PERFORMANCE OF THE KA-TX BEAM STEERING APPROACH OF DSA3

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INTRODUCTION

Whenever a distant spacecraft is moving across the line of sight seen from an antenna on earth, an offset between the receive and the transmit beam (beam aberration) is generated. The size of this offset depends on the travel time of the signal and the magnitude of the cross-velocity component (see Fig 1).

At S- and X-band frequencies, the loss due to the separation of pointing directions of the receive and transmit beam is typically small due to the relatively large beam-width at these frequencies. For a 35m antenna at Ka-band however, the loss is severely impacting the link performance as an offset of 17 mdeg results already in a loss of 12 dB. The upcoming trajectory of the Bepi-Colombo mission to Mercury (Launch foreseen in 2018) will result in Rx-Tx beam offsets up to 34 mdeg and requires therefore an efficient generation of an offset between the receive and transmit beam.

The concept to generate the Rx-Tx beam offset, developed for the 35m antenna of Malargue DSA3, consists of fixed feeds and 2 tilting beam waveguide mirrors (M8 and M12, see Fig 2 and 4). Each mirror can be tilted around two axis. As the Ka-Tx feed remains fixed, the integration of the Ka-Tx amplifier and its interface to the Ka-Tx feed is straightforward. The simplicity of the mechanical integration results however in a complex relationship between the desired Rx-Tx beam offset and the according position of the movable mirrors M8 and M12.

The Ka-Tx positioner and its integration in DSA3 has been finalised in 2016. Antenna pointing measurements with radio stars have been performed using the Ka-Tx feed to verify the pointing accuracy of the Ka-Tx beam steering. The paper presents the observed pointing performance and gain loss figures. The results are compared to the expected values from the design phase.

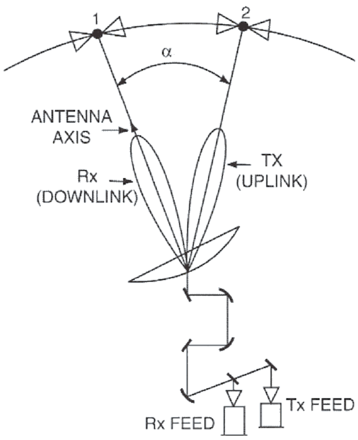

Fig. 1: Generation of a Rx-Tx beam offset in a beam waveguide (BWG) antenna [1].

GENERATION OF THE RX-TX BEAM OFFSET AT KA-BAND FOR DSA3

ESA's deep space antennas are based on a beam waveguide concept [2]. Dichroic mirrors (M6c, M7b) are used to separate the X-band (Rx+Tx), Ka-Rx and Ka-Tx frequency bands (see Fig. 4). In the course of the implementation of Ka-Band transmission capabilities in DSA3, different approaches to generate the Rx-Tx beam offset have been studied [3]. The finally selected technique consists of a fixed Ka-Tx feed combined with two tiltable mirrors controlled by the "M8/M12 Positioner". The ellipsoidal mirror M8 and the plane mirror M12 are tiltable around pivot points [3]. Fig. 2 shows the design drawings and its actual realisation.

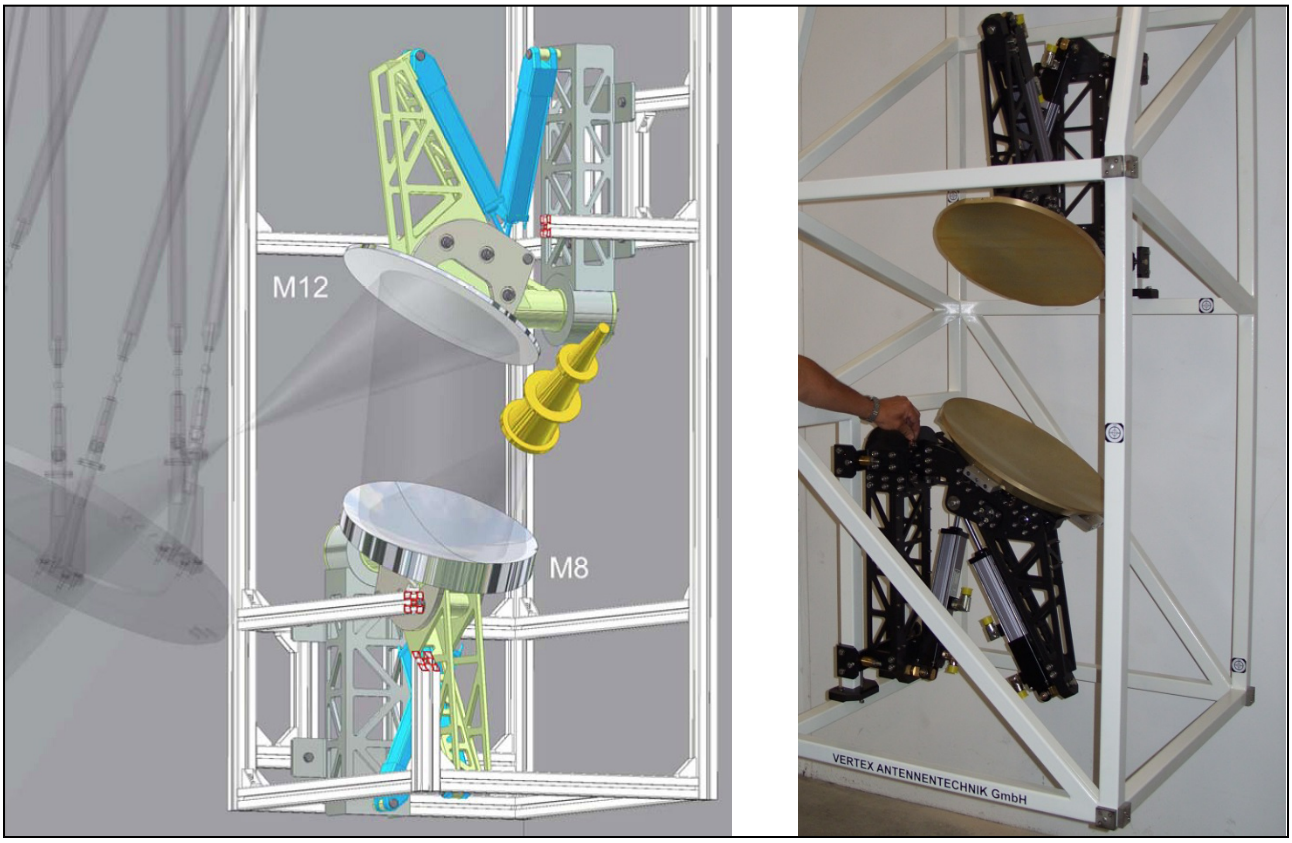

Fig. 2: **Left:** Design of the M8+M12 positioner with mirror M8, mirror M12 and the Ka transmit feed. **Right:** Integration of the mirrors within a cage to allow an accurate relative alignment of the mirrors (right).

In order to achieve the necessary tilt of the BWG mirrors M8 and M12, an accurate and practically backlash free two-axes rotation of both mirrors is required. Each mirror is therefore tilted by two high accuracy linear actuators with planetary roller jackscrew and mechanical backlash compensation. Besides the control of the jackscrews, the positioner software implements also the coordinate transformation (Fig. 3) required to determine from the beam aberration offsets (ΔXEl, ΔEl) at a certain antenna pointing direction (Az,El), the corresponding mirror tilting.

The size of the beam aberration offset changes only by a few mdeg per day due to the long distance to the spacecraft. Due to the earth rotation and the subsequent movement of the antenna in azimuth and elevation however, the orientation of the beam aberration vector changes more rapidly. A continuous positioning of the mirrors is therefore required.

The relationship between the M8/M12 mirror tilts and the beam aberration offset angle θ_{BA} and beam aberration direction angle φ_{BA} cannot be expressed in closed form and is therefore approximated by 2-dimensional second order functions of the beam aberration offsets in (u,v) coordinates (see [3] for details). In summary, the relationship is expressed by the transformation (1) with 16 degrees of freedom.

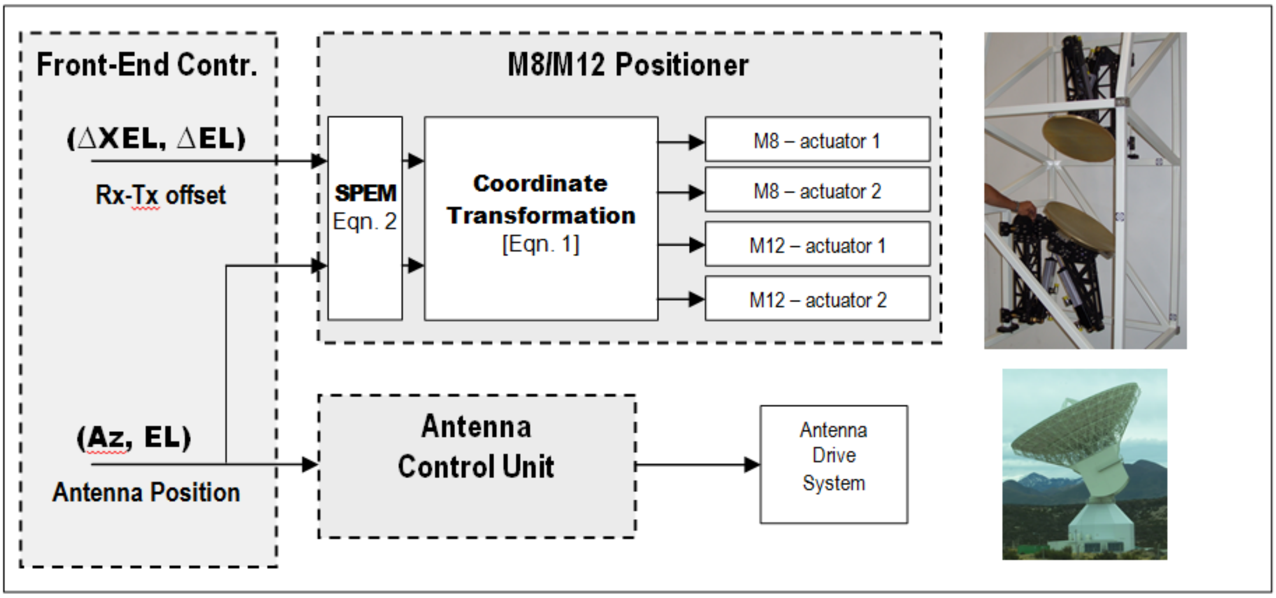

Fig. 3: Block diagram M8/M12 Positioner. The Front-End Controller derives from the predicted spacecraft trajectory data besides the antenna azimuth and elevation position also the required Rx-Tx offset. The elements (Az, El, ΔXEl, ΔEl) are the input to the M8/M12 positioner, which applies a systematic pointing error model (SPEM) correction before determining the corresponding actuator positions. The SPEM correction considers the beam shift with respect to its nominal position due to the polarisation (LHCP or RHCP) and mechanical misalignment effects.

$$\begin{bmatrix} u_{M8} \\ v_{M8} \\ u_{M12} \\ v_{M12} \end{bmatrix} = \begin{bmatrix} C_{M8}^{11} & C_{M8}^{12} & C_{M8}^{13} & C_{M8}^{14} \\ C_{M8}^{21} & C_{M8}^{22} & C_{M8}^{23} & C_{M8}^{24} \\ C_{M12}^{31} & C_{M12}^{32} & C_{M12}^{33} & C_{M12}^{34} \\ C_{M12}^{41} & C_{M12}^{42} & C_{M12}^{43} & C_{M12}^{44} \end{bmatrix} * \begin{bmatrix} u_{BA} \\ v_{BA} \\ u_{BA}^2 \\ v_{BA}^2 \end{bmatrix} \quad \text{where} \quad \begin{aligned} u_{BA} &= \sin\theta_{BA}\cos\varphi_{BA} \\ v_{BA} &= \sin\theta_{BA}\sin\varphi_{BA} \end{aligned} \tag{1}$$

The coefficients **C** of (1) are determined by the simulations. With this approach, which is an approximation valid only for small offset angles, the resulting beam offset has a maximum deviation (pointing error) of less than 1.3 mdeg to the desired beam aberration offset angle $\boldsymbol{\theta_{BA}}$ for $\boldsymbol{\theta_{BA}}$ = 30 mdeg.

In order to take into account the beam shift resulting from the beam wave guide design for different polarisations and to allow also the compensation of the residual mechanical misalignments (including the misalignment of the Ka-Rx feed), a systematic pointing error model based on the coefficients CRX and CRY is applied. Four pairs of the coefficients CRX,CRY are required to handle all the combinations for the zero offset between the receive beam (RHC or LHC) and the transmit beam (RHC or LHC) (see Fig 4.). For the case Rx-RHC/Tx-LHC , the predicted squint is 3.2 mdeg (e.g. NASA spacecraft JUNO is equipped with a Ka transponder, RHC in downlink, LHC in uplink. An early version of the M8/M12 positioner has been used successfully in 2015 to communicate with JUNO generating a transmit beam offset of approximately 10 mdeg) For Rx-RHC/Tx-RHC, the squint is minimal and is only 0.8 mdeg.

$$\begin{aligned} dXEl &= CRX * \cos(Az - El) - CRY * \sin(Az - El) \\ dEl &= -CRX * \sin(Az - El) - CRY * \cos(Az - El) \end{aligned} \tag{2}$$

The tilting of the mirrors M8 and M12 to generate the desired Rx-Tx beam offset results however also in a gain degradation of the Ka-Tx path. When the aperture fields of a reflector antenna are in phase over the extent of the aperture, the main beam points in the direction normal to the aperture plane. Lateral feed displacement in a reflector antenna introduces a planar phase front tilted with respect to the aperture plane. However, a nonlinear phase component is also introduced, leading to pattern distortion, including beam broadening and gain loss. These effects worsen with increasing displacements [3]. Based on the simulations performed in the design phase, the gain degradation of the Ka-Tx path due to the steering of the Tx beam should be less than 2.5 dB for a beam offset of 40 mdeg (see Fig. 5).

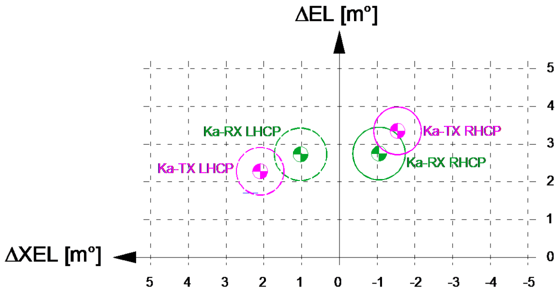

Fig. 4: Predicted beam squint difference between left hand (LHC) and right hand (RHC) polarisation for the receive and transmit beam at Ka-Band for an azimuth/elevation position of (0/0). The beam squint values are calculated with the dichroic mirrors M6c and M7b. The circles are contour lines 0.02 dB below the corresponding peak gain values. The effect is modelled by the SPEM with the coefficients CRX, CRY of (2).

The location of the maximum gain in Fig. 5 requires additional explanations: An offset mirror in a beam waveguide (BWG) always causes some asymmetries of the beam. In the initial unbent BWG layout, the asymmetry caused by the offset mirror M8 was fully compensated by the following offset mirror M5. Spatial restrictions in the antenna equipment room made it necessary to bend the BWG around the vertical axis in the centre of the plane mirror M12. With this modification the compensation of the asymmetry is not perfect any more. The residual beam asymmetries cause the asymmetric gain loss curves in Fig. 5.

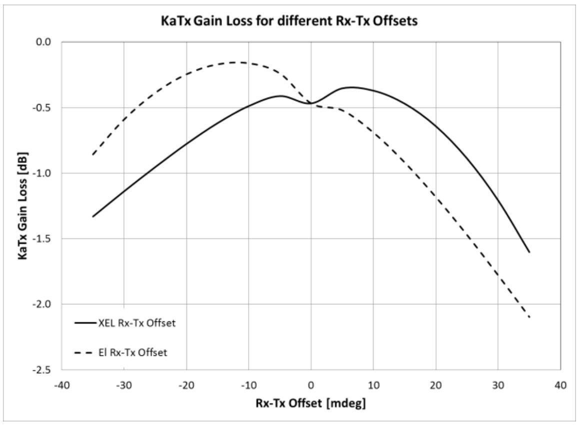

Fig. 5: Predicted Ka-Tx gain loss versus Rx-Tx offsets in cross-elevation and elevation for the position (azimuth/elevation) = (40 deg/ 40 deg).

During the commissioning of the M8/M12 positioner system, the impact of the following effects resulted in unexpected difficulties:

1. The dichroic mirror M7b introduces a vertical shift for the passing Ka-Tx beam. Any uncertainty in the magnitude of this polarisation dependent offset results in a Ka-Tx pointing offset already in the “zero” position of the M8/M12 positioner (See Fig. 4). As this effect has not been measured with sufficient accuracy in the laboratory, pointing measurements at Ka-Tx with M8/M12 in the “zero” position have been performed to determine the vertical position of the M8/M12 arrangement suitable for RHC and LHC. Once the best vertical position had been derived, the M8/M12 mirror cage has been aligned accordingly. The remaining Ka-Tx pointing offsets for the combination Rx-RHC and Tx-RHC when M8 and M12 are in the “zero” position are shown in Fig. 6. These measured offsets are used to determine the coefficients CRX and CRY of (2).

2. The coefficients **C** of (1) have been determined for mirror tilt-axis, which differ slightly from the tilt-axis of the designed and build M8/M12 mirror system. The currently available coefficients **C** are therefore not optimal for the realized M8/M12 positioner resulting. It is expected that the actual Ka-Tx pointing accuracy and the gain loss are slightly worse compared to the technically achievable performance indicated in [3].

MEASURING OF THE RX-TX BEAM OFFSET AND KA-TX GAIN LOSS

As the steering of the Ka-Tx beam during an operational scenario is only possible in an open-loop configuration, a detailed verification of the actually achieved pointing accuracy in combination with the real Ka-Tx gain degradation is required. The approach followed to validate the performance of the system is presented in the following.

With the assumption that the Ka-Band receive direction is the reference for pointing of the antenna reflector, the Rx-Tx beam offset becomes the difference in pointing between the receive and transmit beam. The measurements are therefore broken down into individual measurements of the Rx beam and the Tx beam using the Ka-Rx feed and Ka-Tx feed, both in "receive" configuration.

The antenna pointing of DSA3 at Ka-Rx is measured using the Pointing Calibration System (PCS) developed in the frame of DSA2 [4]. The DSA2 system has been further enhanced and offers now additional functionalities used to determine the Ka-Tx antenna pointing performance and gain loss:

- Line scan technique is available besides the already existing grid scan. The line scan has advantages in case of small Y-factors. The scanning consists of 3 scans with subsequent correction of the identified pointing offset: 1. Initial Elevation-Scan (up and down), 2. Cross-Elevation Scan (clockwise and counter-clockwise), 3. Elevation-Scan (up and down). The Tsys values recorded by the radiometer during each scan are evaluated by curve fitting to obtain the parameters a, b, c, HPBW, D of (3).

$$Tsys(x) = a + bx + c.e^{\frac{-4\ln 2}{HPBW^2}.((D-x)^2)} \tag{3}$$

where

x = scan length from [– HPBW (nominal), + HPBW (nominal)], with the expected star position at x =0
a = background noise temperature
b = elevation dependent slope of background noise temperature
c = peak noise temperature contribution of the radio star
HPBW = antenna 3dB beam width
D = position deviation of the radio star with respect to expected position (= determined El or XEl position error)

- The radiometer of DSA3 has also an input for the down-converted Ka-Tx signal (34.2-34.7 GHz) at 1200 – 1700 MHz (see Fig. 4).
- The PCS can also control the M8/M12 positioner and can forward the elements (Az, El, ΔXEl, ΔEl) to achieve the desired Rx-Tx beam offset when scanning the radio star.

The G/T for Ka-Rx, which has cryogenically cooled LNAs, is approximately 57 dB/K. As the Ka-Tx path has a LNA at room temperature, the G/T is roughly 7 dB lower and leads to distinctly lower Y-factors for the Ka-Tx measurements (see Fig. 4). For the radio stars 1256-057, 2251+158 and 0319+415 visible from the Malargue site, Y-factors of approximately 0.2 dB for Ka-Rx and 0.04 dB for Ka-Tx (zero-position) are obtained. It is obvious that measurements at such low Y-factors have inherently a relatively high measurement error. Individual measurement results are therefore not representative. Conclusions can only be drawn based on several measurements.

The Y-factor for each measurement is taken from the last elevation scan using the parameters a and c obtained from the curve fitting process of (3):

$Y \approx \frac{a+c}{a} = 1 + \frac{c}{a}$ when the elevation dependent slope can be neglected

In order to improve the measurement accuracy, measurements are performed within a short time period to ensure constant conditions. The following campaigns have been carried out:

1. Pointing offset between Ka-Rx and Ka-Tx, when the M8/M12 is in its "zero" position. In case of a perfect system, the observed pointing offset should be 0.
   The campaign consists of alternating between Ka-Rx and Ka-Tx (in "zero" position) radio star scans.

   The pointing accuracy is determined by
   $$(dXEl, dEl)^{Rx\text{-}Tx} = (dXEl, dEl)^{Tx} - (dXEl, dEl)^{Rx} \tag{4}$$

The obtained results are shown in Fig. 7.

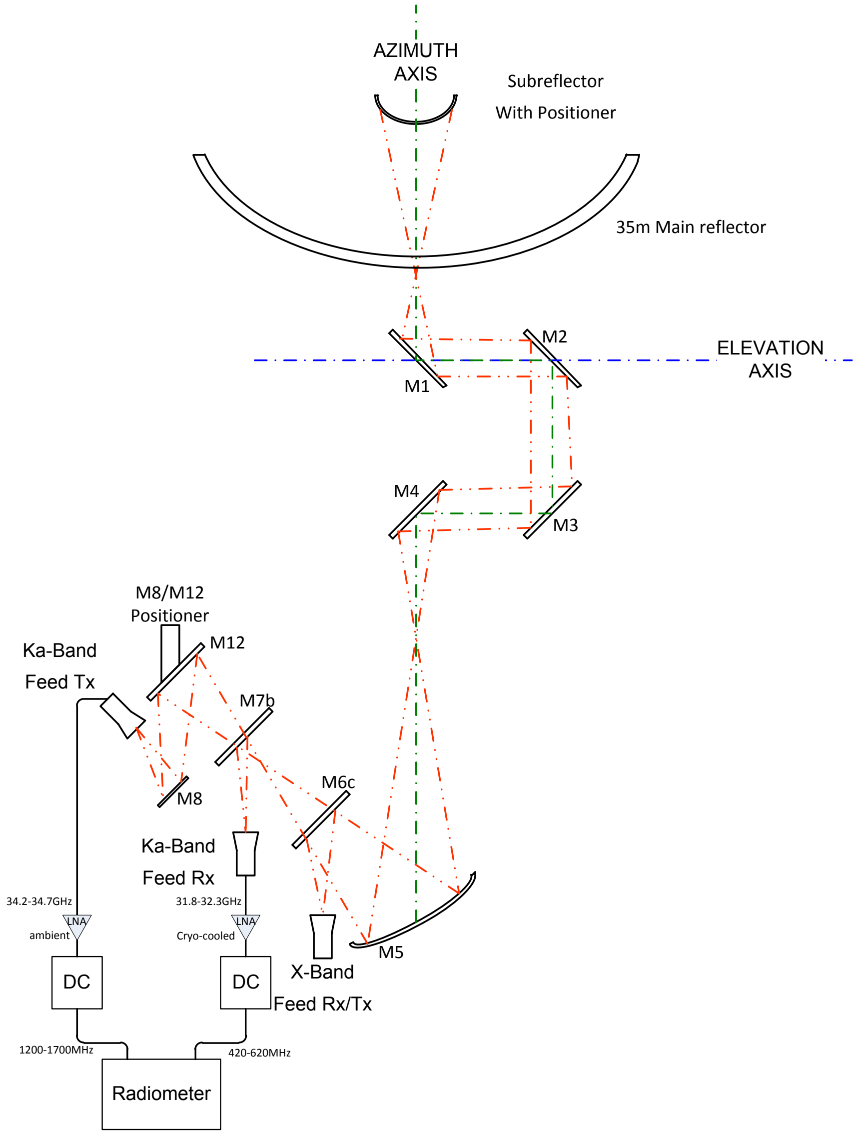

Fig. 6: Optical layout of the DSA3 with the miltable mirrors M8 and M12 and the dichroic mirrors M6c and M7b. In order to determine the pointing of Ka-Tx, a LNA at room temperature and down-converter (DC) is connected to the Ka-Tx feed. The DSA3 radiometer is operated in Total Power Radiometer (TPR) mode for the input frequency range 420-620 MHz (Ka-Rx) and 1200 – 1700 MHz (Ka-Tx) [4]. The radiometer does not allow simultaneous measurements at Ka-Rx and Ka-Tx.

2. Pointing accuracy and Ka-Tx gain loss for Rx-Tx beam offsets of 10,20 and 30 mdeg offsets for each axis. The campaign consists of alternating between Ka-Rx and Ka-Tx (with the desired Rx-Tx offset) radio star scans.
   The pointing accuracy is determined in this case by
   $$(dXEl,\ dEl)^{Rx\text{-}Tx} = (dXEl,\ dEl)^{Tx} - (\Delta XEl,\ \Delta El)^{desired} - (dXEl,\ dEl)^{Rx} \qquad (5)$$

   The Ka-Tx gain loss is obtained as ratio of the Y-factor of the measurement with desired Rx-Tx offsets compared to the reference case with M8/M12 positioner in “zero” position.

$$\Delta G^{Ka\text{-}Tx} = \frac{(Y-1)^{Tx\ with\ offset}}{(Y-1)^{Tx\ in\ "zero"}} = \frac{(\frac{c}{a})^{Tx\ with\ offset}}{(\frac{c}{a})^{Tx\ in\ "zero"}} \qquad (6)$$

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In Fig. 7, the pointing offset $(dXEl, dEl)^{Rx\text{-}Tx}$ (4) is shown, when M8/M12 are in its “zero” position. In this trivial case, the maximum difference measured between the receive and transmit beam is 2 mdeg. The distribution of the error indicates the presence of the expected systematic effects (polarisation dependency, residual mechanical misalignment). This is confirmed by the calculated (preliminary) coefficients CRX = 0.54 mdeg and CRY = 0.26 mdeg for the combination Rx-RHC and Tx-RHC. In order to get reliable coefficients for the SPEM (2), additional measurements have however to be carried out to cover better the full hemisphere.

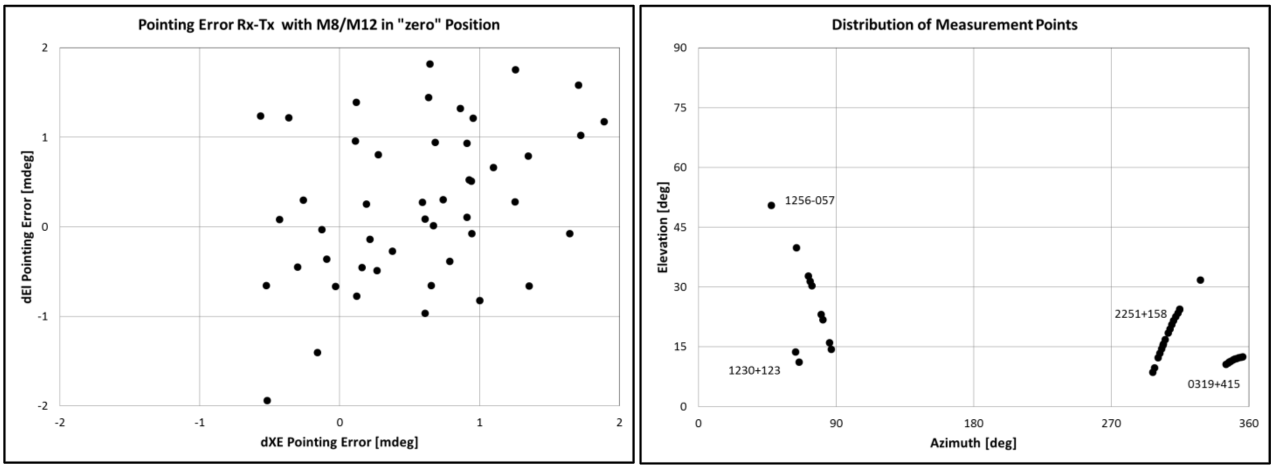

Fig. 7: **Left:** Pointing offset between Rx-RHC and Tx-RHC, when M8/M12 are in its “zero” position. Cross-elevation and elevation pointing errors $(dXEl, dEl)^{Rx\text{-}Tx}$. **Right:** Distribution of the 39 measurements observed with radio stars 2251+158, 0319+415, 1256-057 and 1230+123.

The measured Ka-Tx gain loss as function of the desired Rx-Tx beam offsets is shown in Fig. 8. In general, with increasing Rx-Tx offset, the effective Ka-Tx gain is reduced. The predicted “anomaly”, a gain increase for offsets in certain directions (here positive XEL) discussed in Fig. 5, is also observed in the measurements (Fig. 8, right). Similar to Fig. 5, the maximum gain is approximately 0.5 dB higher than in the “zero” position, in which the mirrors M8 and M12 are not tilted. The worst case Ka-Tx gain loss (Fig. 8, right) for the present configuration can be summarized to ΔG [dB] = -0.002 * (Rx-Tx Offset [mdeg])^2, which only slightly worse than predicted and could be explained with the measurement uncertainty.

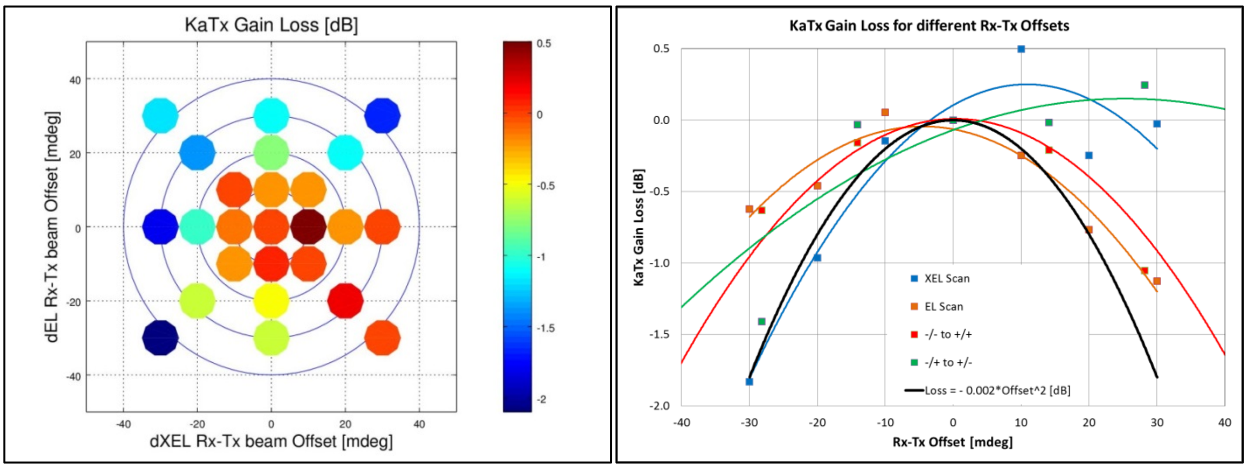

Fig. 8: **Left**: Ka-Tx gain loss according to (6) for different Rx-Tx offset values. (Case: Rx-RHC and Tx-RHC). Each dot corresponds to a measurement point. The Rx-Tx offset values have been varied from -30 to +30 mdeg in 10 mdeg steps. **Right:** Cut through the 2-dim scatter plot on the left side resulting in 4 graphs. The lines represent the best fit 2nd order polynomial for each cut. Additionally, the worst case Ka-Tx gain loss assuming a symmetric behaviour is shown.

Fig. 9, left shows the pointing accuracy respectively the residual pointing error vector. The error vectors show clearly a "vortex" around (0,0), which indicates the presence of systematic effects, which have not yet been considered correctly. The reason for the "vortex" shape is at present unclear, but it might be related to the transformation matrix coefficient C, which are not optimal (see section III). For Rx-Tx offsets of ≈ 10 mdeg, the total pointing error is ≈ 2 mdeg. The pointing error increases to 5 mdeg for an 30 mdeg offset.
Considering the measured (worst case) Ka-Tx gain loss (Fig. 8, right) and the loss due to the pointing error, a total Ka-Tx gain loss for the actual M8/M12 positioner system can be derived to ΔG [dB] = -0.003 * (Rx-Tx Offset [mdeg])^2(see Fig. 9, right). This corresponds for a 30 mdeg Rx-Tx offset to a loss of 2.7 dB, which is approximately 1.5 dB more than expected and primarily caused by the additional losses due to the pointing errors. The measurement data for Fig. 8 and 9 has been taken with the stars 1256-057 and 2251+158 resulting in a sky coverage sufficient to draw general conclusions. In spite of the very low Y-factors, the results exhibit a very clear systematic, confirming the predictions done during the design phase.

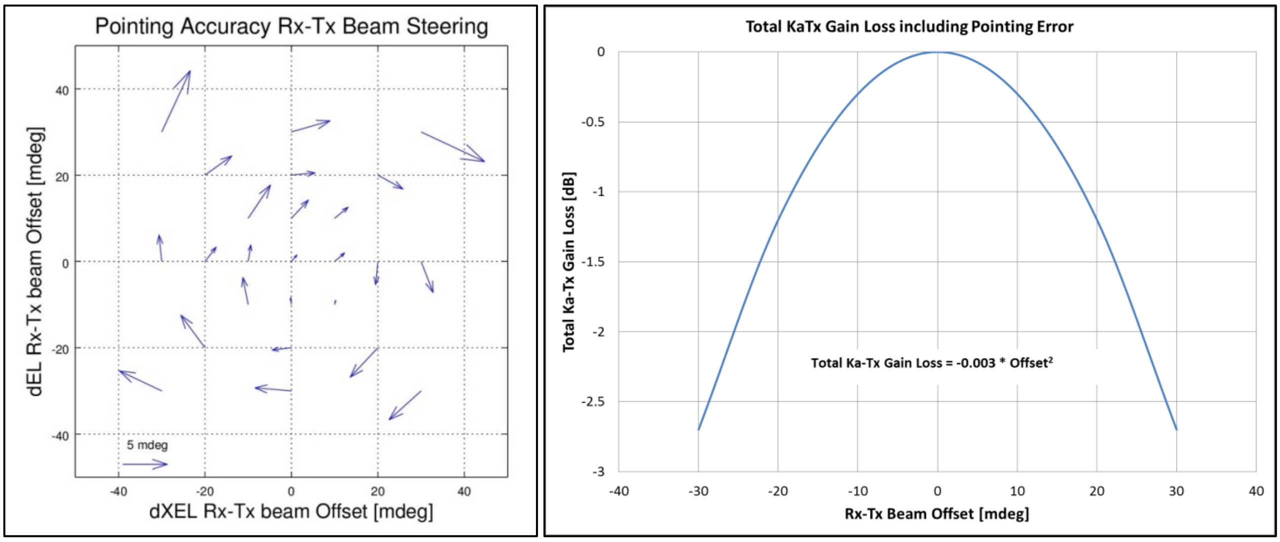

Fig. 9: **Left:** Pointing accuracy of the Rx-Tx beam steering according to (5) for different Rx-Tx offset values. (Case: Rx-RHC and Tx-RHC). The pointing errors are shown as vector.

CONCLUSIONS

The M8/M12 positioner installed in DSA3 to generate the necessary transmit beam offset at Ka-Band in order to cope with the beam aberration effect, is fully functional. In view of the selected novel and challenging approach to move the mirrors M8 and M12 in combination with the bent beam waveguide optics, the obtained performance figures give confidence for the operational usage. The measured performance is however worse than expected and its root-cause seems to be related to the non-optimal transformation matrix. In particular the unexpected large residual systematic pointing errors ("vortex") require additional thoughts, but once understood and solved, would also give the opportunity for a performance increase. An equation to determine the total Ka-Band transmit gain reduction has been derived for the present system. The distinct asymmetry of the present system (maximum gain is not in "zero" position) results in a penalisation of all directions, even if the reduction occurs in one directions only. Further analyses including simulations are therefore required to obtain a more symmetric relationship between the Ka-Tx gain loss and beam offset.

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