Pointing Correction at DL0SHF 10 GHz

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Introduction

To establish a pointing correction for the 7m diameter antenna on 10 GHz, a number of observations of the Sun and the Moon are undertaken between 6 dec 2014 and 8 april 2015, resulting in numerous position measurements covering the sky accessible for these two celestial bodies (Fig.1)

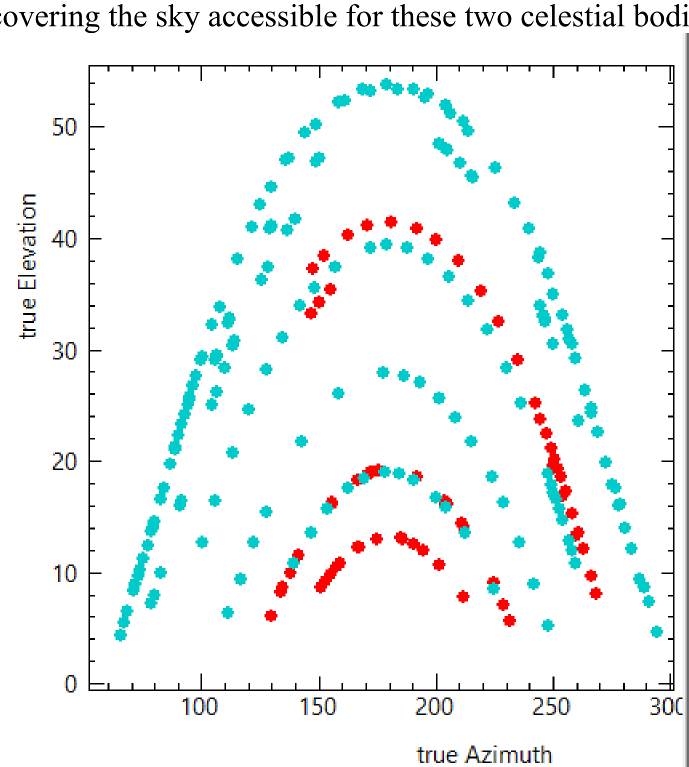

Fig.1 *The entire data set from 6 dec 2014 to 8 april 2015. The red dots are measurements with the Sun, blue green dots with the Moon.*

Measurement Technique

The data from 6/7 dec is obtained by the simple method of searching for the position which gives the highest signal level. All other data are secured by bracketing the maximum signal both horizontally and vertically, by offsetting to get a signal about 1 dB below the maximum. A typical example for such a record is shown in Fig.2. This technique has been found to yield results as accurate as 0.01°, the resolution of the positioning system. First, one offsets by typically 0.2° to the left in azimuth. After one or two minutes of observing the signal level, one offsets by the same amount to the right of the initial position. Small adjustments in the azimuth offset are applied until the signal is brought to the same level as on the left side. Then the true azimuth position is in the middle of the two offset positions.

Similarly, the elevation is determined. Due to the averaging the achievable resolution is better than 0.01°: In Fig.2 the deduced elevation offset is (0.07-0.34)/2 = 0.135, i.e. twice better than the resolution for the input to the positioning software. This situation is quite often encountered.

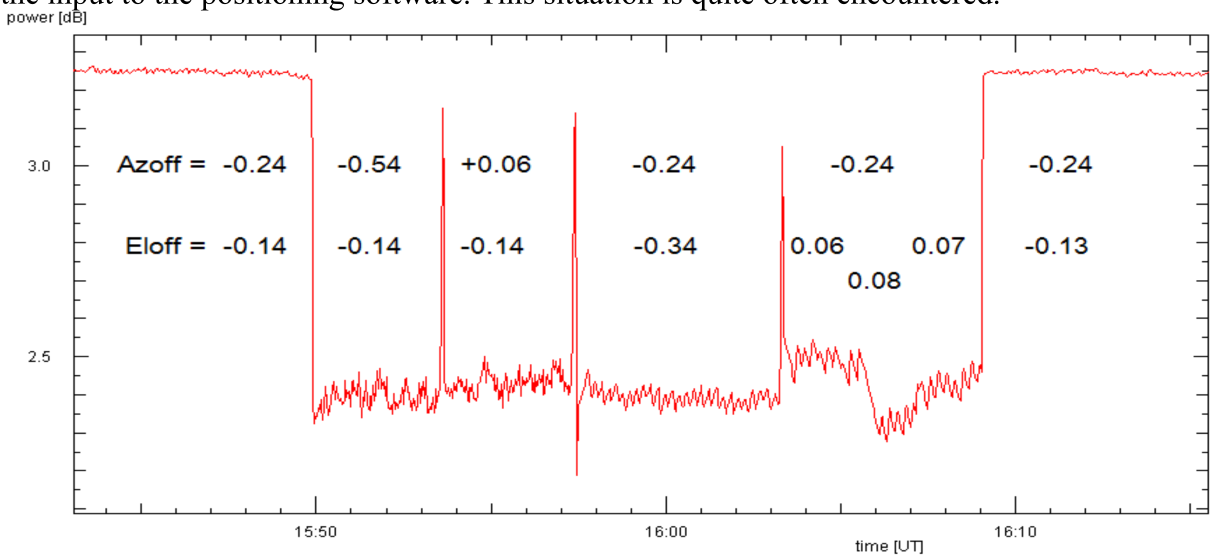

Fig.2 *An example of the bracketing measurement of the offsets between the actual and predicted position of the Moon. While the current azimuth is confirmed, the elevation requires a slight adjustment.*

The advantage of the bracketing technique can be seen in the comparison of the two lunar observations of 6/7 dec and 26 march. At both runs the Moon passed at the same maximum elevation of about 53°. Fitting a complete Q18 model to the march 2015 data gives a r.m.s. residual of 0.0058° which is quite satisfactory.

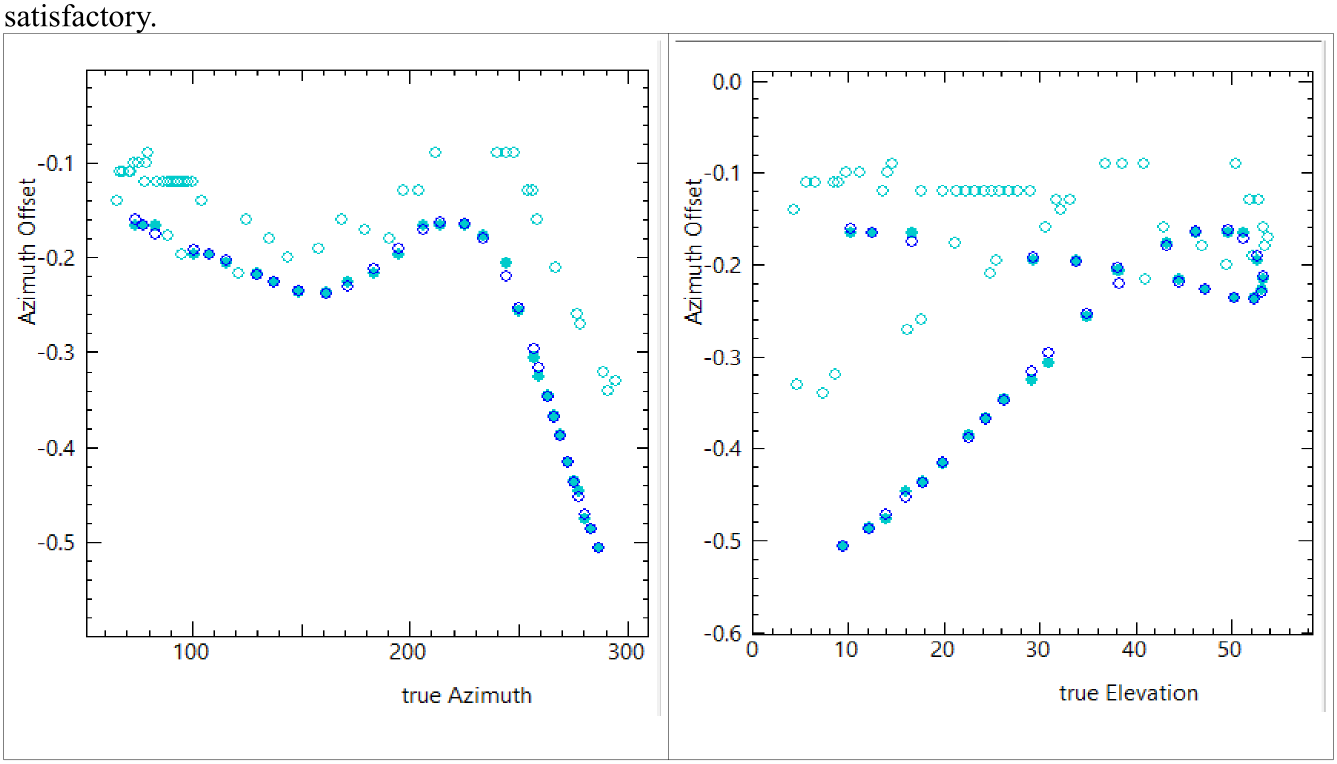

Fig.3 *Azimuth offsets measured on the lunar path on 6 dec 2014 (blue-green open circles) and 26 mar 2015 (blue-green dots) compared with the predictions based on the fit of the Q18 model to the 2015 data (blue circles).*

Inspection of the azimuth offsets (Fig.3) reveals that the two data sets giver very similar results, the only difference being the larger inherent scatter in the 6/7 dec data, due to the simple search method. The bracketing technique allows to trace the pointing errors with an accuracy of 0.01°, which allows to literally follow the evolution of the errors between successive measurements.

The azimuth offsets

- remain near -0.2° for azimuths below about 240°, but then show a very strong dependence on azimuth. One notes that they change by 0.4° over an azimuth range of only 50°.
- exhibit a loop-like dependence on elevation.
- show a nearly constant offset of about 0.1°. This is undoubtedly due to the necessary reconfiguration of the positioning system's base parameters on 1 feb 2015.

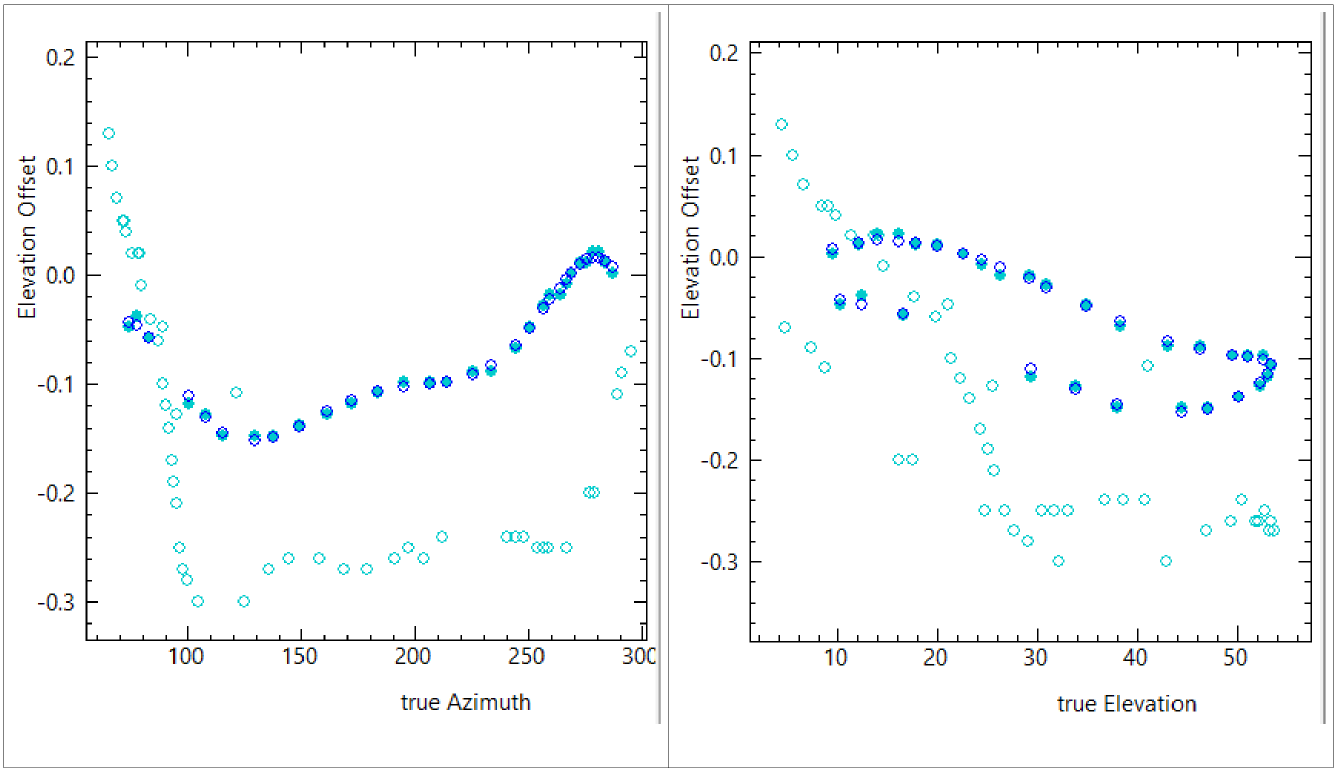

Fig.4 *Similar to Fig.3, but for the elevation offsets*

The elevation offsets (Fig.4)

- also show what seems to be a constant offset of about 0.3°, due to the reconfiguration.
- in the 6/7 dec data decrease very strongly from +0.12° to -0.3° between azimuths 60° and 100° as the Moon is rising, while there is no such hint in the 26 march data. Such a drastic change is also absent in any of the other data
- before Moon set on 7 dec show a stronger increase than the 26 march data. As such strong variations are not found in the later measurements, done with the bracketing technique, it seems rather likely that they are caused by the simple maximum search approach.
- from the 26 march measurements show more gentle variation with position than the azimuth offsets.

Could there be any errors in the predicted lunar positions computed during the observations and used for the determination of the offsets? Figure 5 compares these positions with the ones recomputed for the recorded times of observation. The lunar elevation differences are made to cluster very closely to the expected elevation dependence by assuming a time delay of 7 seconds for the computed position. The origin for this does not lie with the accuracy of the position predictions, but apparently is due to the difference of the positions issued to the motor control and the actual position where the motor is stopped, which is of the order of 0.02°. With this adhoc correction there remains only a random scatter of maximal 0.02° which is the basic setting accuracy of the positioning system. In elevation it is apparent that the correction for refraction is also correctly applied.

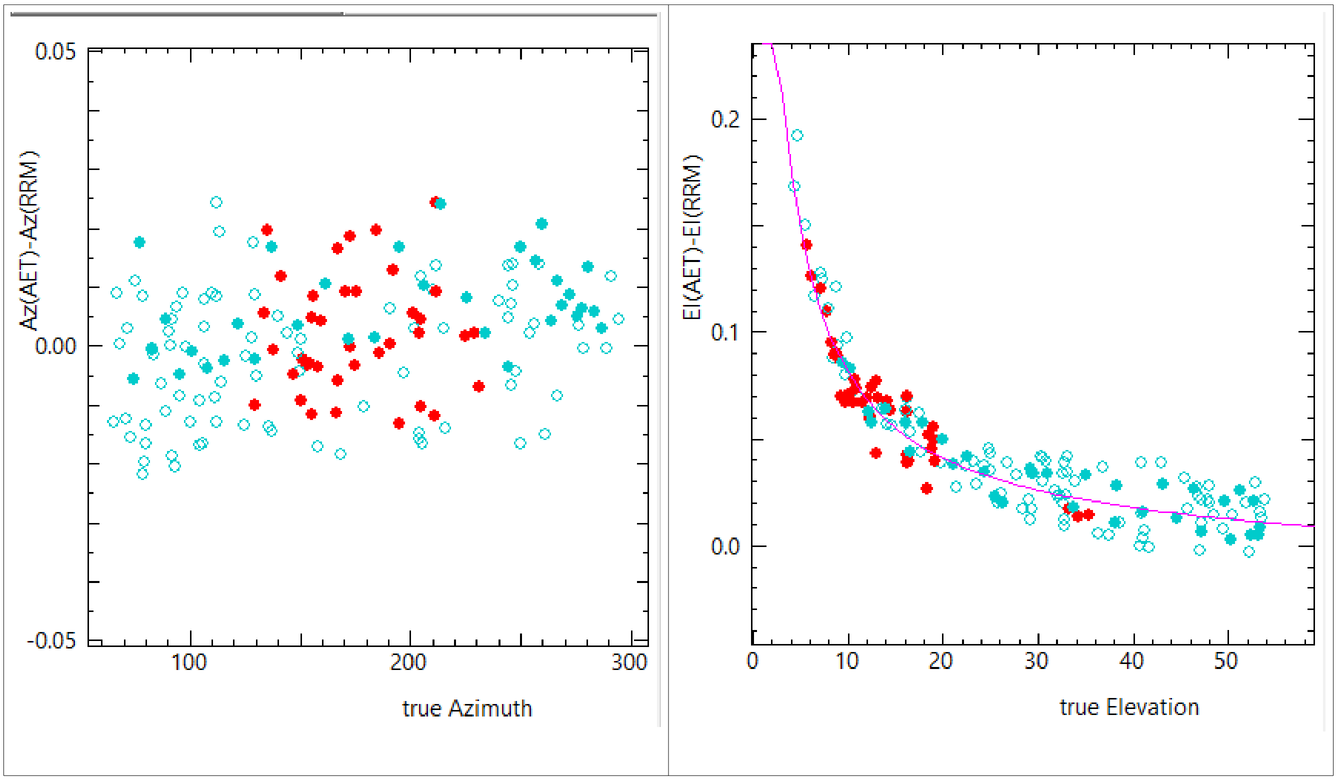

Fig.5 *Comparison of the true positions used in the observations with those computed afterward from the recorded timestamps*

Different Pointing Correction Models

The outstanding feature of the pointing errors for this antenna is the strong dependence of the azimuth offsets with azimuth, in particular the steep systematic drop beyond 240°. How do the pointing correction models deal with it? Already the overall fitting error, the r.m.s residual, gives an impression that the normal Bodenschief model, the P-model without the non-instrumental P6 term, and the Q10 model give rather poor fits.

	r.m.s. residual
Bodenschief	0.1015
P-model without P6	0.0784
P-model with P6	0.0124
Q10 model	0.0591
Q10 + asase + asace	0.0083
Q18 model	0.0059

The presence of the P6 term is obviously beneficial. Equally helpful is it to add to the Q10 model these terms for the horizontal correction:

$$H(A, E) = \ldots + \sin A * (asase * \sin E + asace * \cos E)$$

which apparently enhance the freedom of the method to fit the azimuth-dependence of the azimuth offset.

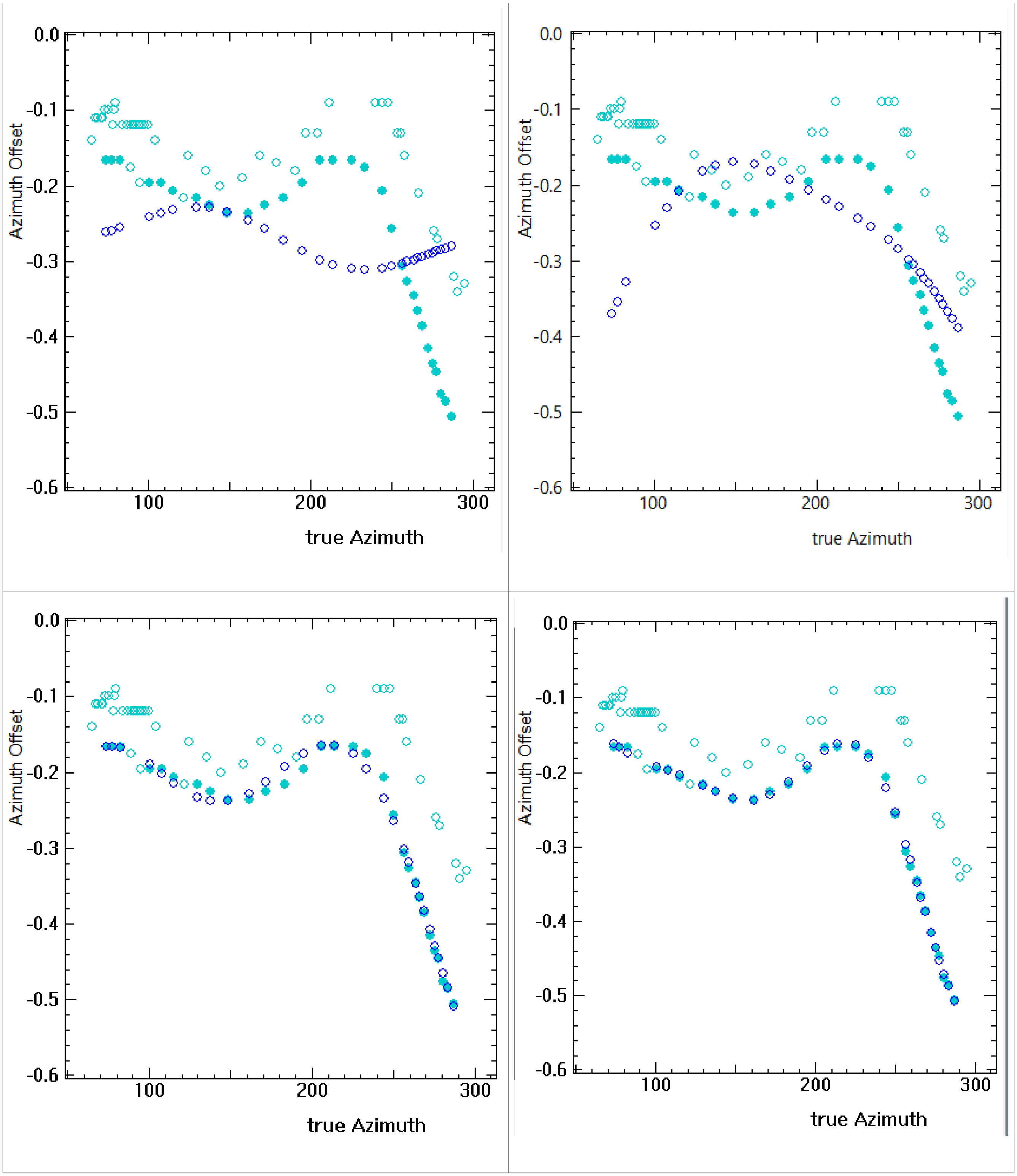

Fig.6 *Results of fitting the 26 march data with the normal Bodenschief model (uuper left), the P-model without the P6 term (upper right), the P-model with P6 term (bottom left) and the full Q18 model (bottom right).*

The Data of March and April 2015

Within about two weeks, from 26 march to 8 april, observations of the Moon and the Sun are collected which forms a consistent data set of measurements that are done in the same way and with the same level of reliability. Thus they can serve as the basis for a comprehensive pointing correction scheme. The sky coverage is shown in Fig.7. It appears that four tracks of the Moon, covering the range of 46° in declination, are sufficient to define a reliable pointing model.

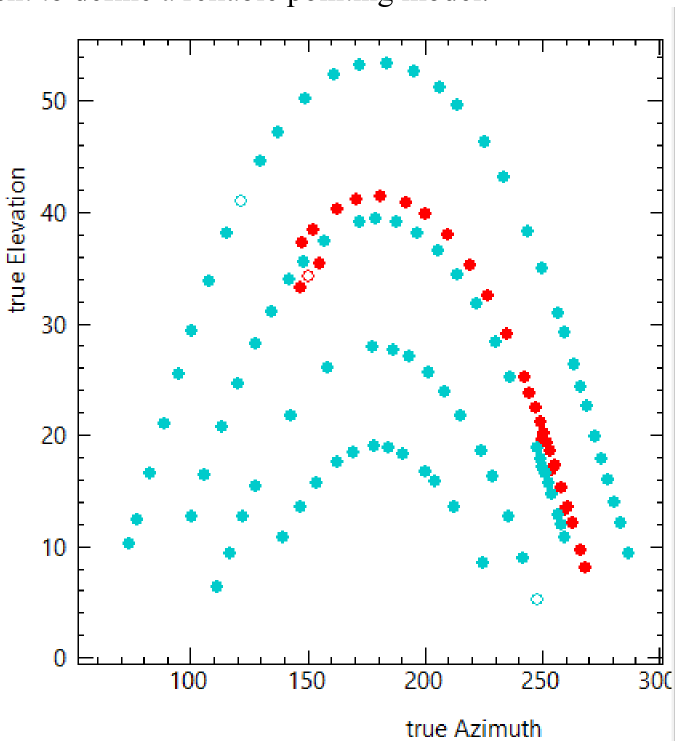

Fig.7 *The positions in the sky where measurements of pointing errors are taken with the Sun (red dots) and the Moon (blue-green dots) between 26 March and 8 April. The lunar observation are from 26 March (top track), 1 April, 4/5 April, and 7/8 April (bottom track)*

The r.m.s. residuals obtained with various pointing models for this data set do not differ very much: Bodenschief and the P-models give a value twice as high as the Q-models. This indicates that trying to match the sky tracks at different elevations calls for compromises.

	r.m.s. residual
Bodenschief	0.0844
P-model without P6	0.0796
P-model with P6	0.0700
Q10 model	0.0545
Q10 + asase + asace	0.0472
Q18 model	0.0445

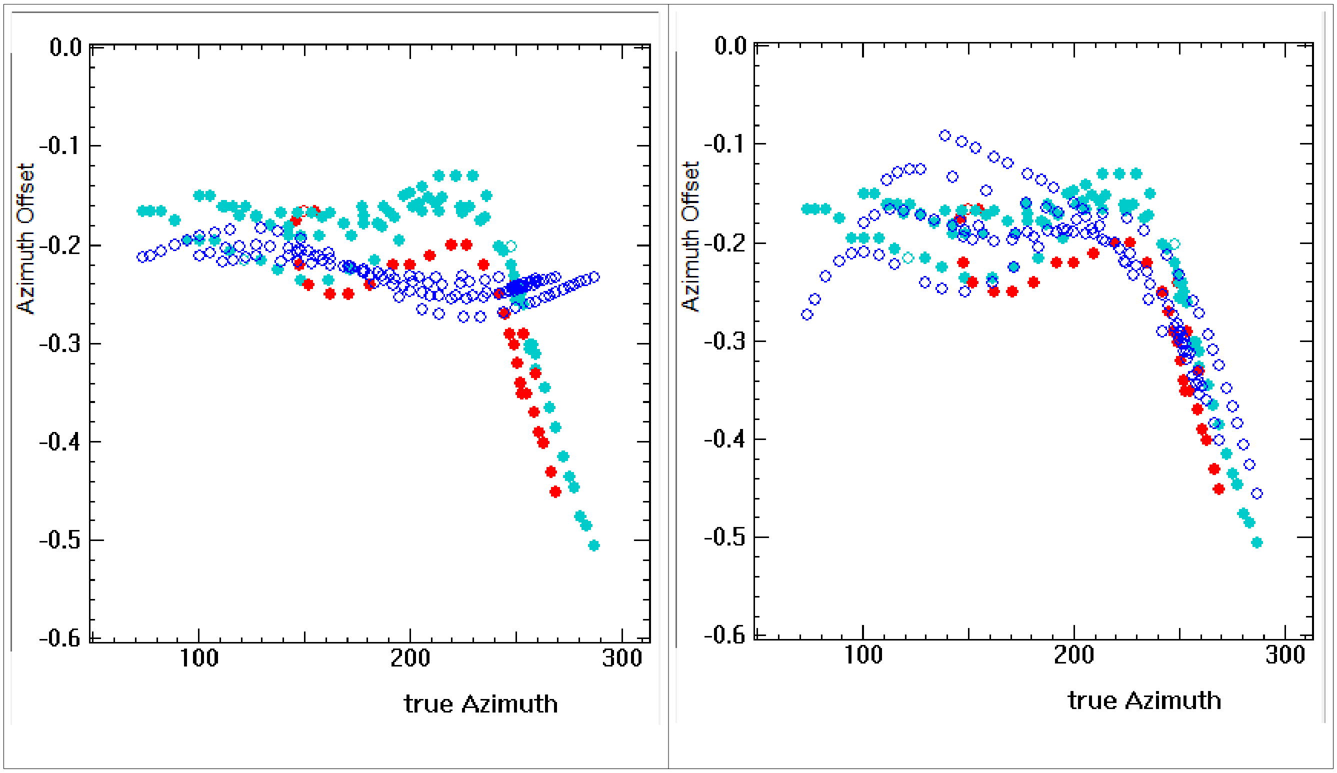

Fig.8 *Azimuth offsets as a function of azimuth for the March/April data of the Moon (blue-green dots) and the Sun (red dots), compared to the predictions from the best fits of the Bodenschief model (left) and the full Q18 model (right).*

Figure 8 shows that the Bodenschief model can only deliver a poor compromise. At azimuths larger than 240° the systematic strong variation of the azimuth offset cannot be reproduced, and therefore the pointing error there will remain large. This pertains only to sky tracks whose maximum elevation exceeds about 30°, and the problems appear in the West and Northwest. The lower sky tracks are well represented.

The full Q18 model is better suited to match the data (Fig.8 right), but this comes at a price: For azimuths below about 100° (viz. towards the East) the model tends to predict too low azimuth offsets. While these deviations remain below 0.1°, it indicates that the Q18 models require further correction terms. This is also apparent from the existence of a remaining systematic dependence of the azimuth residuals on azimuth (Fig. 9 left), while there is no such trend in elevation residuals (Fig 9 right)

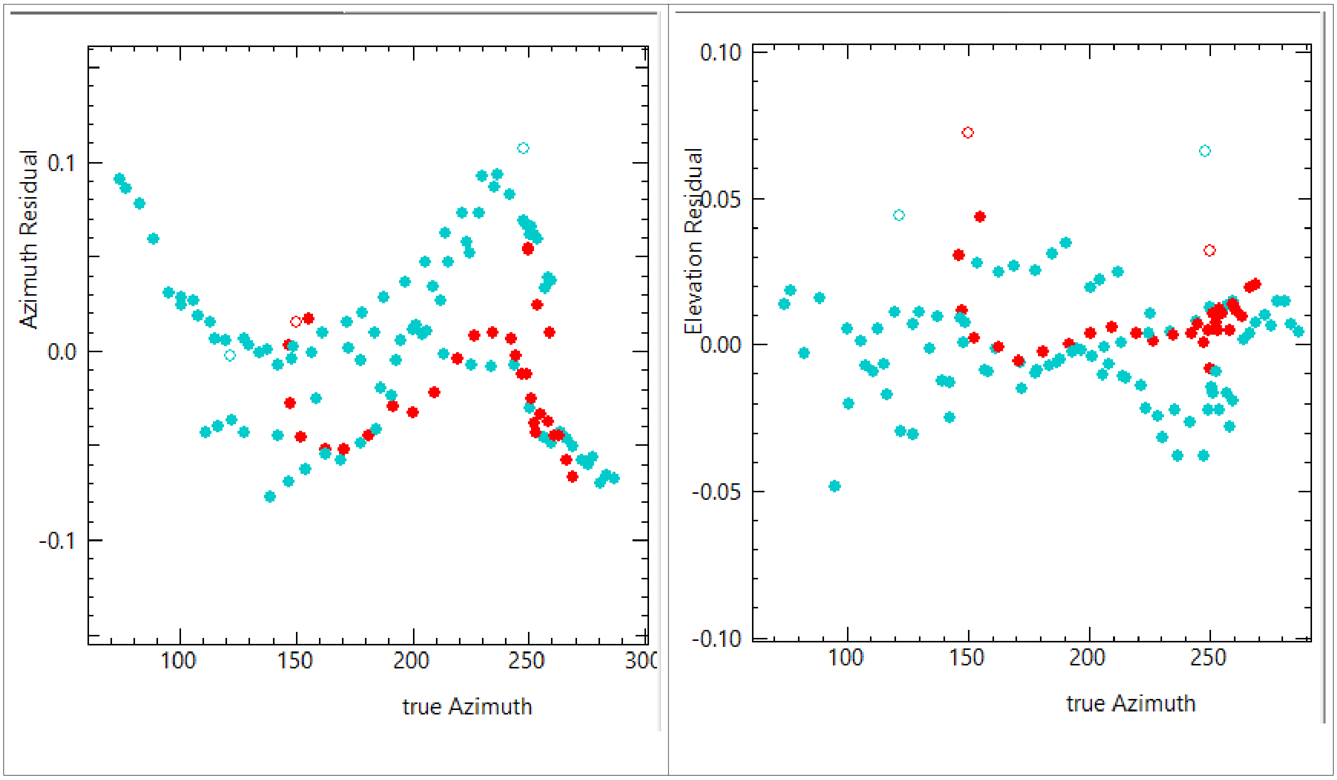

Fig.9 *Azimuth and elevation residuals as a function of azimuth.*

Most likely, the additional terms should enhance the model's capacity to deal with strong azimuth-dependence of the azimuth correction. This is indicated by the fact that predicted variation in the solar data (maximum elevation 41°) is as steep as the measurements, but that the variations for the lunar data (maximum elevations 28 and 18°) are steeper than measured. In order to match both data, the model is forced into a compromise, as it cannot model both data on their own.

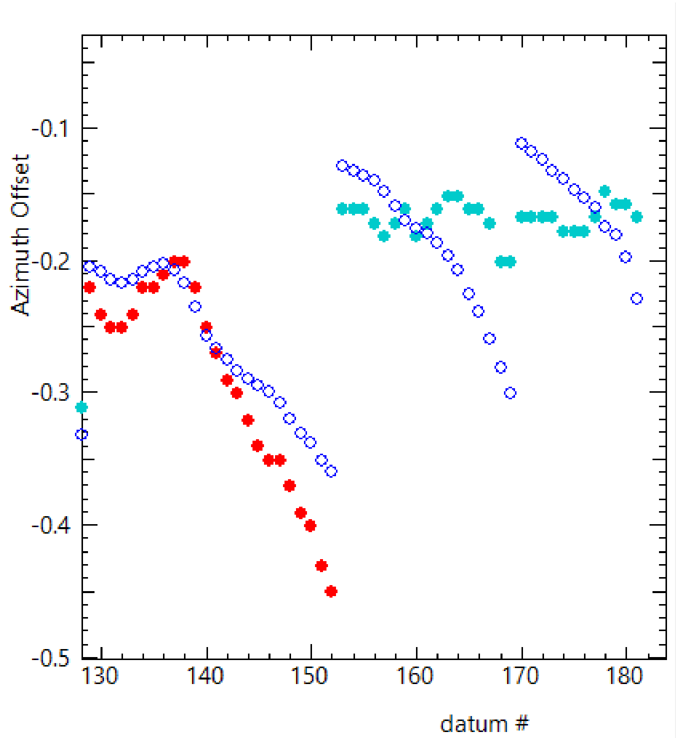

Fig.10 *Measured azimuth offsets (filled dots) compared to the predictions of the Q18 model (blue circles, for the high elevation track of the Sun on 4 April (red) and the low elevation measurements of the Moon (blue-green) on 4/5 and 8 April.*

Other Data

After the reconfiguration of the pointing system's base parameters, solar and lunar measurements are done on 2..4 February. The data does not show systematic differences with the March/April set, but since during these earlier observations the bracketing technique is developed and refined, the internal scatter of these data is higher. For this reason, these data are not used in this report and are not recommended for use in a pointing correction model.

Higher Order Corrections

To explore the effects of additional corrections, the following higher order terms are added to the azimuth correction:

$$
\begin{aligned}
H(A, E) = \ldots &+ q19*\cos(2A) + q20*\sin(2A) \\
&+ q21*\cos(3A) + q22*\sin(3A) \\
&+ q23*\cos(4A) + q24*\sin(4A)
\end{aligned}
$$

Results are most encouraging, as the r.m.s. residual decreases to 0.019°. Experimentation shows that the 2A and 3A terms are the important ones.

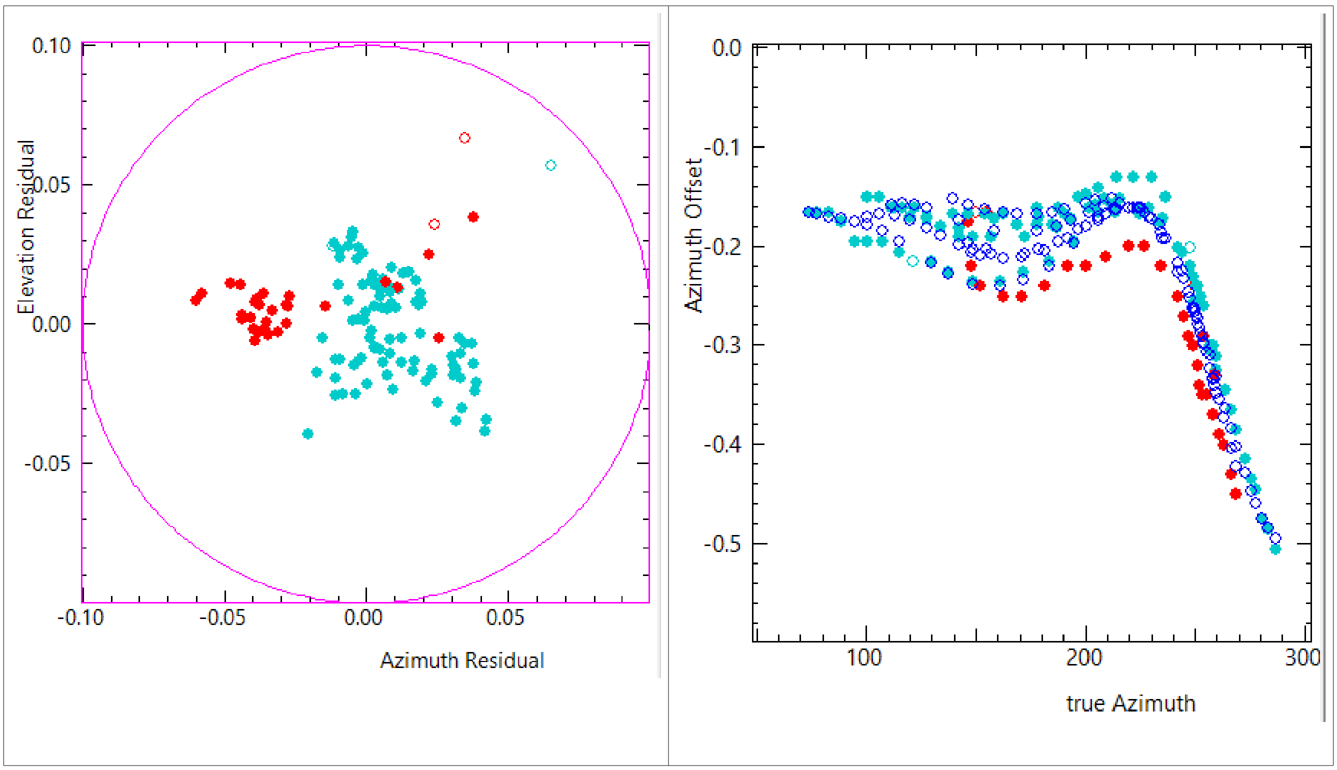

Fig.11 *Results from a model with azimuth corrections involving terms of higher order in azimuth. The plot of the residuals (left) and the azimuth dependence of the azimuth offsets, measured and computed (right, like in Fig.8)*

The residuals (Fig.11 left) cluster together in a small area. However, the solar data (from 1 April) form a cluster well separated from the lunar data. The azimuth offsets are reproduced in a much better way than by the Q18 model (Fig.8 right). However, the predicted offsets do not coincide with the solar data, but are found in between the lunar and solar data, most pronounced in the steep West side. This hints at an incompatibility or inconsistency of solar and lunar data.

Experimentation with other formulations, such as using mixed terms like sin2A*sinE, have not lead to models that are able to remove this unexpected feature.

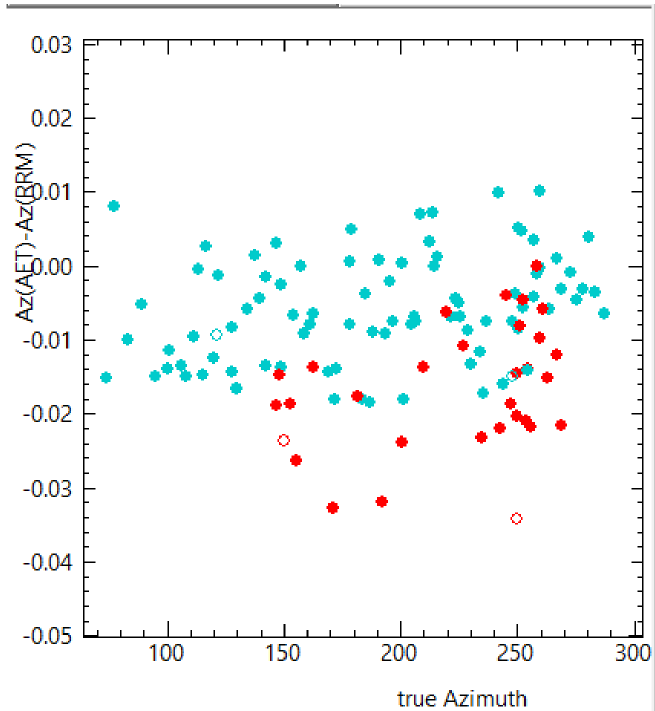

Fig.12 *Differences of the recorded azimuths and the ones computed from the recorded time stamps, as a function of azimuth. Red dots indicate solar measurements, blue-green ones are done with the Moon.*

Figure12 shows that there are systematic differences between the recorded azimuths and those computed from the recorded times. As had been noticed earlier (cf Fig.5) the overall accuracy of the pointing system is 0.02° and there can be slight differences between the demanded position and true position. This is apparent in the scatter of the data points. In Fig.12 the data are used without the adhoc time delay correction mentioned earlier. It shows that the average azimuth difference of the Moon grows from -0.05° in the East to 0.0°, while that of the Sun grows from about -0.02° to -0.01°. There is an azimuth-dependence of this position difference for either object, but also an offset for the Sun by 0.01°. The same pattern is found irrespective whether the positions are computed with the formulae of Meeus (1991) or from Montenbruck and Pfleger (1999), both of which agree with positions from JPL's Horizon ephemeris within 0.005°. Since the same formulae are used in the RönneRadiometer software for the prediction of the positions where the antenna is pointed as well as for the later analysis, the prediction formulae cannot be the origin of this discrepancy, but the antenna pointing system cannot be blamed, as it does not distinguish between a solar and a lunar position.

On April 4, before the long stretch of solar observations, the computer clock had to be manually set, as it had been running 7 sec fast. A time error of only 2 sec can cause an error of 0.0083° in azimuth, in the order of this discrepancy. As the clock usually speeds up, it cannot be ruled out that some of the observations are done without a specific effort to synchronize the clock, thus accepting a seemingly slight timing offset. This does not explain the error pattern seen in the predicted positions, but in the absence of a definitive explanation, it is taken as a temporary hypothesis ...

This error is slightly less than the accuracy of the pointing system, and so far had been masked by the random errors in the measuring and model fitting. But with the accuracy possible from the bracketing technique and the inclusion of higher order terms in the pointing model, it has become visible.

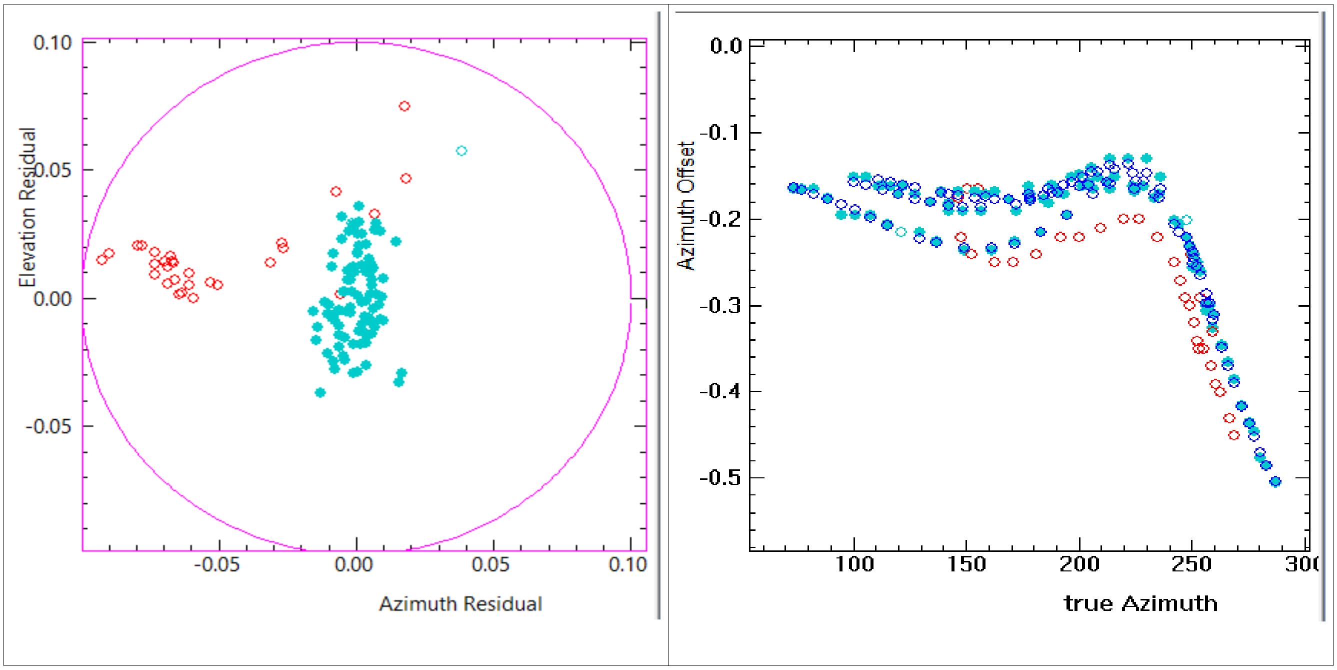

Fig.13 *Same as Fig.11, but using only the lunar measurements.*

If for a demonstration one uses only the Moon measurements, the fit becomes even better, with a r.m.s. residual of 0.0184°. As seen in Fig.13, the scatter in the azimuth offsets is about 0.01°, the resolution with which the user can enter positions or offsets. However, the scatter in the elevation residuals remains as high as in Fig.11, which indicates that further correction terms for the elevation would be required.

Conclusions

- Improvements in the measuring of the position errors by the bracketing technique bring the accuracy for a single measurement to 0.01°.
- With this accuracy it is possible to obtain data which allow to distinguish unambiguously between pointing corrections models, and to show the limitations of a certain model. It is possible to identify which correction terms would be useful to add to given model.
- A slight problem remains in an offset of 0.01° in the recorded true positions of Sun and Moon.

- For position measurements the computer clock must be synchronized to true UT within less than 1 second.
- The 10 GHz antenna requires the inclusion of higher order terms, in particular for the azimuth correction. While the Q18 model still gives a quite satisfactory match with a r.m.s. residual of 0.04°, more correction terms can bring the residual down to the resolution of the user-specified positions.
- The data set taken with the Sun and the Moon within 14 days in March and April 2015 is a good base to establish a reliable pointing correction model.
- The 'classical' Bodenschief model is not able to provide corrections for high-elevation tracks (i.e. maximum elevation larger than 30° which lead a celestial source to azimuths larger than 240°). Remaining errors of up to 0.2° would have to be accepted.