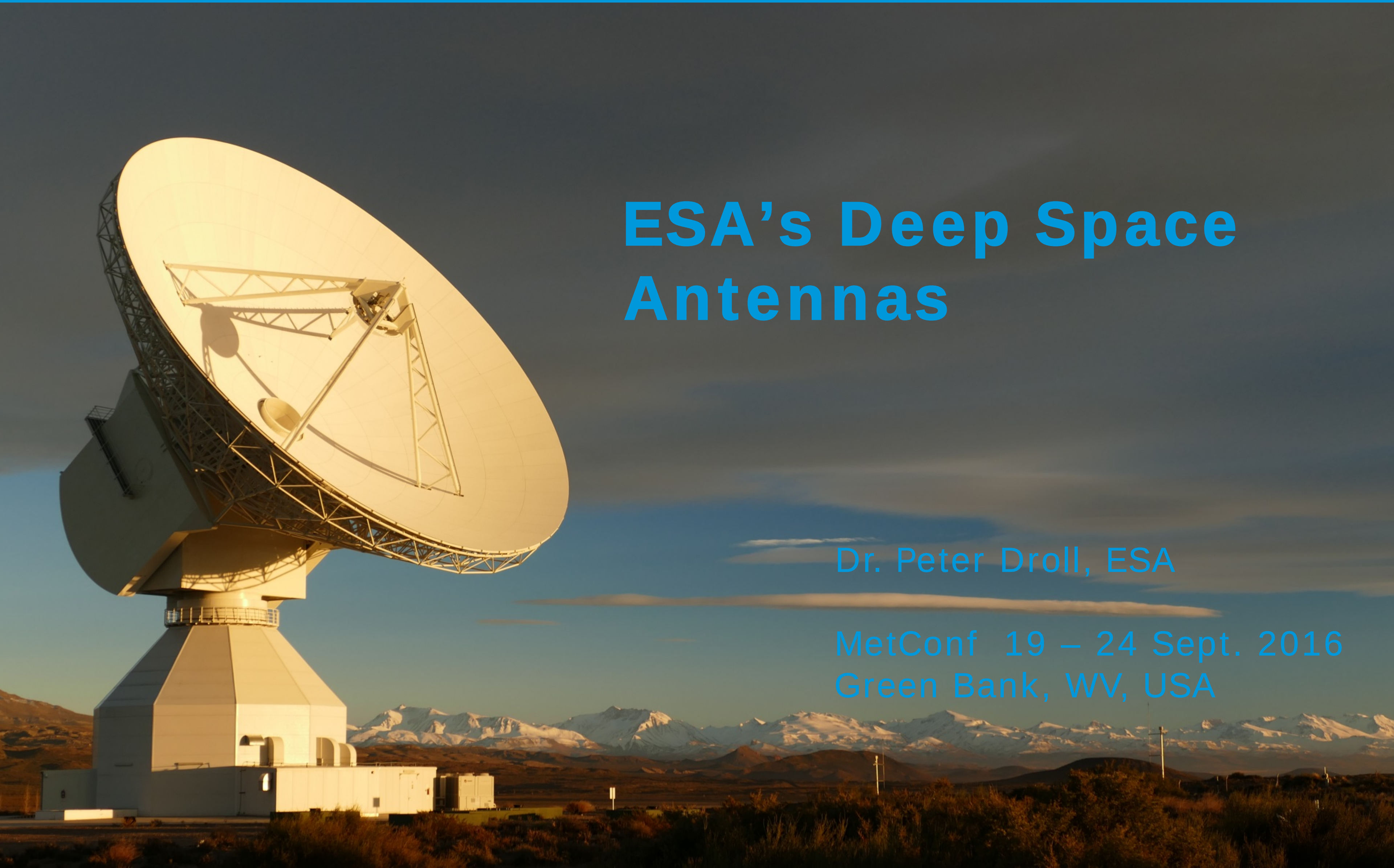
ESA's Deep Space Antennas



Dr. Peter Droll, ESA

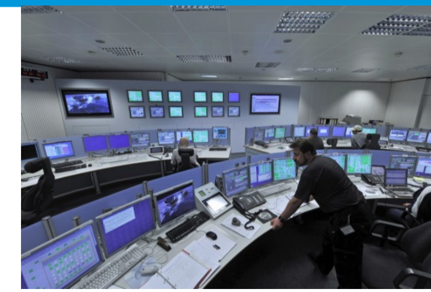
MetConf 19 – 24 Sept. 2016
Green Bank, WV, USA

Outline

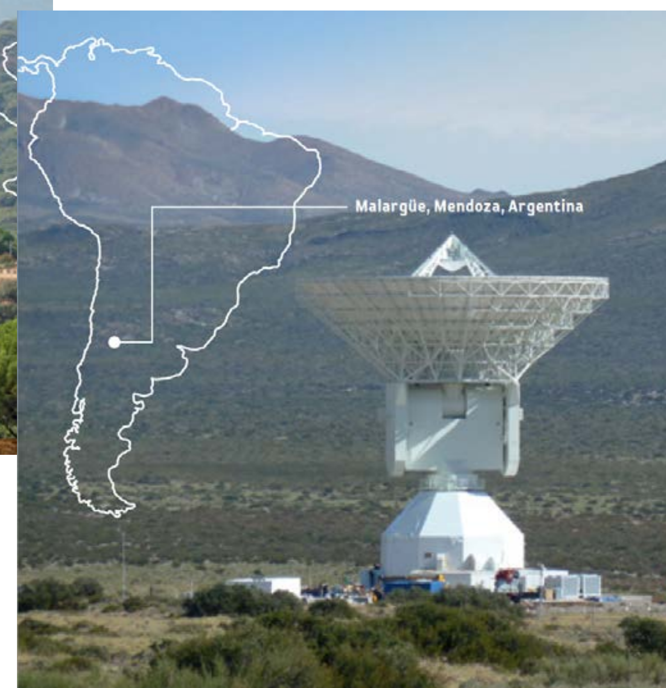
1. ESA's Deep Space Antenna Network
2. Characteristic of the 35m Beam Wave Guide Antennas
3. Pointing Error Model and Pointing Calibration System
4. Pointing Performance
5. Ka-Band Rx-Tx Beam Offset Generation and Performance

ESA's Deep Space Antenna Network

Antennas are remote controlled from control centre at ESOC, Germany



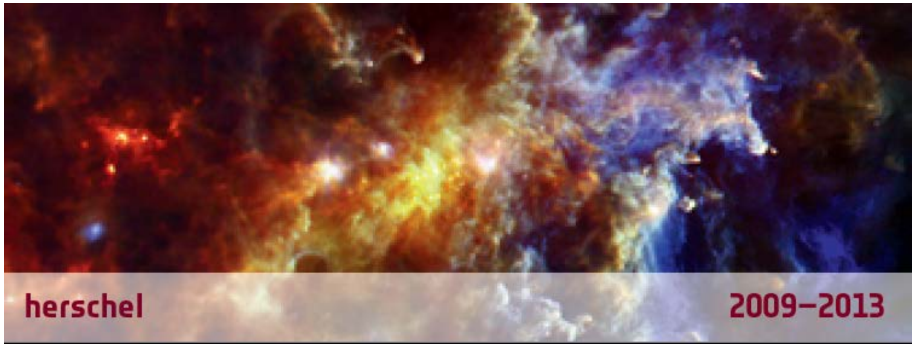
DSA2 (Malargue)
Argentina

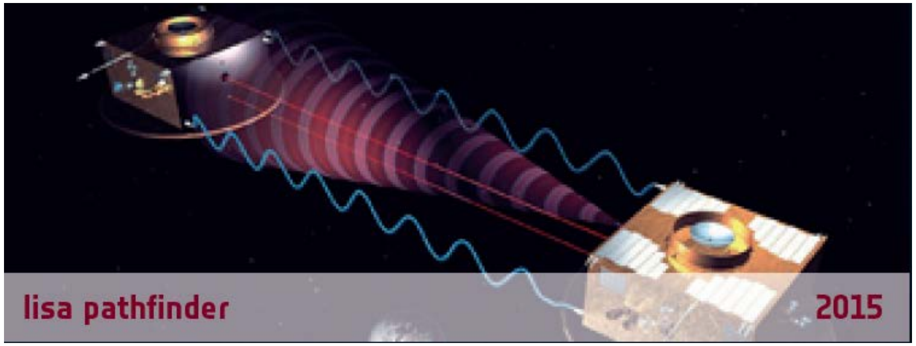


DSA1 (New Norcia)
Australia

DSA2 (Cebreros)
Spain

Missions supported by ESA's 35 m Antennas

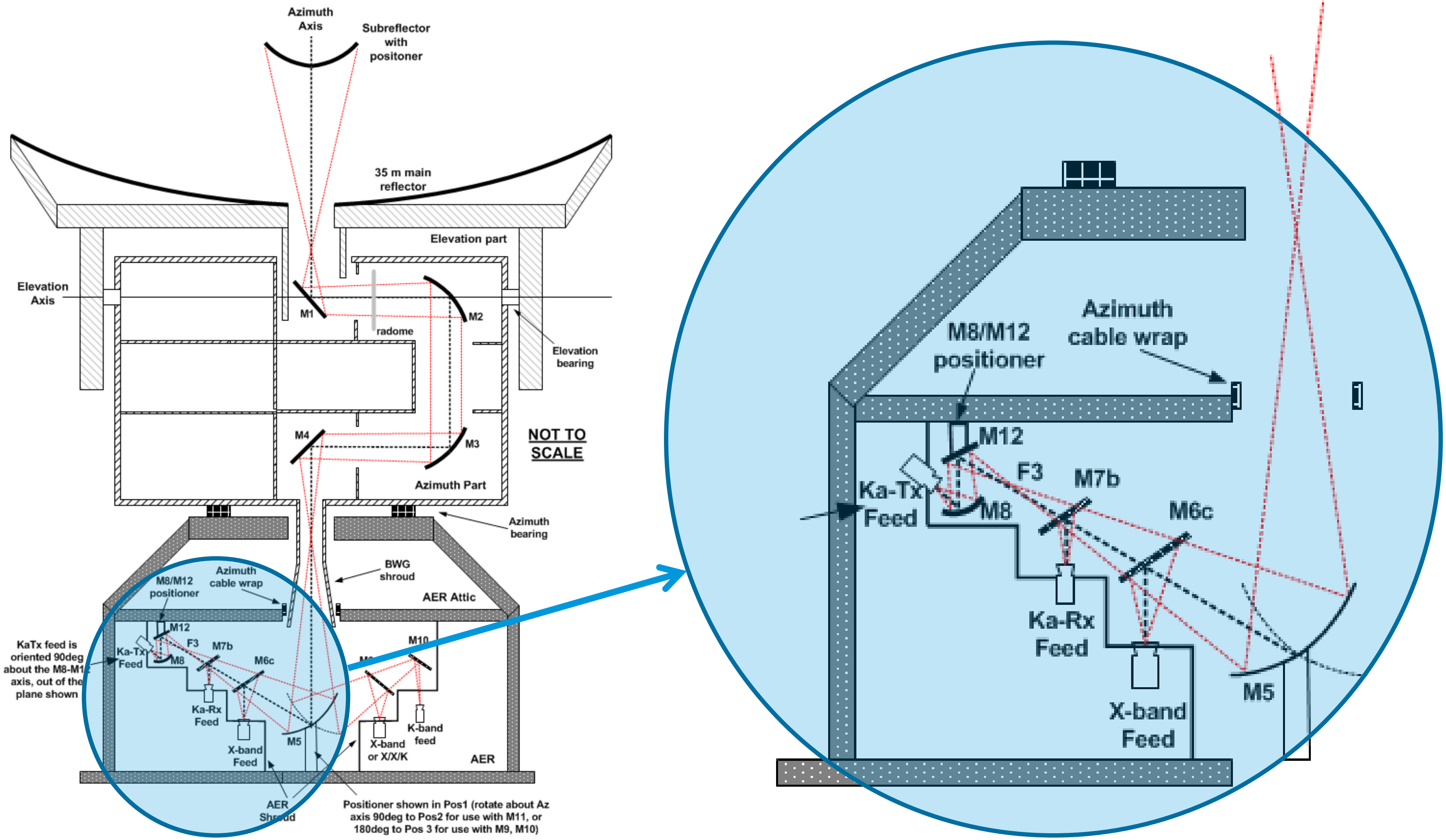




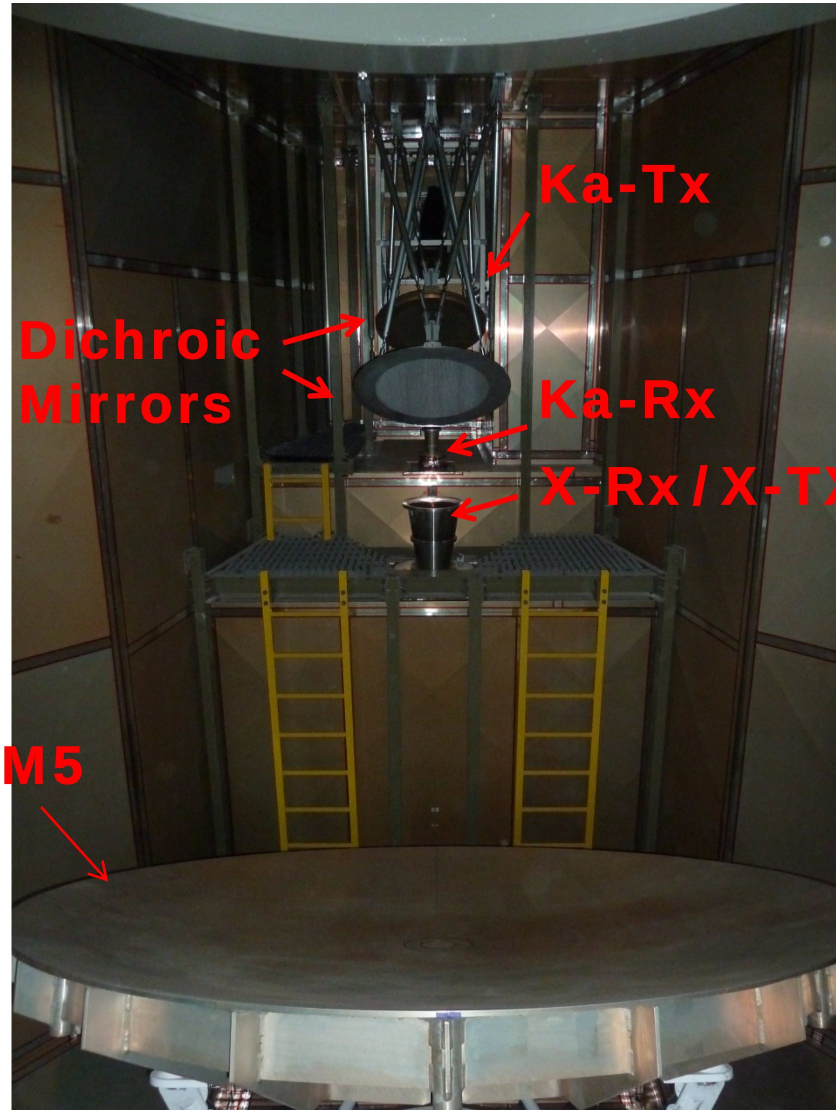
Characteristic of the 35m BWG Antennas

Operational Frequency Bands	Up to 32 GHz, Feeds with cryogenically cooled LNAs (X-Band, Ka-Band)
Uplink	20 kW Klystron amplifier @ X-Band 500 W klystron amplifier @ Ka-Band
Main reflector surface accuracy	< 0.30 mm RMS @ wind at 45/60km/h
Dynamic pointing accuracy (open loop pointing) to be achieved @ 99.7 % of time	≤ 5.5 mdeg @ wind 45 / 60 km/h ≤ 6.5 mdeg @ wind 50 / 70 km/h ≤ 20 mdeg @ wind 100 / 120 km/h
Lowest Antenna Eigenfrequency	> 2 Hz

35m BWG Antenna I (DSA3)



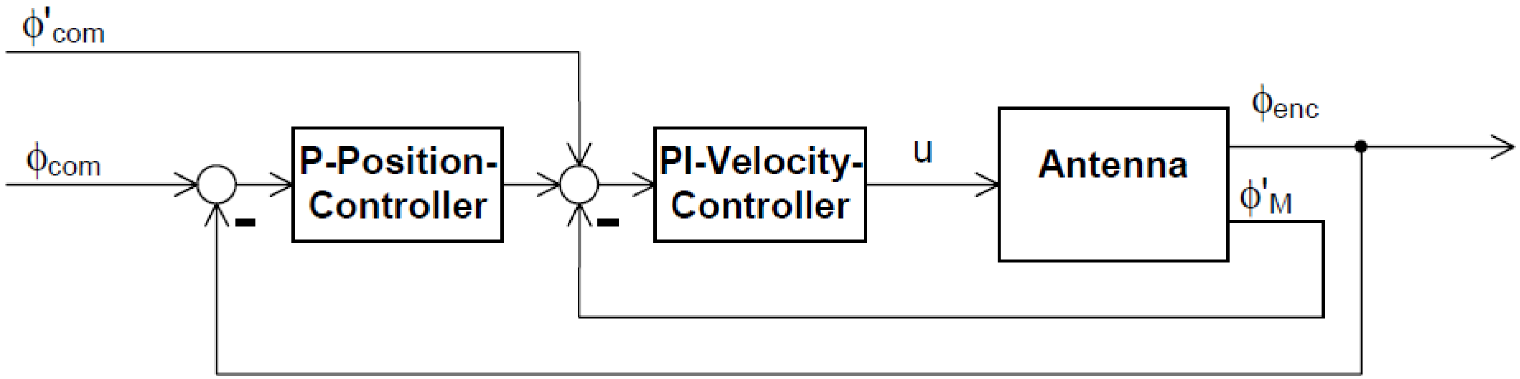
35m BWG Antenna II



Antenna Servo System

Servo Controller is based on fully digitally implemented Cascade Controller Structure:

a. P for position controller
b. PI controller for velocity controller
c. Identical controller structure for Az and El



u - commanded motor torque

φ - position (angle)

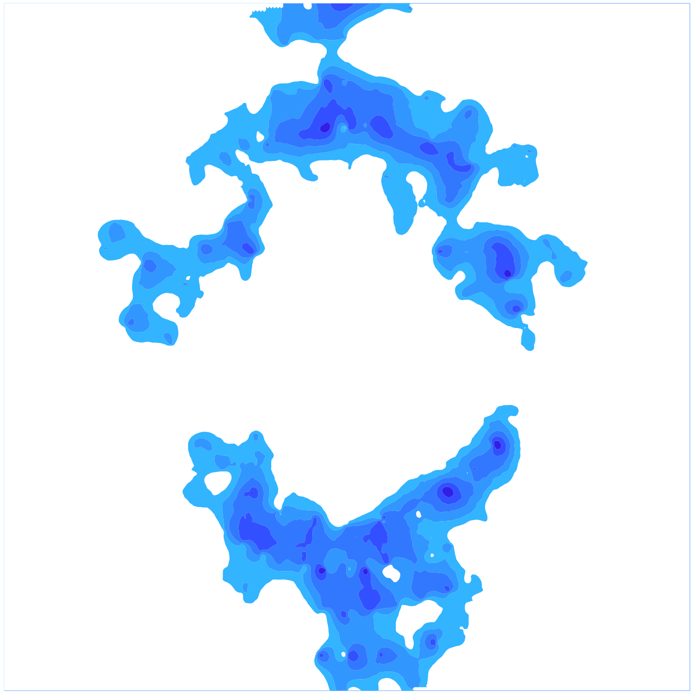
φ' – velocity

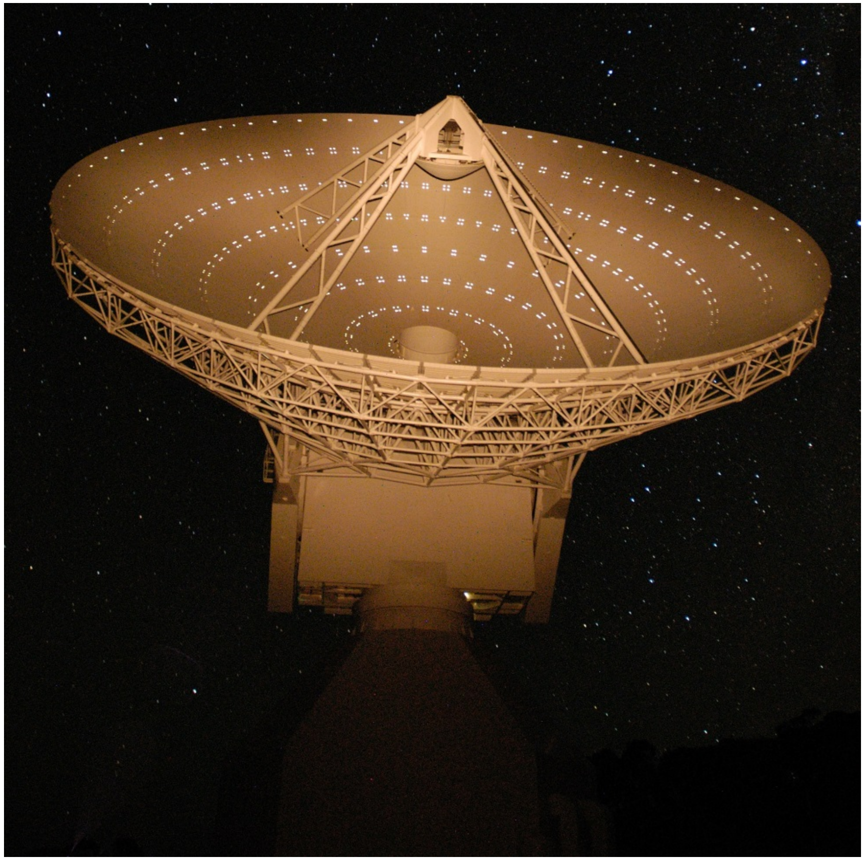
(..)com - commanded

(..)enc - encoder

(..)M - motor

Alignment of panels with theodolite and photogrammetry measurements

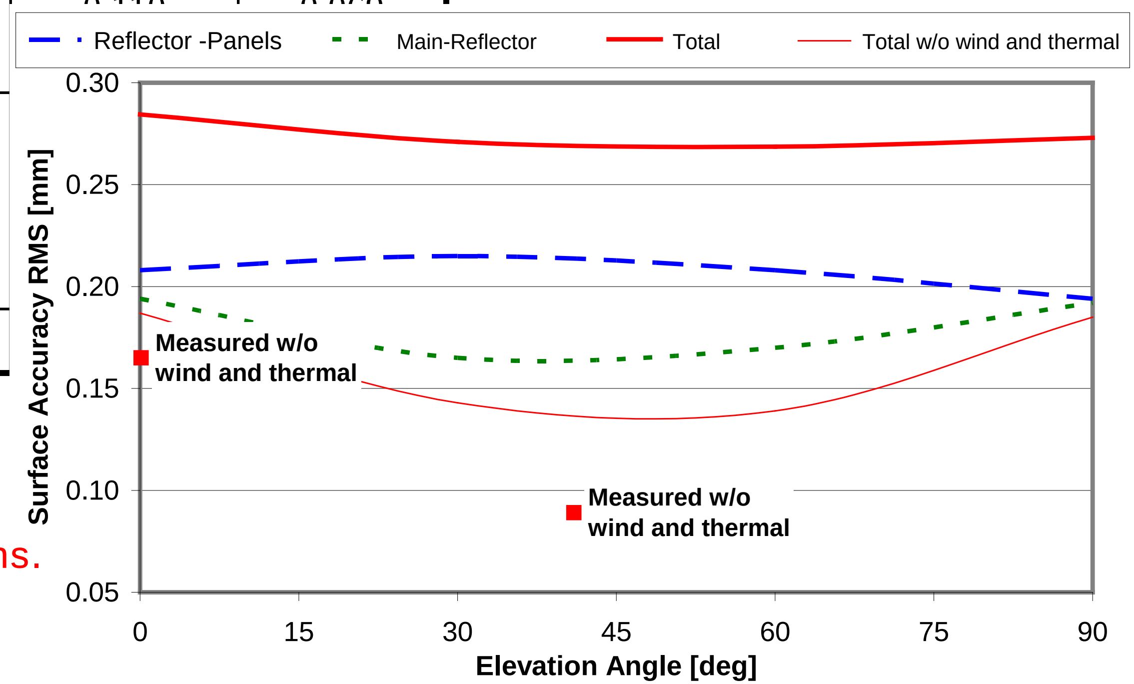




Surface Accuracy – Performance under worst case conditions

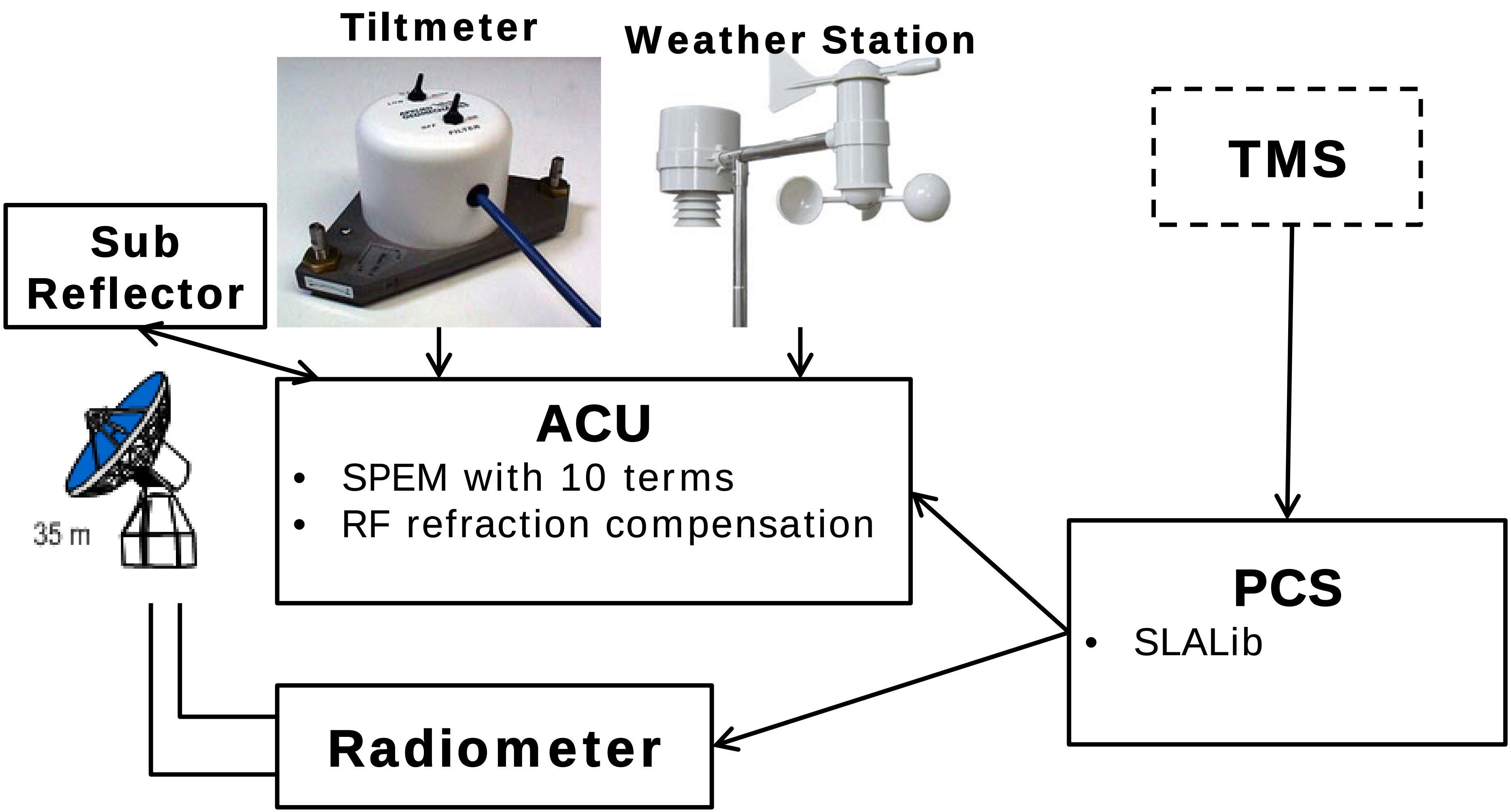
Source of surface error	Surface accuracy [mm] RMS		
	Elevation angle [deg]		
	0	30	90
Panel Manufacturing	0.081	0.081	0.081
Panel Alignment	0.089	0.089	0.089
Gravity (dead weight)	0.080	0.069	0.023
Wind (50/70 km/h)	0.069	0.110	0.069
Temperature gradient (dT = 1K)	0.138	[illegible]	[illegible]
Gravity deformation (adjusted at 45^{o})	0.118 0.166	[illegible]	[illegible]
Wind load (50/70 km/h)	0.113	[illegible]	[illegible]
Temperature gradient		[illegible]	[illegible]
Total (RSS)	**0.304**	[illegible]	[illegible]

Surface Error Budget for Main reflector surface accuracy.



Simulation results and measurement results are combined to determine performance under worst case conditions.

Block Diagram Antenna Pointing Error Compensation



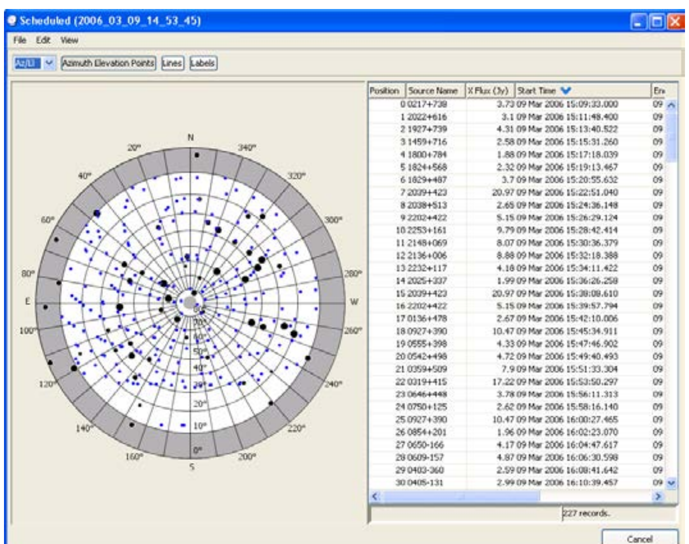
Systematic Pointing Error Model

The systematic pointing error model (SPEM) of the ESA DSAs consists of the following 10 terms:

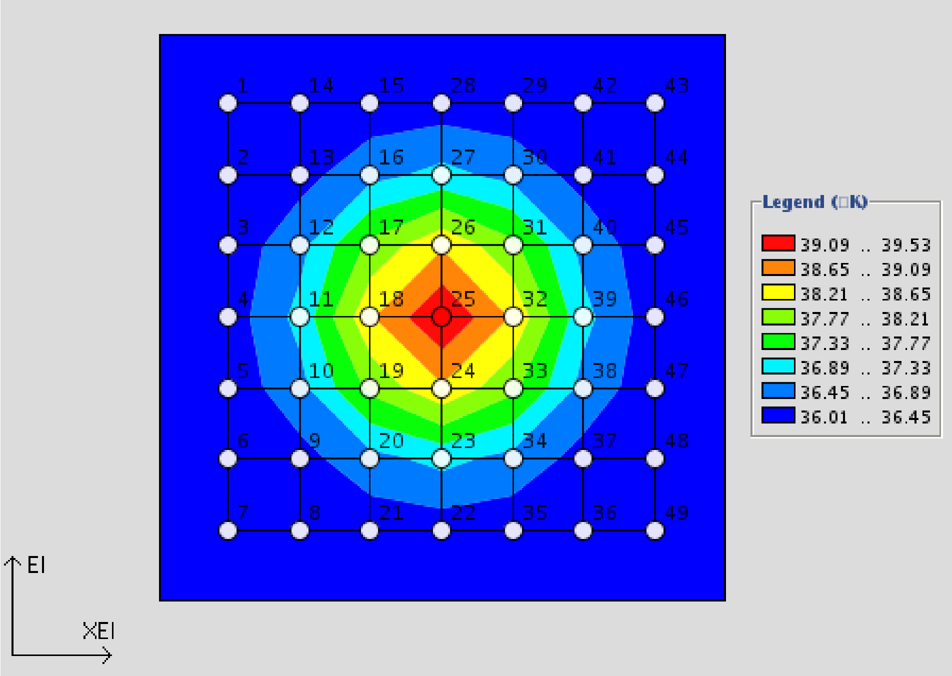
SPEM Coefficient	Description	Az Correction Formula	Elevation Correction Formula	Determined Value Ka RHCP, example, (mdeg)
IA	Azimuth encoder offset	IA		-31.8
IE	Elevation encoder offset		IE	81.7
DTF	Flexure due to gravity		$DTF \cdot \cos(El)$	-80.0
AN	Tilt of azimuth axis in north direction	$AN \cdot \tan(El) \cdot \sin(Az)$	$AN \cdot \cos(Az)$	5.7
AW	Tilt of azimuth axis in west direction	$AW \cdot \tan(El) \cdot \cos(Az)$	$-AW \cdot \sin(Az)$	6.5
CA	Collimation of RF axis	$\frac{CA}{\cos(El)}$		5.9
NRX	This is a horizontal shift between the elevation axis and the azimuth axis.	NRX	$NRX \cdot \sin(El)$	-0.04
NRY	This is a vertical shift between the elevation axis and the azimuth axis.	$-NRY \cdot \tan(El)$	$-NRY \cdot \cos(El)$	10.3
CRX1	Polarization dependent beam squint due to the dichroic plate and elliptical mirrors.	$\frac{CRX1 \cdot \sin(Az - El)}{\cos(El)}$	$\frac{-CRX1 \cdot \cos(Az - El)}{\cos(El)}$	-0.5
CRY1	Polarization dependent beam squint due to the dichroic plate and elliptical mirrors.	$\frac{-CRY1 \cdot \cos(Az - El)}{\cos(El)}$	$\frac{-CRY1 \cdot \sin(Az - El)}{\cos(El)}$	-0.9

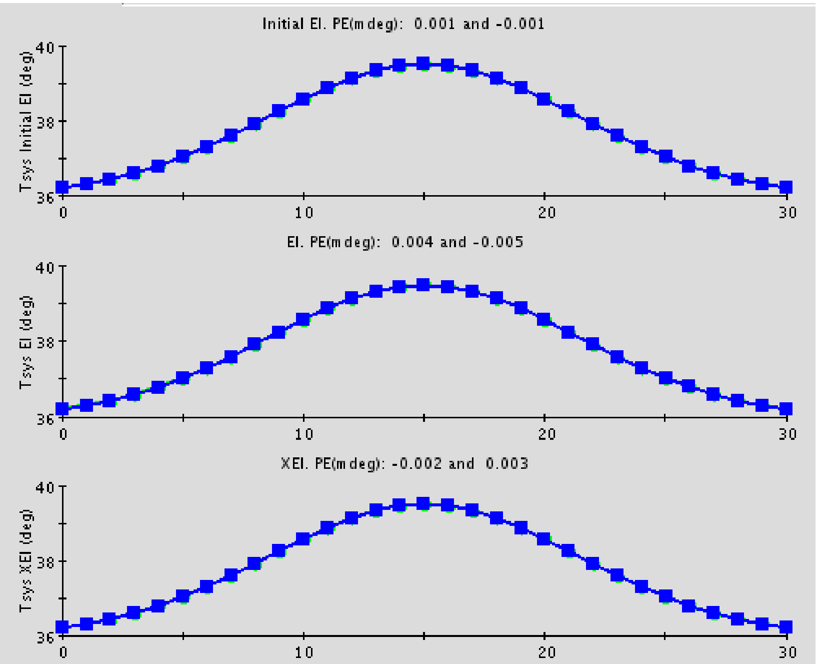
Pointing Calibration System I

- Pointing Calibration System supports pointing measurements in X, K, Ka-Rx and Ka-Tx.
- Fully automated scanning of pre-selected radio stars and semi-automated determination of SPEM coefficients.
- Powerful graphical user interface
- Currently limited to SPEM with 10 coeff.



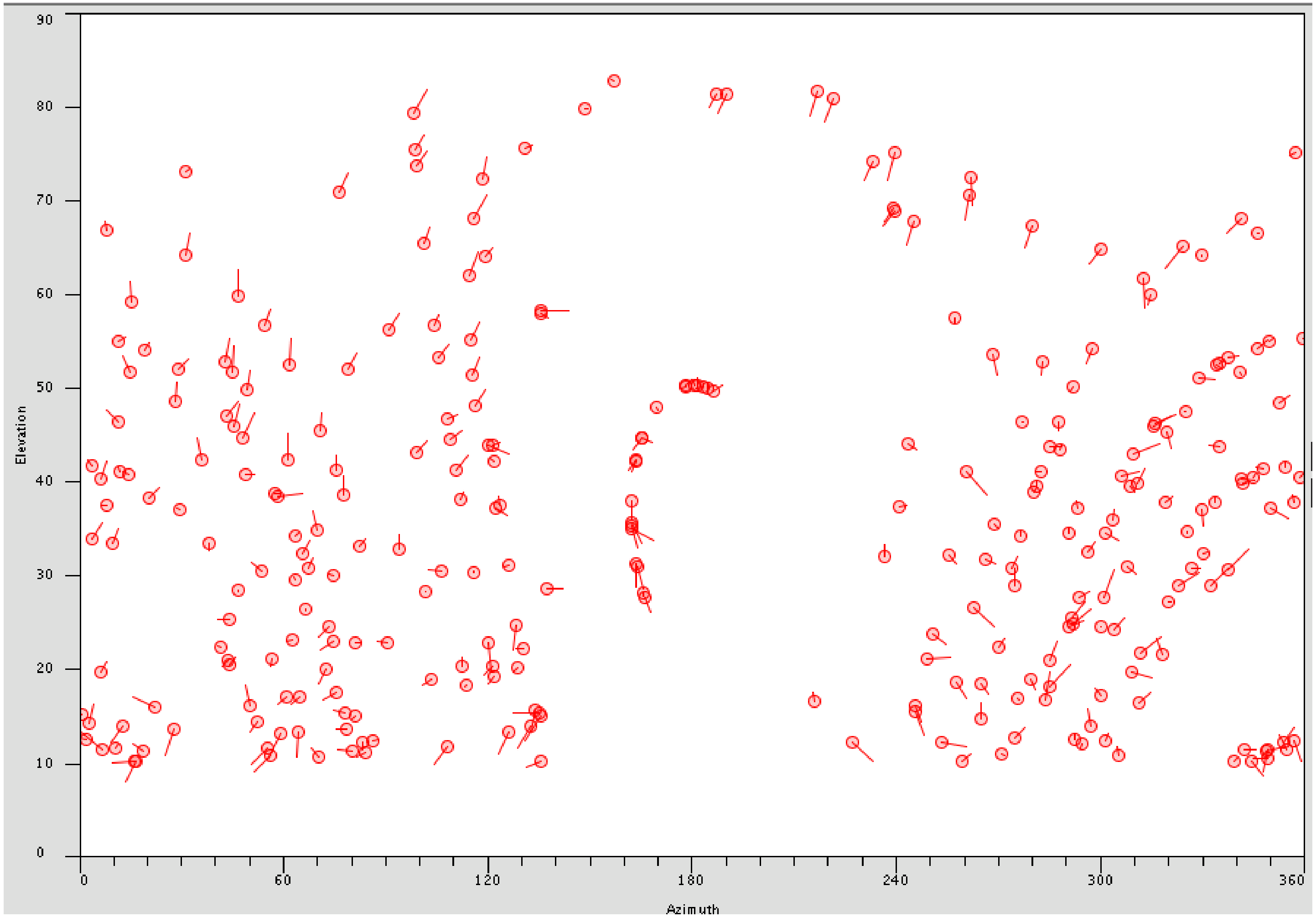
2 Scanning methods available in PCS:



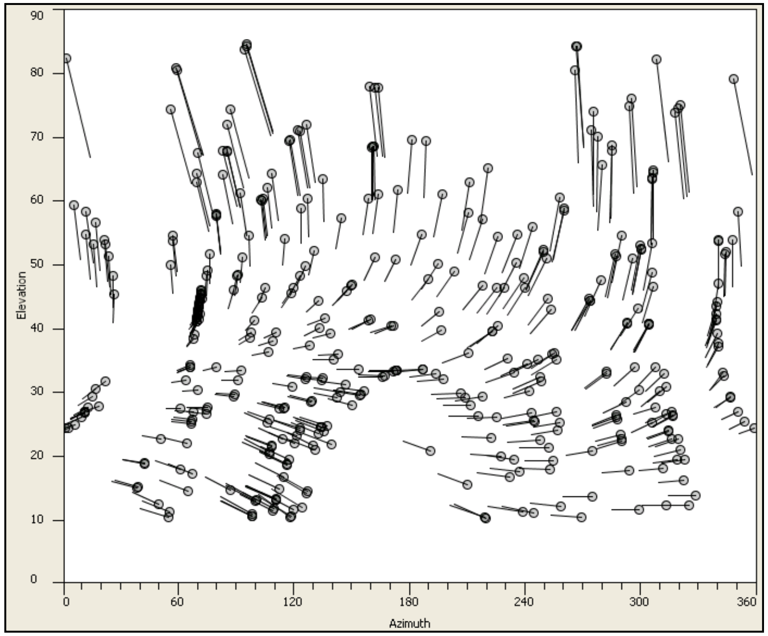


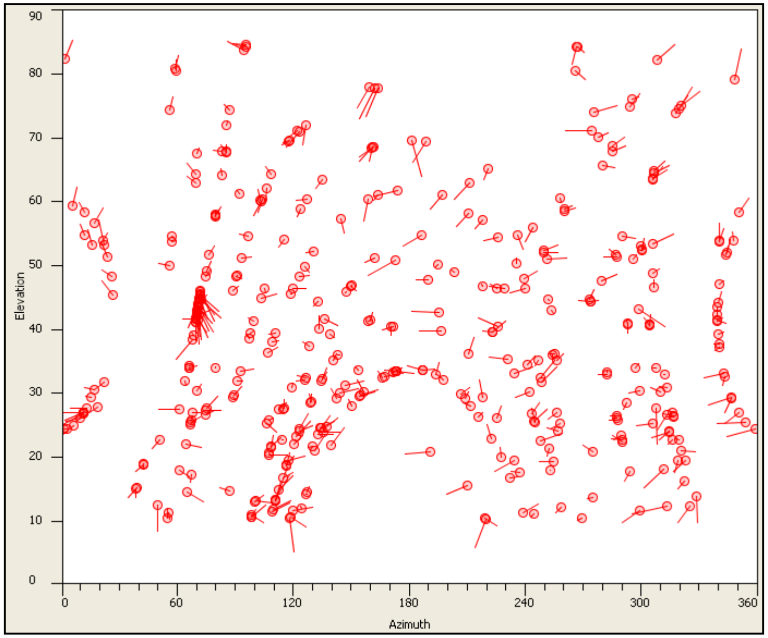
Pointing Calibration System III

- Distribution of radio star measurements.
- Arrows show direction of measured pointing offset.
- Measurements cover well the hemisphere
- Measurements are input for SPEM coefficient determination
- Typically 100 – 300 measurements required for good model



Pointing Calibration System IV

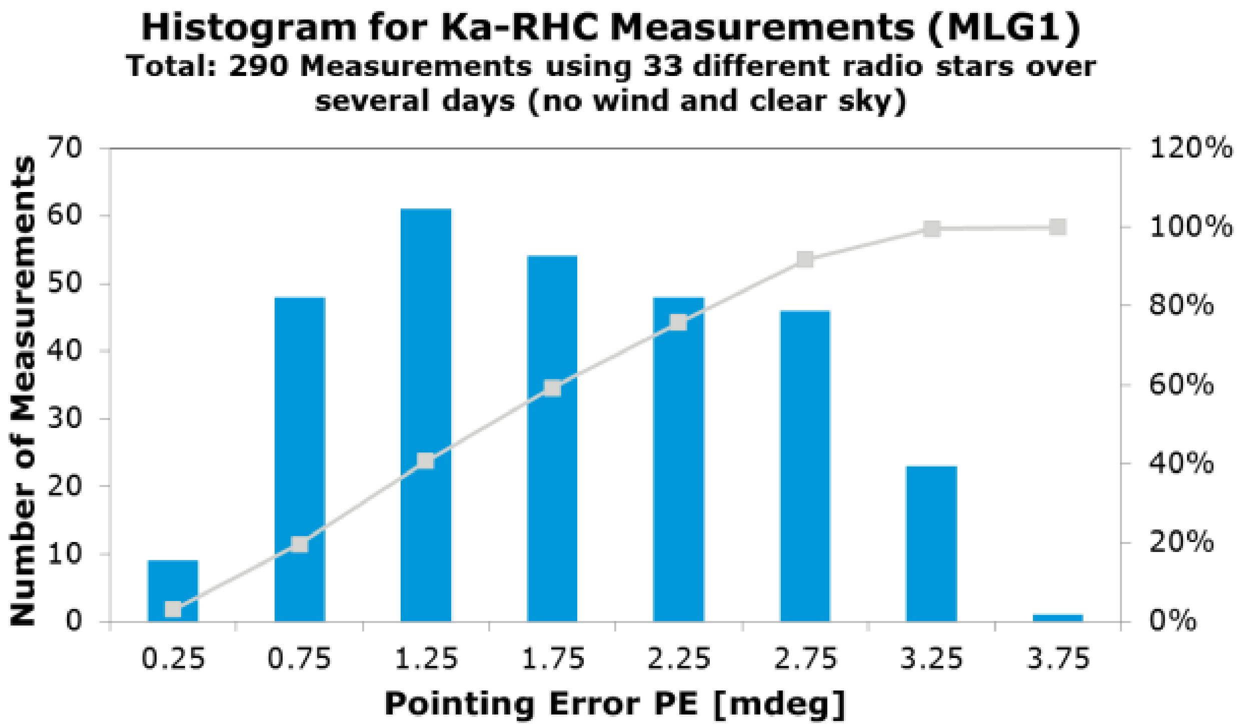




- SPEM has to be determined for each frequency band and polarisation.
- For proper determination of SPEM coefficients, full coverage of hemisphere is important.

Antenna Pointing Performance, MLG1

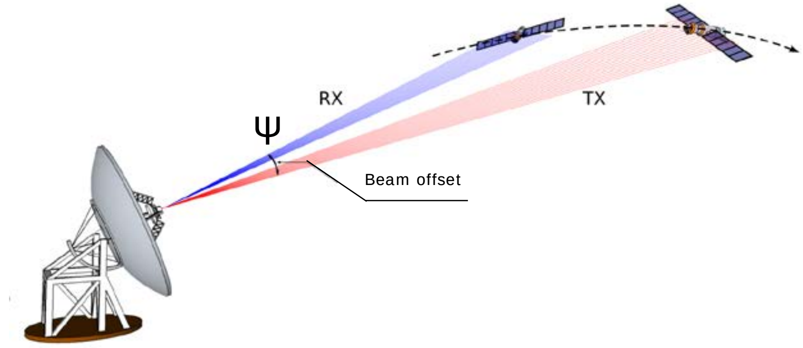
- 32 GHz, RHCP
- 290 measurements over 4 days
- Clear sky, cold and dry weather
- approx. 80% of measurements better 2.25 mdeg



	Max. total PE
32 GHz, RHCP, no wind, **measured**	3.8 mdeg
32 GHz, RHCP, wind 45/60 km/h, **extrapolated**	5.3 mdeg

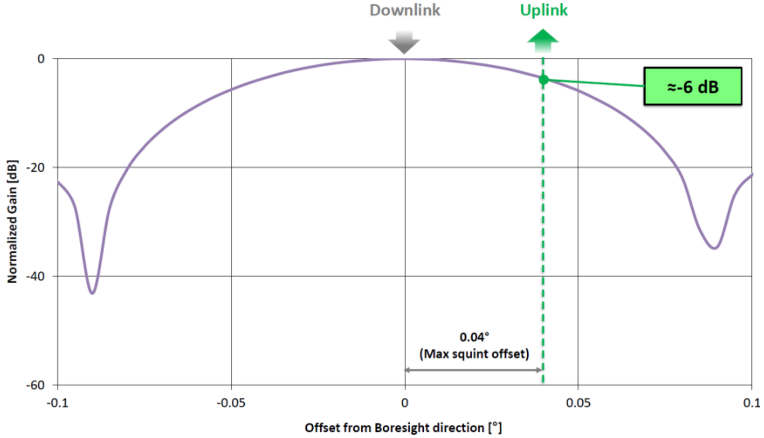
Generating Rx-Tx Squint at 32 GHz

- Spacecraft in movement generates an offset between RX and the TX beams (RX-TX squint)
- Worst case Receive (Rx) – Transmit (Tx) offset for future ESA missions (BepiColombo) ~ 40 mdeg

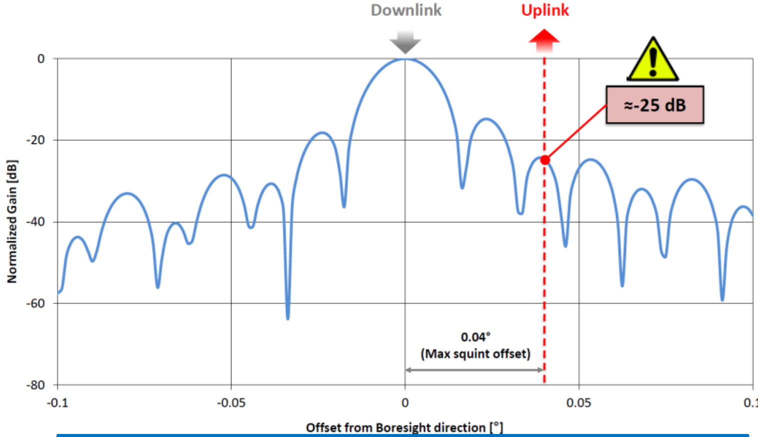


Ψ dependent on:

- RTLT
- Transversal velocity component



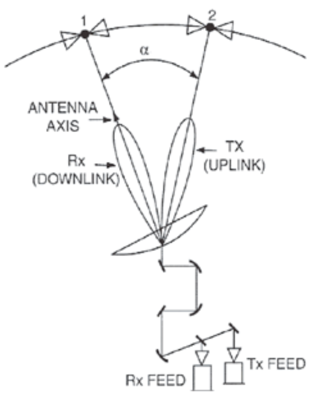
DSA3 / X-band

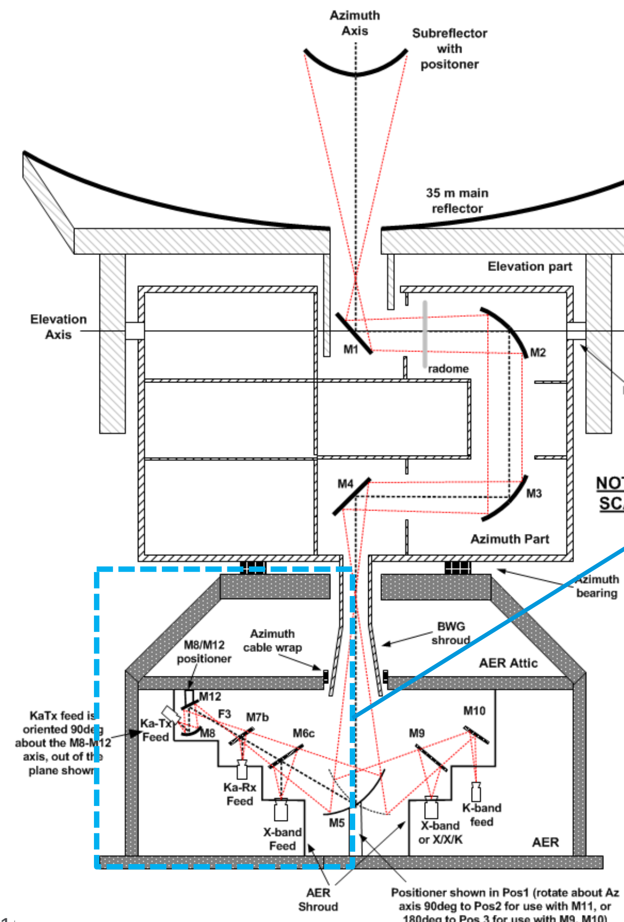


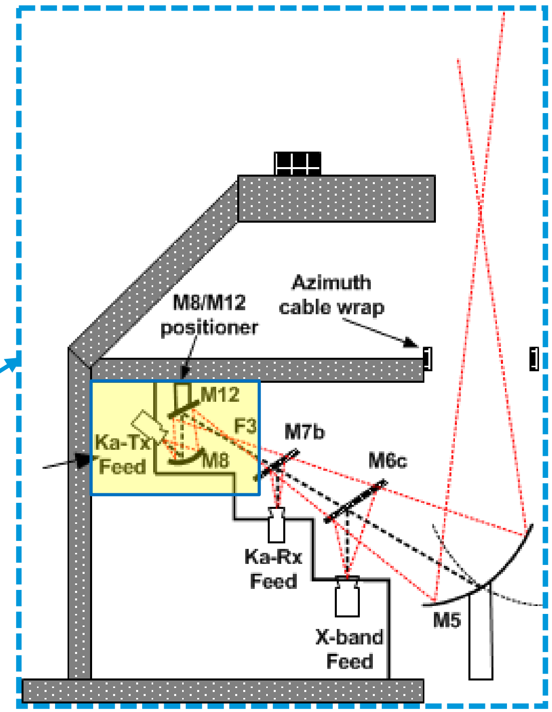
DSA3 / Ka-band

RX-TX Beam Offset Generation I

- Rx-Tx offset compensation concept: M8/M12 BWG mirrors tilting system







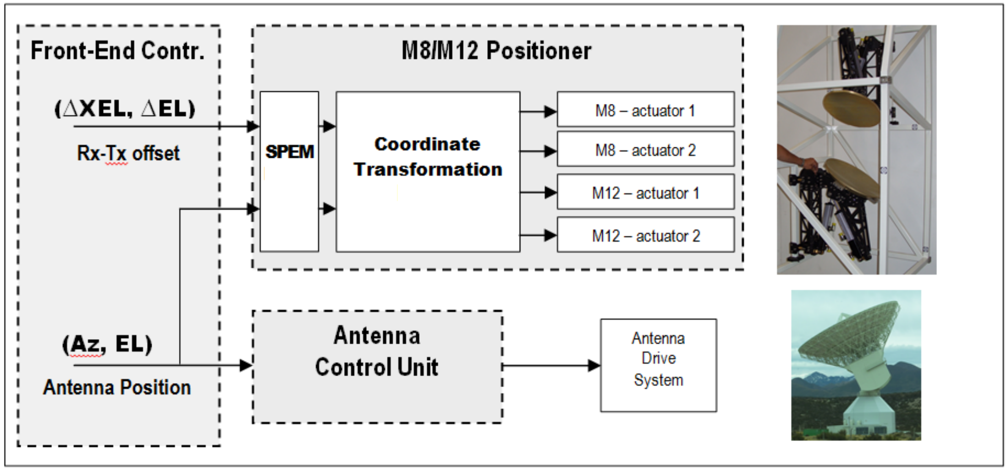
RX-TX Beam Offset Generation II

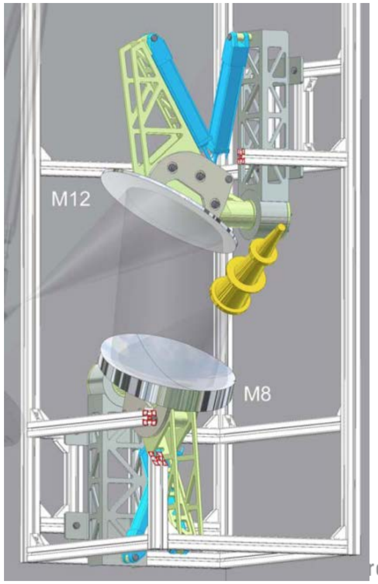
- Accurate two-axes M8/M12 rotation implemented by linear actuators
- Relationship between mirror tilts & beam aberration angles (θ_{BA}, φ_{BA}) given by 16 degrees of freedom

$$\begin{bmatrix} u_{M8} \\ v_{M8} \\ u_{M12} \\ v_{M12} \end{bmatrix} = \begin{bmatrix} C_{M8}^{11} & C_{M8}^{12} & C_{M8}^{13} & C_{M8}^{14} \\ C_{M8}^{21} & C_{M8}^{22} & C_{M8}^{23} & C_{M8}^{24} \\ C_{M12}^{31} & C_{M12}^{32} & C_{M12}^{33} & C_{M12}^{34} \\ C_{M12}^{41} & C_{M12}^{42} & C_{M12}^{43} & C_{M12}^{44} \end{bmatrix} * \begin{bmatrix} u_{BA} \\ v_{BA} \\ u_{BA}^2 \\ v_{BA}^2 \end{bmatrix}$$

$$u_{BA} = \sin\theta_{BA} \cos\varphi_{BA}$$
$$v_{BA} = \sin\theta_{BA} \sin\varphi_{BA}$$

- The mirror tilting occurs after SPEM correction to automatically compensate systematic pointing error contributions



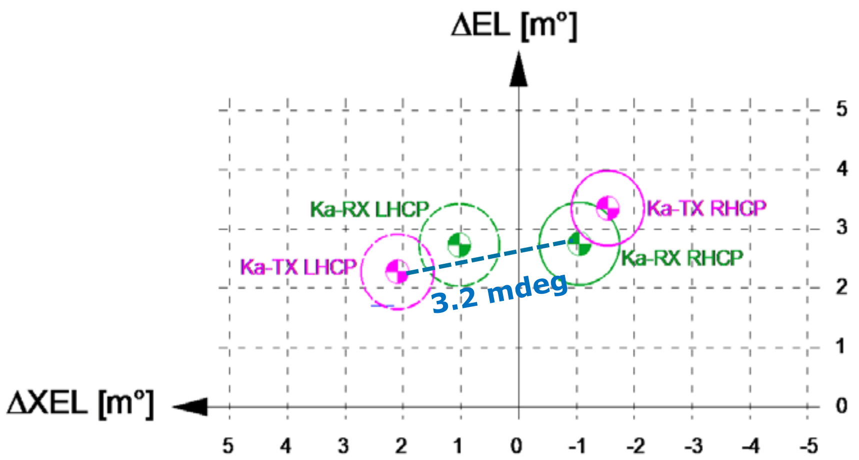


RX-TX Beam Offset Generation III

- BWG design intrinsically introduces beam shifts (frequency and polarization dependent) → SPEM compensation based on CRX, CRY coefficients

$$dXEl = CRX * \cos(Az - El) - CRY * \sin(Az - El)$$
$$dEl = -CRX * \sin(Az - El) - CRY * \cos(Az - El)$$

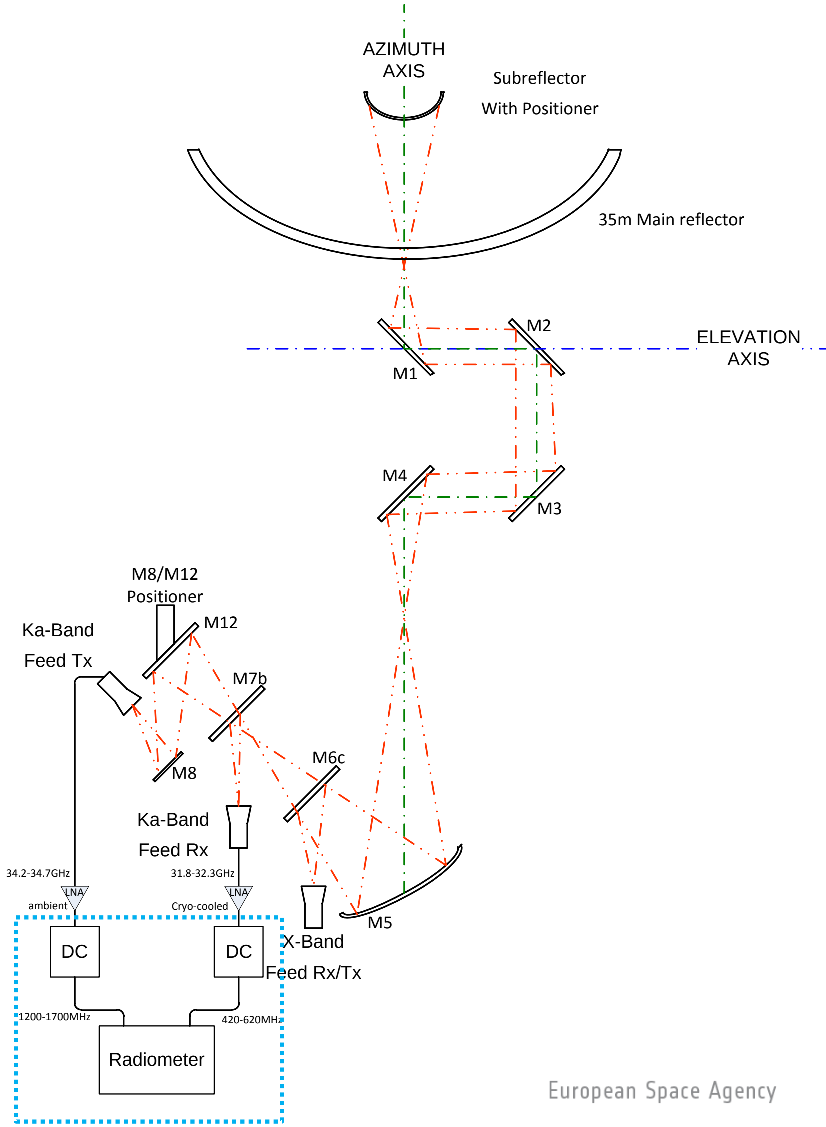
- Design of BWG aims at minimizing differences between the possible configurations
- Remaining difference can however not be neglected



Simulated for AZ/EL = 0/0 deg (with dichroics) → **Effect modelled by CRX / CRY**

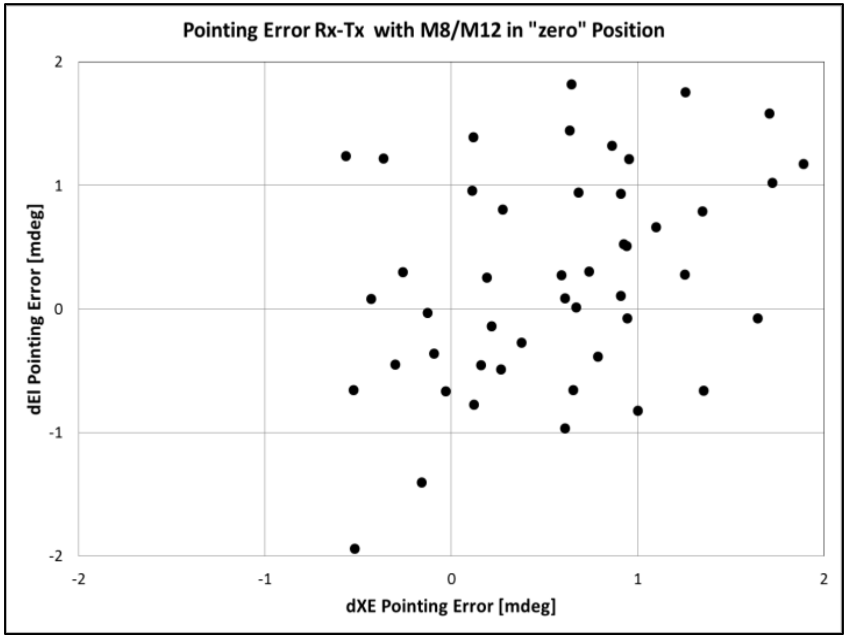
Measuring of Rx-Tx beam offset & Ka-TX gain loss

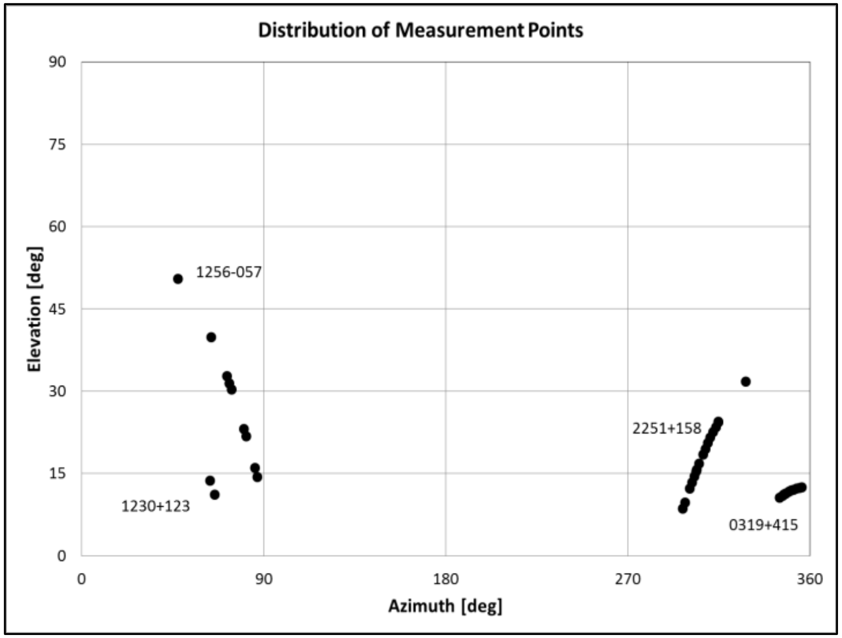
- Ka-Tx steering in open loop to verify:
  - Pointing accuracy
  - Gain degradation
- Ka-Rx is the “zero” pointing reference
- Both Ka-TX\x and Ka-Rx in “receive” mode (radiometer)
- No simultaneous measurements at Ka-RX/TX



Rx-Tx beam steering performance I

- No commanded offset → pointing error due to systematic effects (polarisation dependency, residual mechanical misalignment) → **CRX = 0.54 mdeg, CRY = 0.26 mdeg**

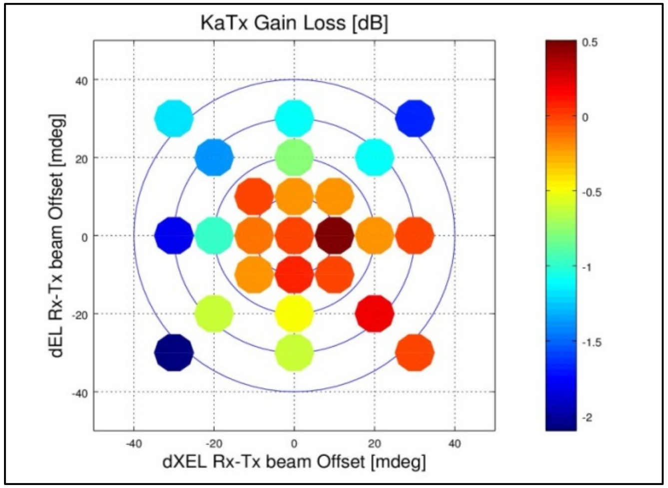


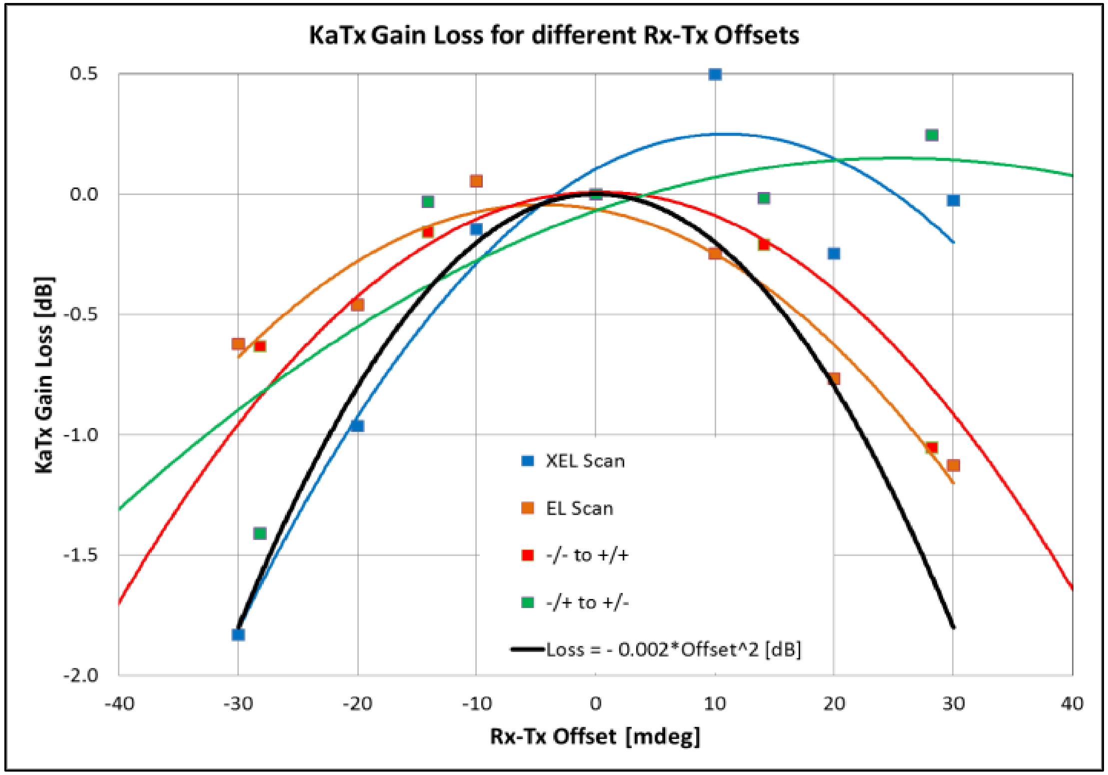


Need for more meas. to better cover full hemisphere

Rx-Tx beam steering performance II

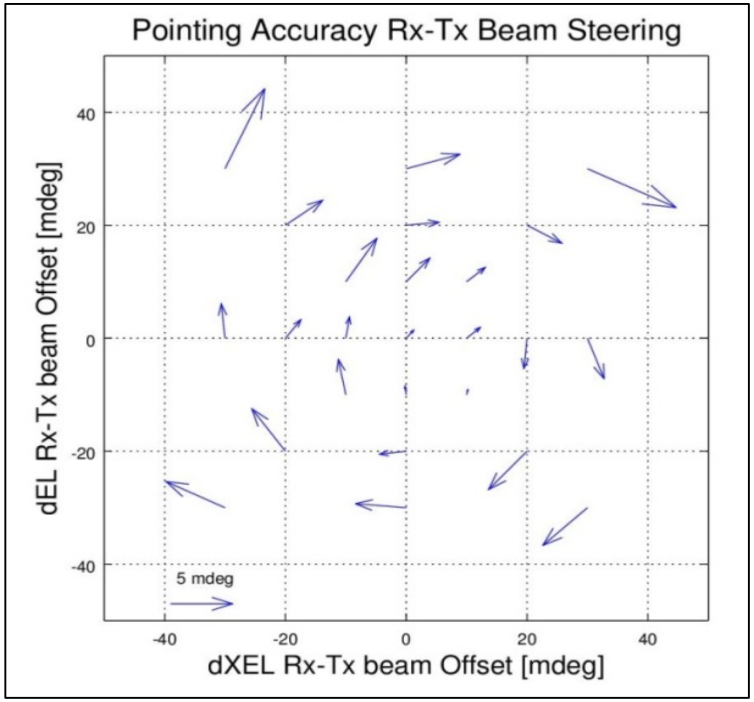
- Commanded offset → anomaly detected as gain increase for certain offset directions (i.e. XEL direction)
- Worst case gain loss (black line) is worse than expected → due to meas. uncertainty?

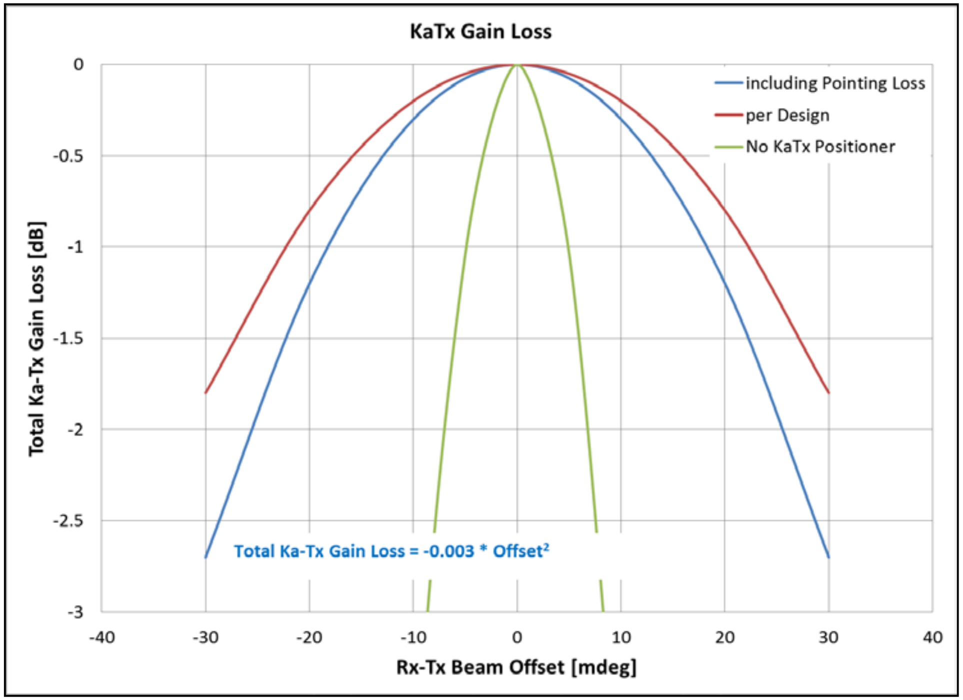




Rx-Tx beam steering performance III

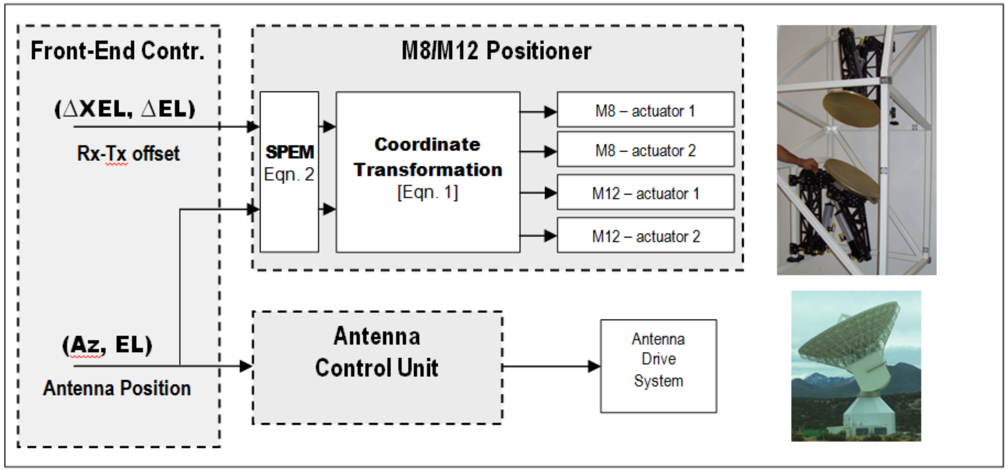
- Commanded offset → systematic residual pointing error vectors in a “vortex” around 0,0
- Due to not optimum C-matrix coefficients?
- Additional losses due to unexpected large pointing errors → -1.5 dB at 30 mdeg





Next Step: Optimizing Ka Rx-Tx pointing

esa



$$\begin{bmatrix} u_{M8} \\ v_{M8} \\ u_{M12} \\ v_{M12} \end{bmatrix} = \begin{bmatrix} C^{11}_{M8} & C^{12}_{M8} & C^{13}_{M8} & C^{14}_{M8} \\ C^{21}_{M8} & C^{22}_{M8} & C^{23}_{M8} & C^{24}_{M8} \\ C^{31}_{M12} & C^{32}_{M12} & C^{33}_{M12} & C^{34}_{M12} \\ C^{41}_{M12} & C^{42}_{M12} & C^{43}_{M12} & C^{44}_{M12} \end{bmatrix} * \begin{bmatrix} u_{BA} \\ v_{BA} \\ u^2_{BA} \\ v^2_{BA} \end{bmatrix}$$

$$u_{BA} = \sin\theta_{BA} \cos\varphi_{BA}$$
$$v_{BA} = \sin\theta_{BA} \sin\varphi_{BA}$$

Combination dependent coefficients Feasible? →

$$\begin{bmatrix} \Delta C^{11}_{M8} & \Delta C^{12}_{M8} & \Delta C^{13}_{M8} & \Delta C^{14}_{M8} \\ \Delta C^{21}_{M8} & \Delta C^{22}_{M8} & \Delta C^{23}_{M8} & \Delta C^{24}_{M8} \\ \Delta C^{31}_{M12} & \Delta C^{32}_{M12} & \Delta C^{33}_{M12} & \Delta C^{34}_{M12} \\ \Delta C^{41}_{M12} & \Delta C^{42}_{M12} & \Delta C^{43}_{M12} & \Delta C^{44}_{M12} \end{bmatrix}$$

Current limitations:

- Same coefficients for all combinations Rx (RHC, LHC and TX (RHC, LHC)
- Coefficients are based on a symmetric conditions, the different combinations hit however the elliptical mirror NOT in its vertex.

➔Introduction of “corrections” for each/some coefficient to consider the different combinations