference temperature 13.2 °C
- Temperature compensation during bundle adjustment



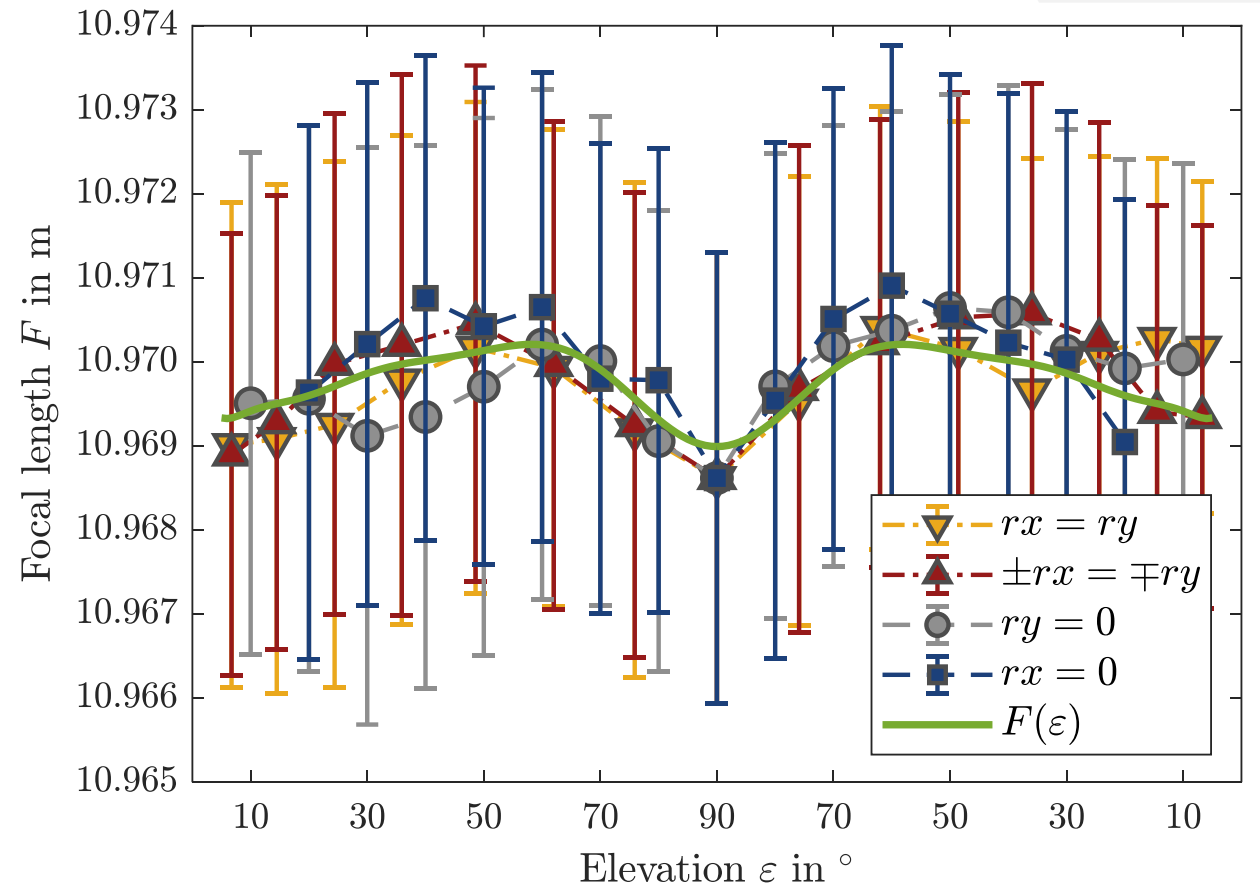
Paraboloid

- Input data from bundle adjustment
 - Surface points
 - Fully populated dispersion matrix

- Rotationally symmetric paraboloid

$$\mathcal{P}: 0 = \frac{x^2 + y^2}{4F} - z$$

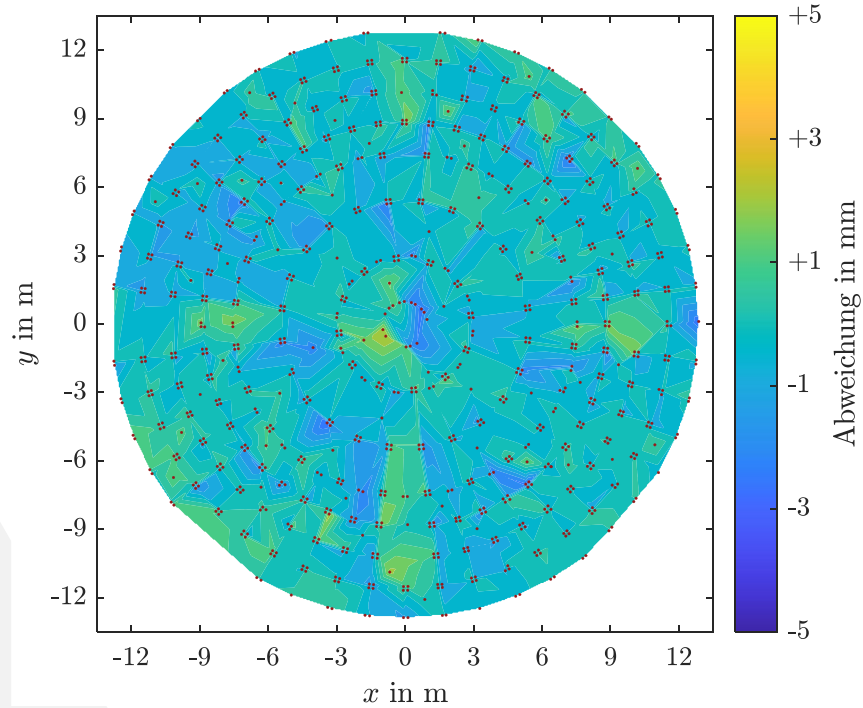
- Small variation in focal length
 $\Delta F \approx 1.5 \text{ mm}$



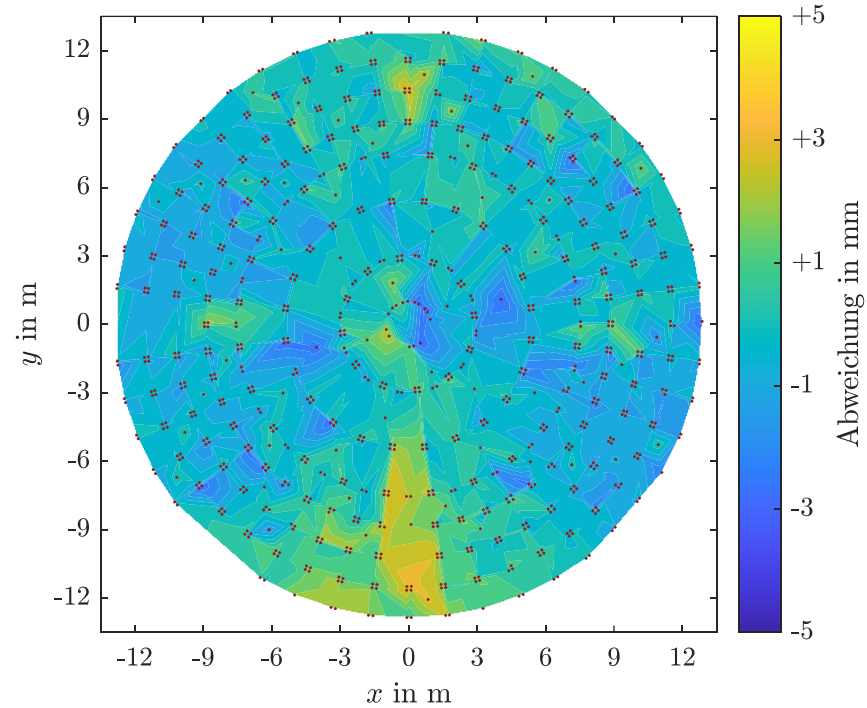
Paraboloid

- Orientation depending systematic deviations in the shape

Elevation $\varepsilon = 90^\circ$



Elevation $\varepsilon \approx 4^\circ$



Zernike Polynomials

- Aberrations of lenses with circular apertures (optics)

$$Z: 0 = \sum_{(n,m) \in \mathcal{S}} c_n^m Z_n^m(\rho, \varphi) - z$$

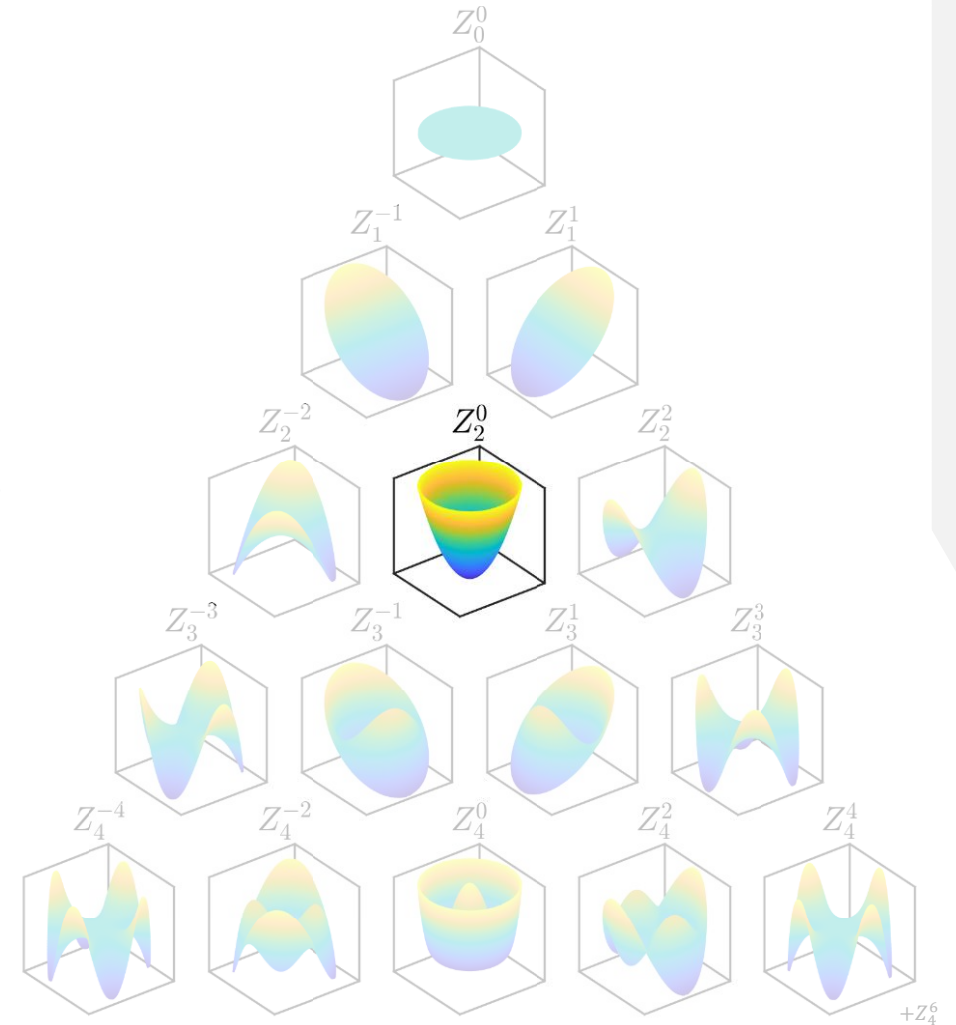
- Even Zernike polynomials $Z_n^{+m}(\rho, \varphi) = R_n^m(\rho) \cos(m\varphi)$

- Odd Zernike polynomials $Z_n^{-m}(\rho, \varphi) = R_n^m(\rho) \sin(m\varphi)$

- Radial polynomials

$$R_n^m(\rho) = \sum_{k=0}^{\frac{(n-m)}{2}} \frac{(-1)^k (n-k)!}{k! \left(\frac{(n+m)}{2} - k\right)! \left(\frac{(n-m)}{2} - k\right)!} \rho^{n-2k}$$

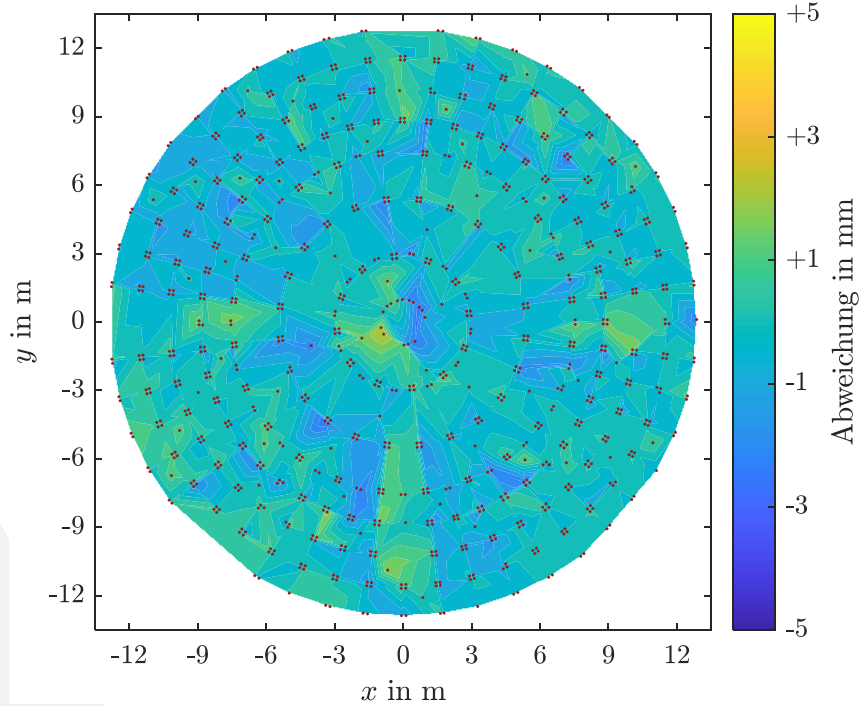
- Index set $\mathcal{S}_{\mathcal{P}} = \{(2, 0)\}$ corresponds to the paraboloid



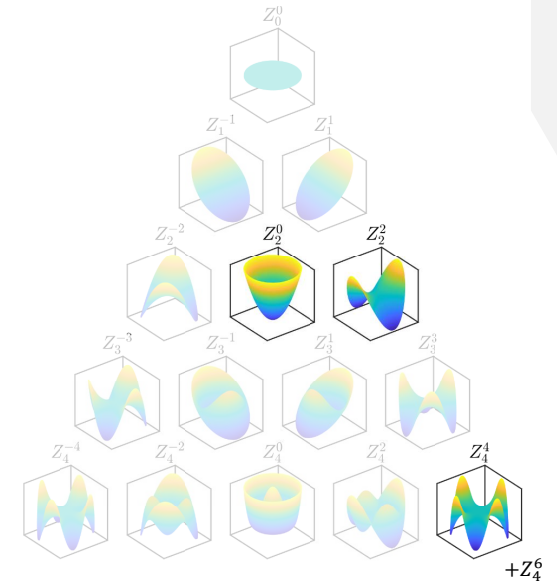
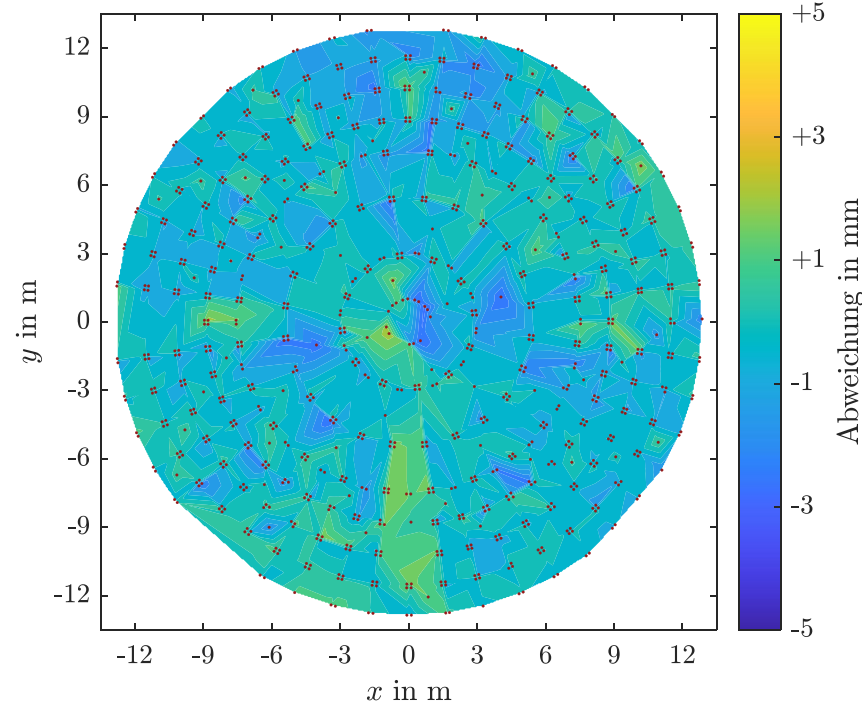
Zernike Polynomials

- Deviations in the shape for $\mathcal{S}_Z = \{(2, 0), (2, 2), (4, 4), (6, 4)\}$

Elevation $\varepsilon = 90^\circ$



Elevation $\varepsilon \approx 4^\circ$

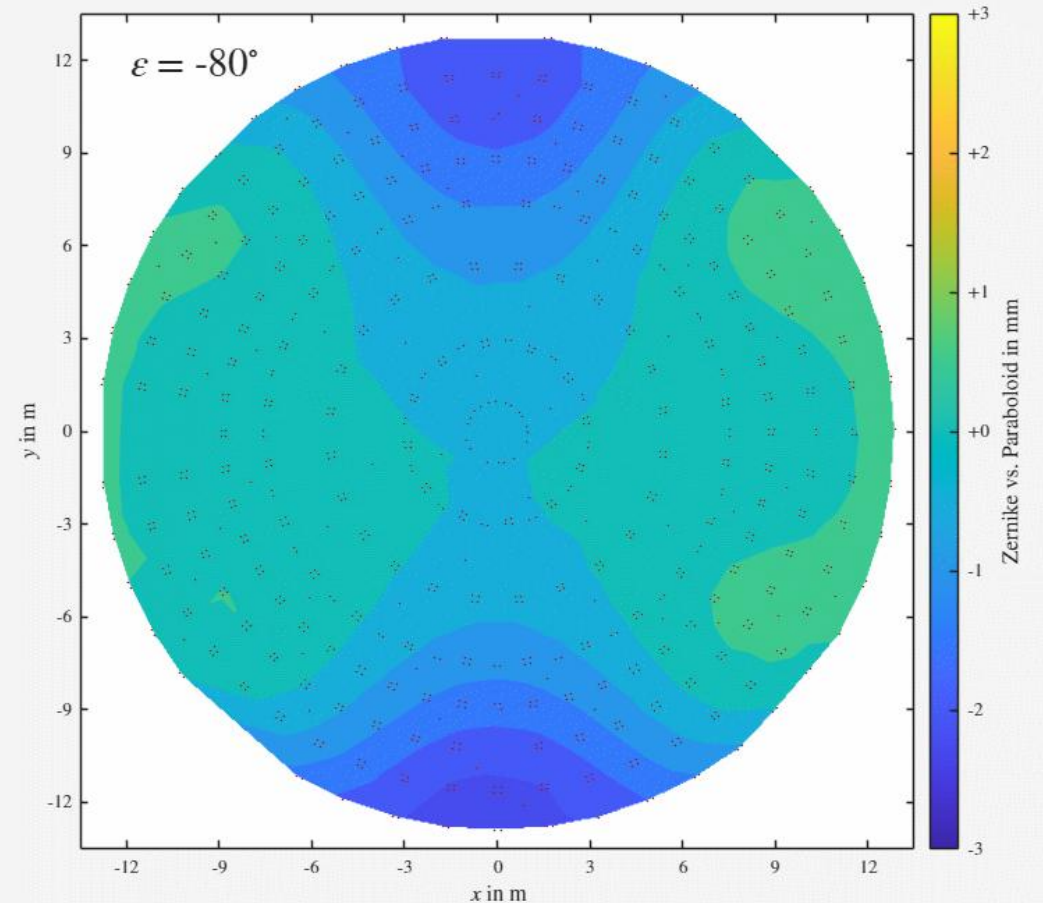
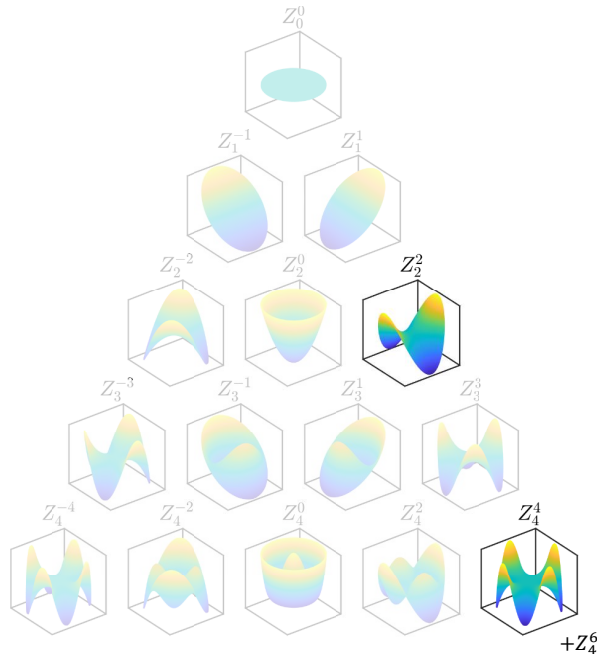


Paraboloid vs. Zernike Polynomials

Hobart26

- Deviations in the shape

$$\mathcal{S}_{\mathcal{P}} = \{(2, 0)\} \quad \text{vs.} \quad \mathcal{S}_{\mathcal{Z}} = \{(2, 0), (2, 2), (4, 4), (6, 4)\}$$

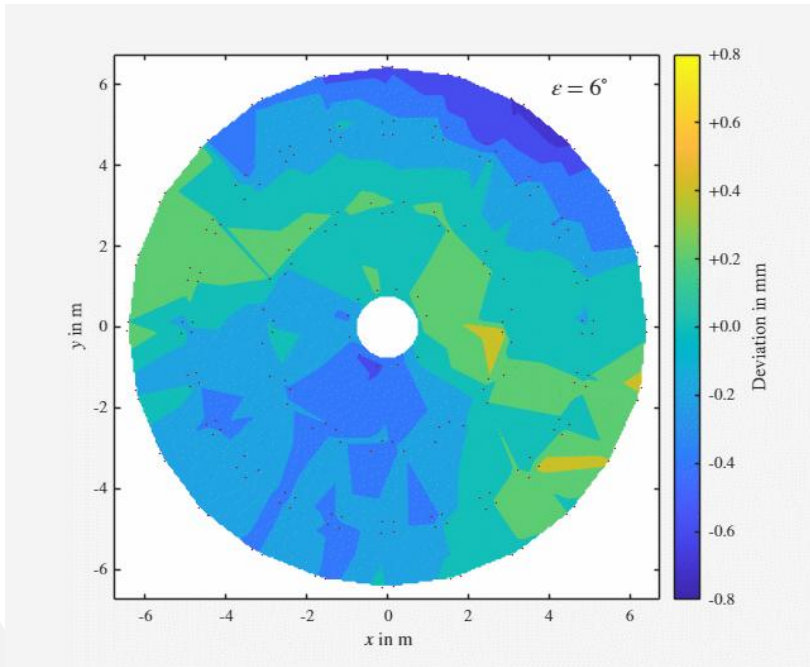


Zernike Polynomials

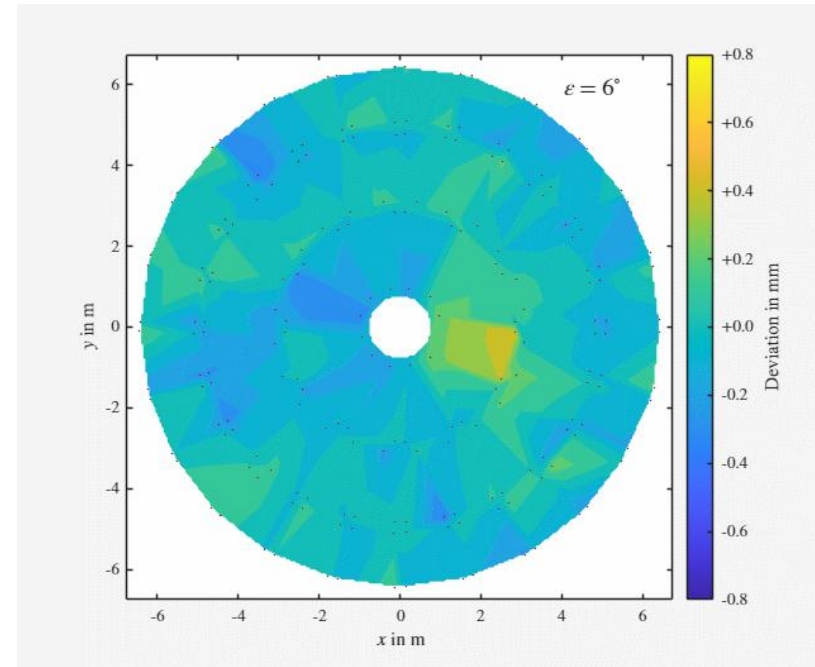
OTTW

- Preliminary deformation pattern of the *VGOS radio telescope at Onsala*

$$\mathcal{S}_Z = \{(2, 0)\}$$



$$\mathcal{S}_Z = \{(2, 0), (2, -2), (2, 2), (3, -1)\}$$



Paraboloid vs. Zernike Polynomials

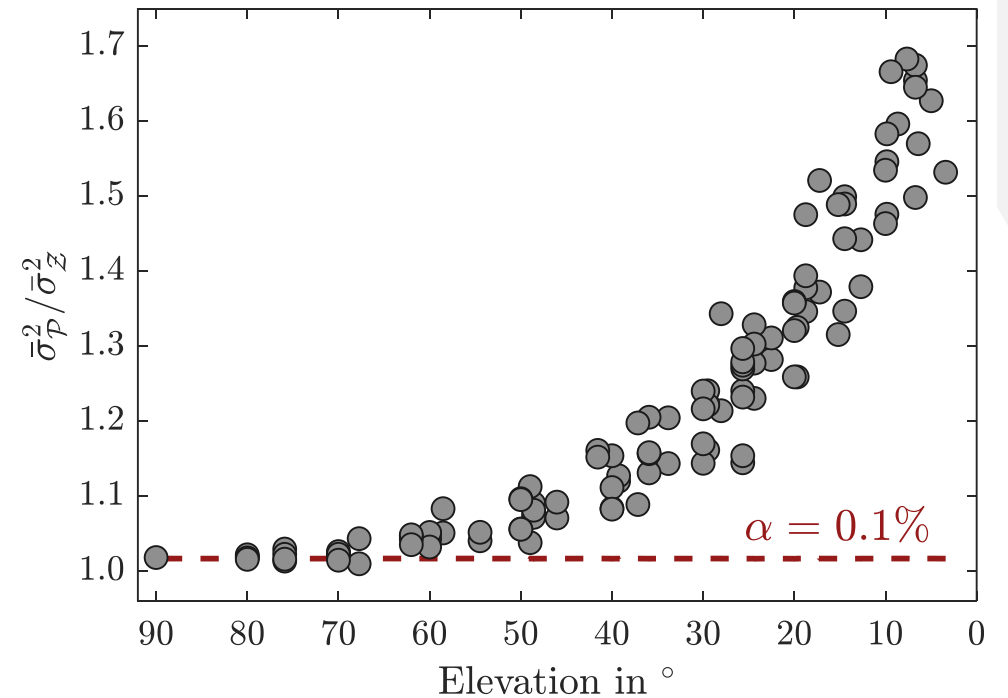
- Deviations in the shape

$$\mathcal{S}_{\mathcal{P}} = \{(2, 0)\} \quad \text{vs.} \quad \mathcal{S}_{\mathcal{Z}} = \{(2, 0), (2, 2), (4, 4), (6, 4)\}$$

- Evaluation of additional model parameters in nested models
- Likelihood ratio test for objective model evaluation

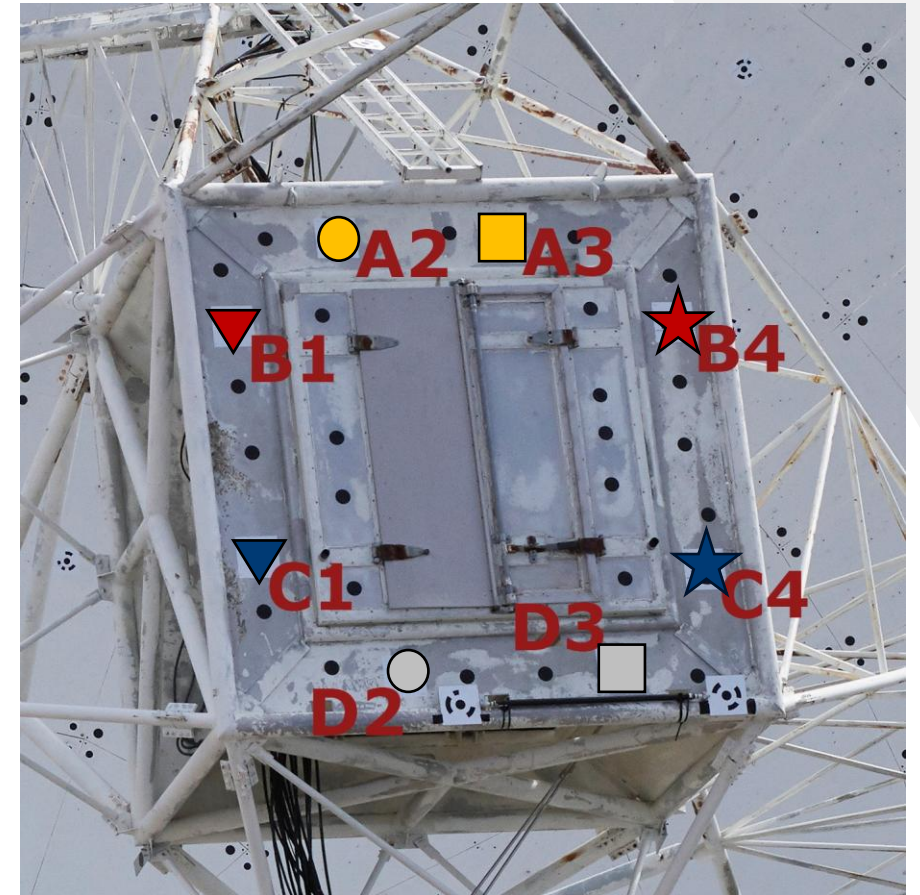
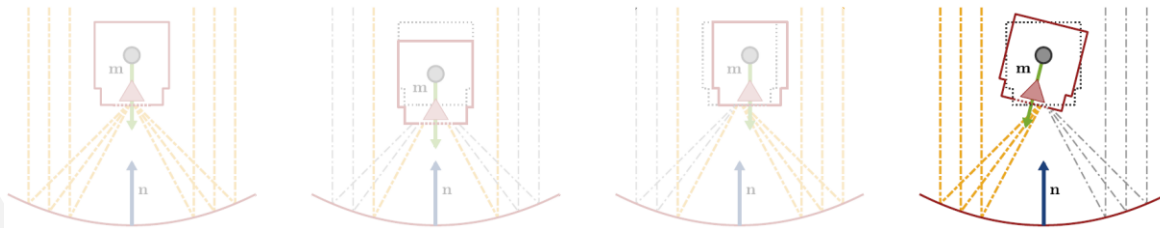
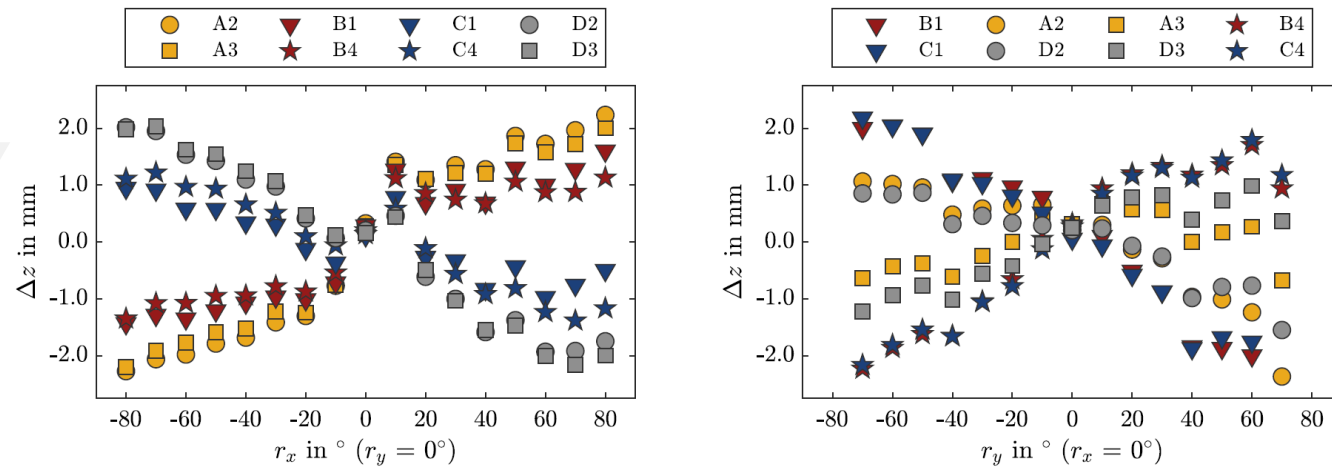
$$T = -2 \log \left(\frac{\max \mathcal{L}_{\mathcal{P}}}{\max \mathcal{L}_{\mathcal{Z}}} \right) = k \log \left(\frac{\bar{\sigma}_{\mathcal{P}}^2}{\bar{\sigma}_{\mathcal{Z}}^2} \right)$$

- Zernike-Polynomials provide more suitable surface approximation
- Highly significant for elevation angles $\varepsilon < 60^\circ$



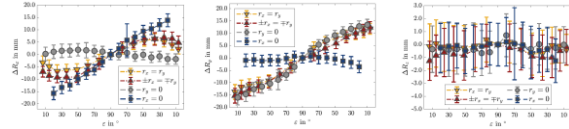
Receiver Box

- Movement patterns of the coded markers on the receiver box

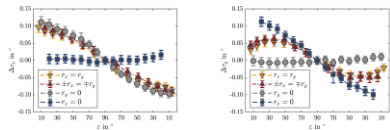


Spatial Ray Tracing

- Shift transferable from centre of gravity

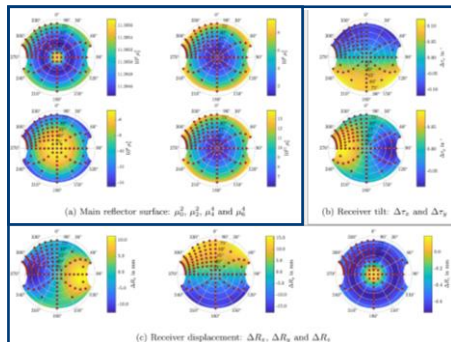


- Inclination derived from estimated planes



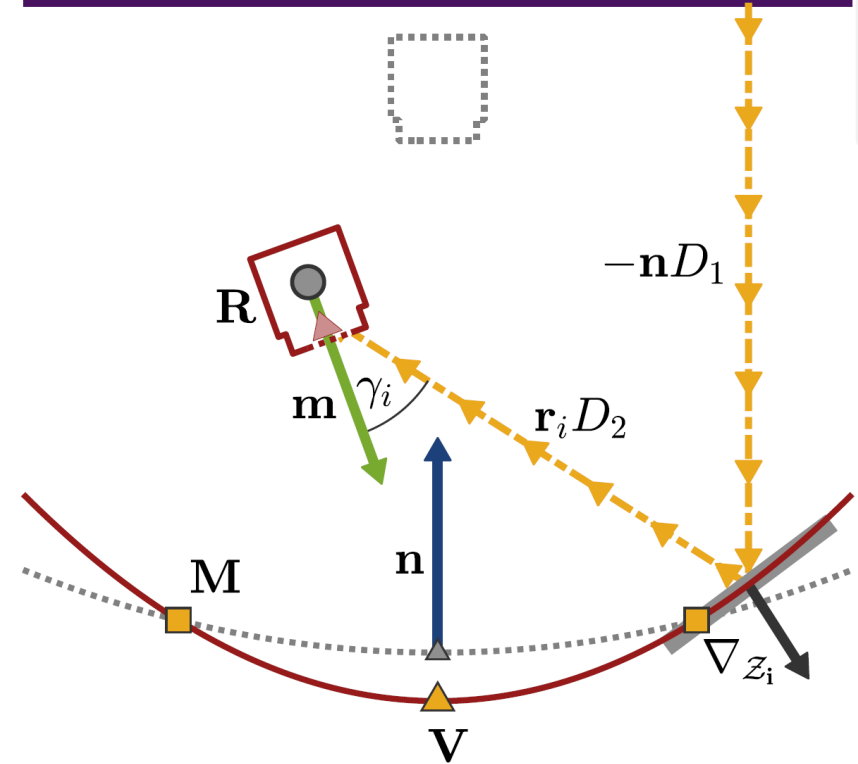
⇒ Zernike polynomials for parameterising

- surface shape



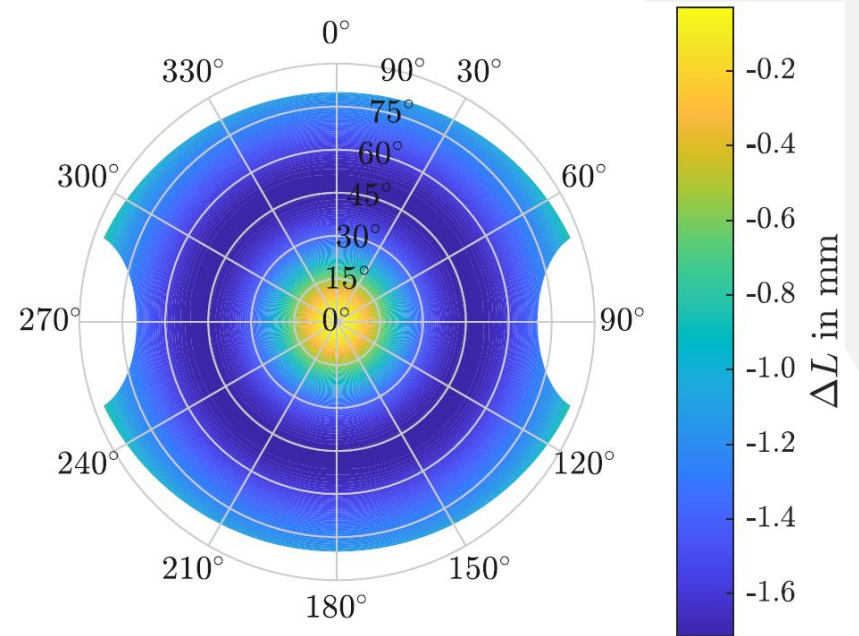
- box movement

Reference plane



Combination to Delay

- Modelling of all components of the receiving unit according to technical specifications
- Modelling of the movements of the components using Zernike polynomials
- Ray tracing within a wavefront for all telescope orientations
- Consideration of the illumination function of the feed horn
- Derivation of the orientation-dependent delay for each telescope orientation



Discussion

Latest surveying service

- Significantly detectable deformation of components of whole receiving unit
- Valid models to parametrise deformations e.g. using Zernike polynomials
- Derivation of orientation-dependent delay provided for whole working range

Status of VLBI analysis

- Only models for a rare number of telescopes and mostly only elevation-dependent
- Increasing resolution in VLBI observations, so increasing demand for more detailed models

Discussion

- Members of JWG Metrology of Space Geodetic Infrastructure
 - Theresa Pfaffinger
 - Christoph Holst
 - Michael Lösler
- Representative of stations with investigated telescopes
 - Rüdiger Haas
- IVS Analysis Coordination and Combination
 - Benedikt Soja
 - Manuela Seitz

Thank You for Your Attention

Reference

Lösler, M., Eschelbach, C., Greiwe, A., Zhou, B., McCallum, L.: Innovative approach for modelling gravity-induced signal path variations of VLBI radio telescopes. *Earth, Planets and Space*, 77(1), 9, 2025. DOI: 10.1186/s40623-024-02110-8

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