Pointing Correction for the DL0SHF 24 GHz Antenna

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Classical Pointing Model

The classical pointing theory of an astronomical telescope can be applied to a single-dish radio telescope; it describes fundamental alignment errors, like zero-offsets of encoders, eccentricity of encoders, incorrect alignment of azimuth and elevation axes, elastic deformation of the telescope structure, and collimation error of the radio beam. Stumpff (1972) formulated a widely used approach, which will be called the 'P-model': Because of the finite precision of the construction of the antenna, there will be differences between the the commanded (true) and the real azimuth (A) and elevation (E) values in the positioning system:

$$\delta A = A_{cmd} - A_{real}$$
$$\delta E = E_{cmd} - E_{real}$$

The horizontal and vertical true angles of this mispointing are

$$\delta h = \delta A \cos E$$
$$\delta v = \delta E$$

For small errors, the position corrections can be approximated by sums of individual errors which are given by nine parameters P_i and appropriate functions H and V of A and E (Stumpff, 1972, quoted from Greve et al. 1996):

$$\delta h = P_1 H_1(A,E) + P_2 H_2(A,E) + \ldots + P_9 H_9(A,E)$$
$$\delta v = P_1 V_1(A,E) + P_2 V_2(A,E) + \ldots + P_9 V_9(A,E)$$

with the functions specified for each term:

Type of error		H(A, E)	V(A, E)
Az-encoder zero-offset	P1	cos E	0
Collimation error	P2	1	0
El-axis tilt	P3	sin E	0
Az-axis N-S tilt	P4	cos A sin E	– sin A
Az-axis E-W tilt	P5	sin A sin E	cos A
El-encoder zero-offset	P7	0	1
Gravitational bending	P8	0	cos E
Gravitational bending	P9	0	sin E
Dec. error of source	P6	sin A	cos A sin E

This model has been used in several professional radio telescopes, such as the 30 m dish at IRAM.

Bodenschief

Martn Süfke's Bodenschief model comprises the encoder zero-offset terms P1 and P7, the tilt terms P4 and P5 for the azimuth axis, and a quadratic expression for the gravitational bending of the structure:

Type of error		H	V
AZ Ofs = Az-encoder zero-offset	P1	cos E	0
NS Roll = Az-axis N-S tilt	P4	cos A sin E	– sin A
EW Roll = Az-axis E-W tilt	P5	sin A sin E	cos A
EL Ofs = El-encoder zero-offset	P7	0	1
EL Sag = Gravitational bending		0	(90°-E)
EL Sag2 = Gravitational bending		0	$(90°\text{-}E)^2$

Note that in the code the corrections terms have opposite signs as in this report, because of the alternative definition of the errors as $\delta A = A_{geber} - A_{true}$. Although the original Bodenschief model is a subset of the P-mode, it differs slightly from it:

- the corrections for the Az-axis tilt are computed from the exact expressions of the 3-D rotation of the axes. Thus, they will also apply for larger corrections of several degrees and more. However, since the errors encountered in the DL0SHF antennas are small, this extra computational effort is not really necessary.
- the tilt corrections are done after the application of the other terms. In view of the smallness of the corrections this does not appear to be a significant difference.

Extended Bodenschief

The original Bodenschief model could be extended by adding two of the errors from the P-model. This would allow a greater freedom for fitting the data:

Type of error		H(A, E)	V(A, E)
Collimation error	P2	1	0
El-axis tilt	P3	sin E	0

Observations of the Sun

In September 2014, DK7LJ took measurements of the Sun which gave the following optimal solution:

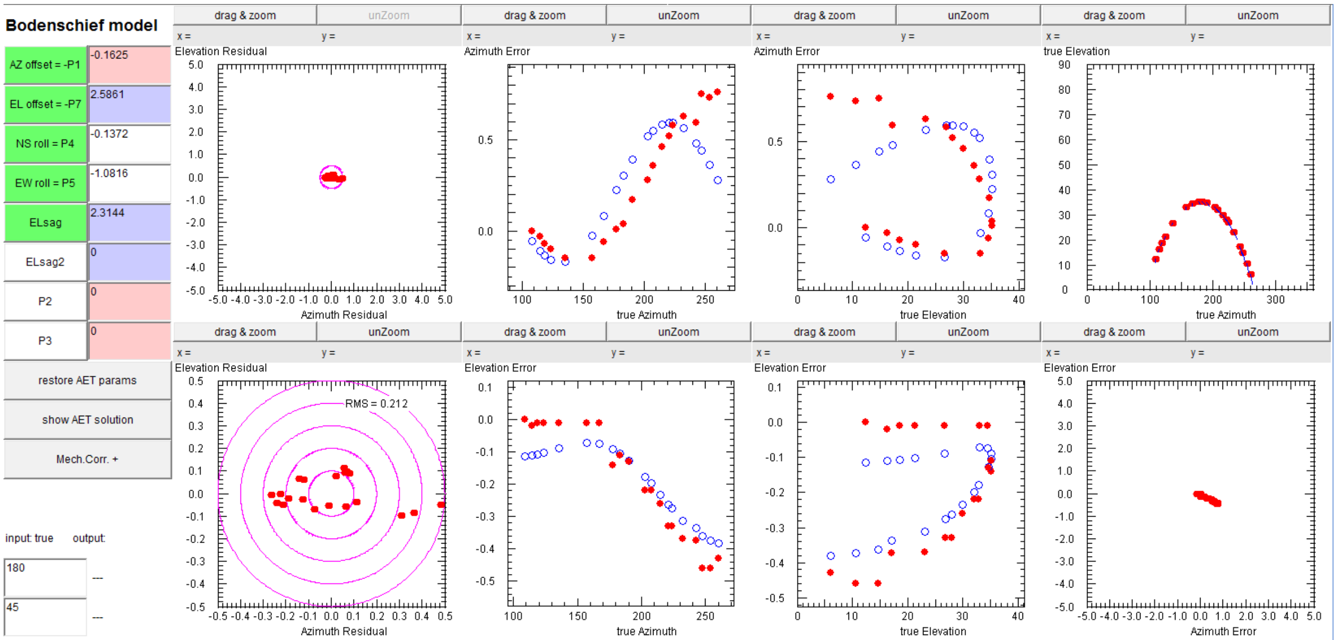

Fig. 1 *Fit with the standard Bodenschief model of the observations of the Sun during one day with the DL0SHF 24 GHz antenna. Red dots are measurements, blue circles the model predictions for that position.*

The remaining r.m.s. error is 0.21° which is rather disappointing, considering that the tracking error of the antenna is 0.02°. This best model reproduces only in a rough way the variations of Az and El errors with azimuth and elevation. While the elevation residuals are within ±0.1°, the azimuth residuals spread out as far as 0.5°. In particular, the predicted Az error varies with azimuth like a sine-function, but the data points are shifted towards higher azimuths, and above Az = 250° the azimuth error continues to increase.

The data points show a slight scatter about their mean relation. This can be taken as an indication for the accuracy of the position measurements. Except for a few larger jumps of 0.1° one may estimate the mean scatter as perhaps 0.03° which is close to the tracking accuracy of the antenna, viz. the threshold of 0.02° error for the antenna control system to update the position.

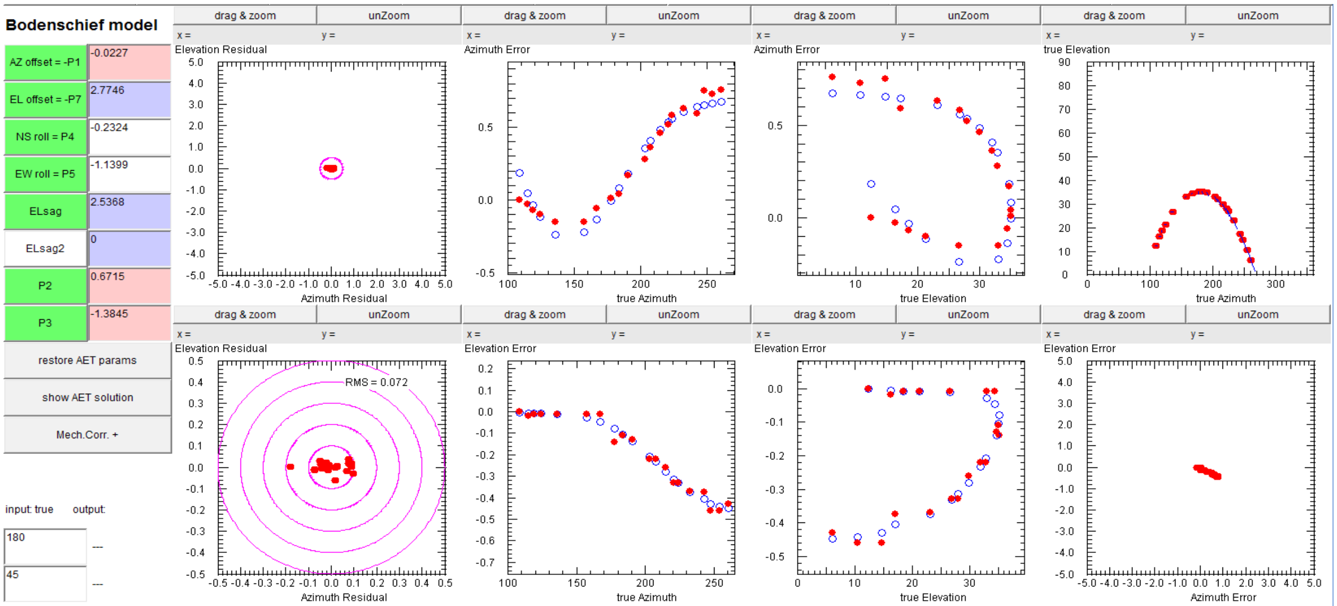

Fig. 2 *Fit with the extended Bodenschief model of the observations of the Sun during one day with the DL0SHF 24 GHz antenna.*

Simply adding the P2 and P3 terms – which is equivalent to applying the full P-model – improves the solution substantially: The remaining error now is 0.072° and the dependencies of Az and El errors on position are much more closely matched.

We note that the EL Sag2 term is kept as zero. Experiments showed that this parameter does not help very much in the fitting.

The Q-models

The P-model approach can be generalized by allowing simple combinations of sine and cosine terms of azimuth and elevation, which I shall call the Q-model: Note that both horizontal and vertical corrections comprise of 9 terms each, and that the corrections in azimuth and elevation which are equivalent to the tilt terms P4 and P5 are no longer linked by having common coefficients. Thereby we give up the physical interpretation of the individual terms, but with this greater freedom a closer fit may be achieved.

designation	H or V	P-equiv. for Az	P-equiv. for El
a0 or e0	1	P2	P7
ca	cos A		P5
sa	sin A	P6	P4
ce	cos E	P1	P8
se	sin E	P3	P9
cace	cos A cos E		
case	cos A sin E	P4	P6
sace	sin A cos E		
sase	sin A sin E	P5	

We may employ two varieties of models: In the Q10 model only the first five correction terms for azimuth and elevation are used, thus only simple sine or cosine functions, while the Q18 model includes all terms.

Fitting the solar data with these models results in a better match: The Q10 model gives an r.m.s. residual of 0.041°. With Q18 one gets an excellent fit with r.m.s. error of 0.023° which is close to the antenna's tracking error, and shown below:

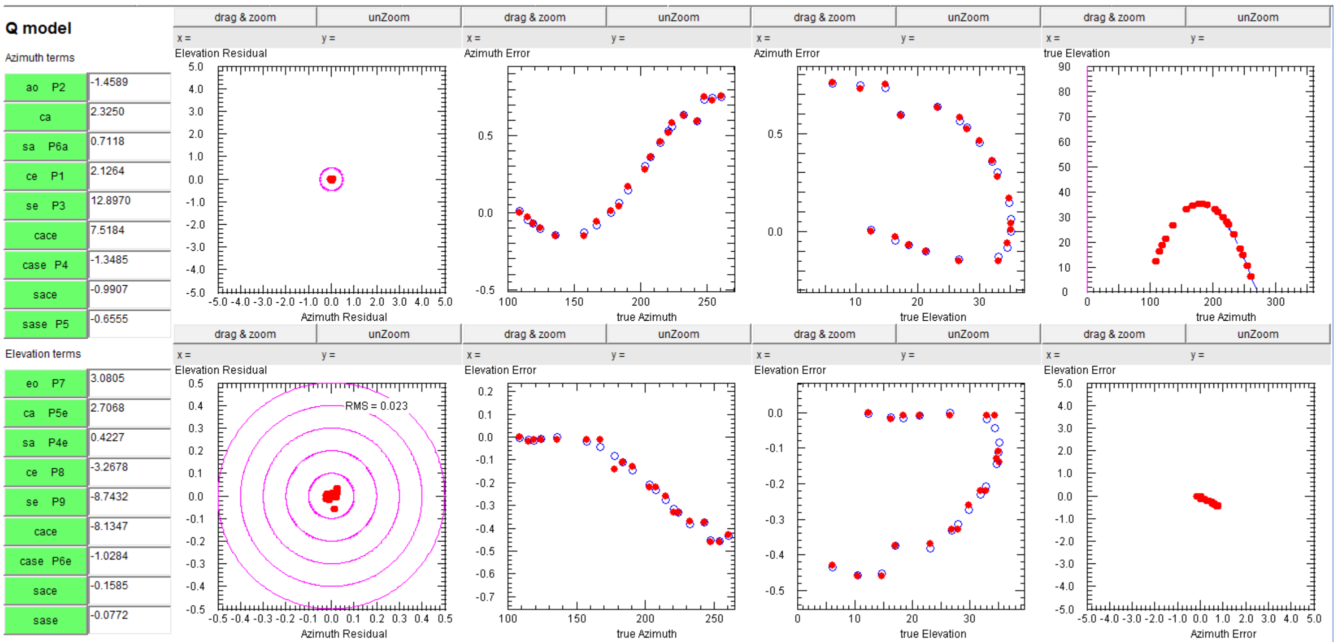

Fig. 3 *Fit with full Q18 model of the observations of the Sun during one day with the DL0SHF 24 GHz antenna.*

Since in the Q-models there is no linkage of azimuth and elevation corrections, as via the titlt corrections (P4 and P5 terms) in Bodenschief and P-models, the Q-model has a greater freedom to match the data. It is remarkable that the Q10-model already gives an improvement by a factor of 2 over the P-model. Thus, the eight additional, mixed terms in Q18 seem to be of a more cosmetic nature.

Inclusion of Moon Observations

While the solar data can give an excellent fit with models that are more complex than Bodenschief, such a fit applies only to the path of the Sun on the day(s) of observation. To cover a wider range in elevation, it would be necessary to observe the Sun both in winter and summer. However, the Moon goes through its range of declinations once per month. Therefore, observations of the Moon were done in autumn 2014 when its declination was lower and higher than that of the Sun.
By batch operations every hour, a 5 by 5 pixel map of 2° angular width was done of the area around the predicted lunar position. Fitting the data with a 2-D Gaussian profile gave the true lunar position. Since the antenna's positioning was controlled by the Bodenschief corrections from the preceding solar observations, Fig.4 shows the results – relative to the solar corrections – from the fit with the Q18 model.

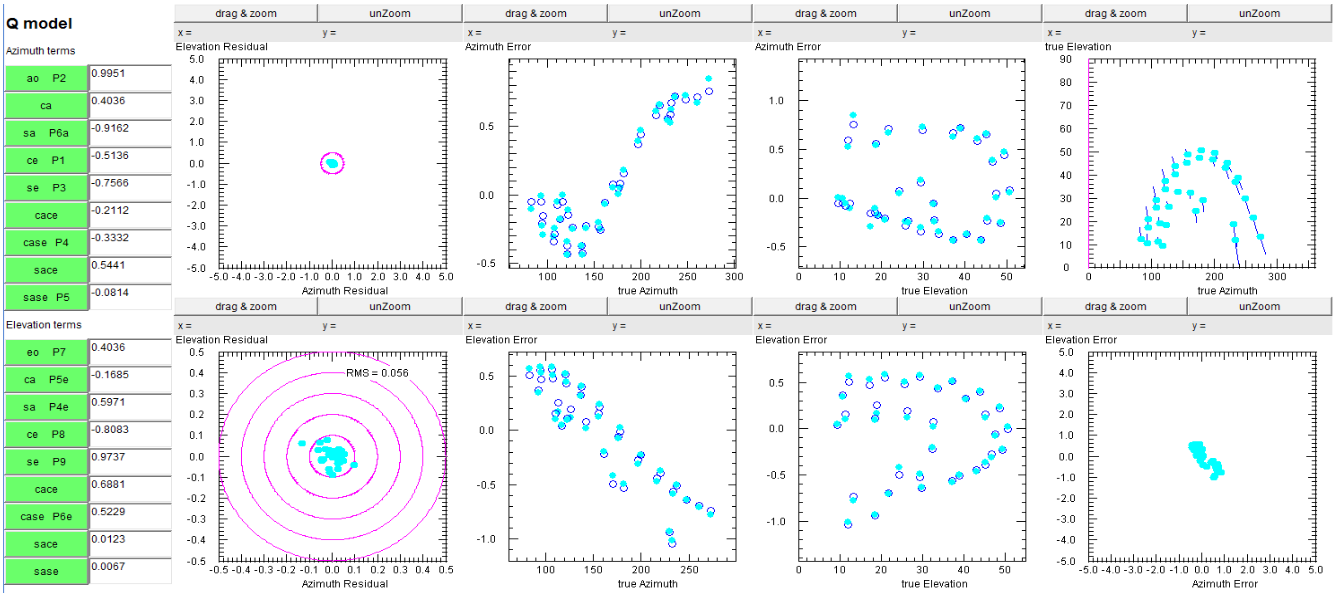

Fig. 4 *Fit with full Q18 model of the observations of the Moon during several nights with the DL0SHF 24 GHz antenna, relative to the Bodenschief-corrected positions (obtained with the Sun). The cyan dots are measurements.*

For these data, Bodenschief gave r.m.s. residual of 0.2°, the P-model 0.16°, the Q10 model a substantially better 0.089°, and the full Q18 model a slightly improved 0.056° (Fig.4).

Combining the solar data with the lunar data – with compensation of the Bodenschief solar corrections – one obtains the following residuals: original Bodenschief 0.4°, P-model 0.35°, Q10-model 0.18°, and Q18-model 0.16°, shown in Fig.5. The reason why the Q-models give only moderate improvement is probably the presence of noise in the lunar data. The automatic, unsupervised making of the maps may still suffer from positional uncertainties. The differences found in the levels for the maximum lunar signal from batch operations and those secured by manually searching for the maximum indicate position uncertainties of about 0.1°.

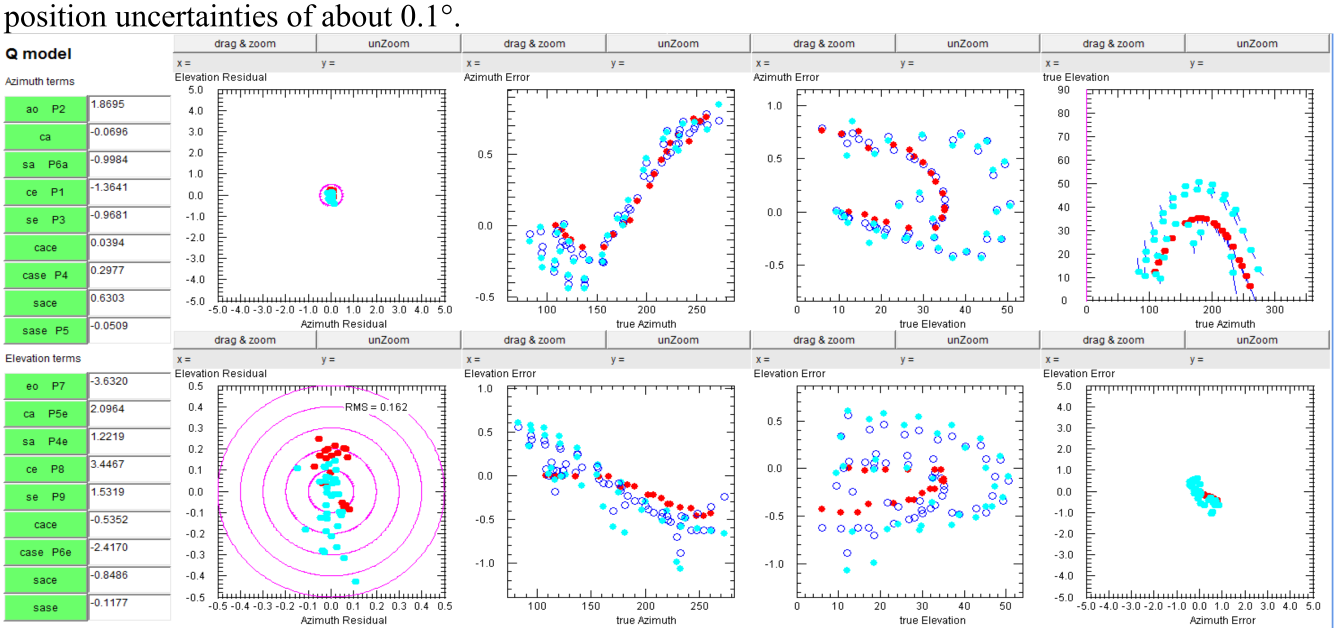

Fig. 5 *Fit with the Q18 model of the entire data on Sun and Moon from the DL0SHF 24 GHz antenna.*

Correction Tables

Since tables have been in use that specify azimuth corrections as a function of azimuth and elevation corrections as a function of elevation, which are compiled from manual observations of the Sun or other bodies, it is instructive to see how such an approach would fare for the above solar and lunar data.

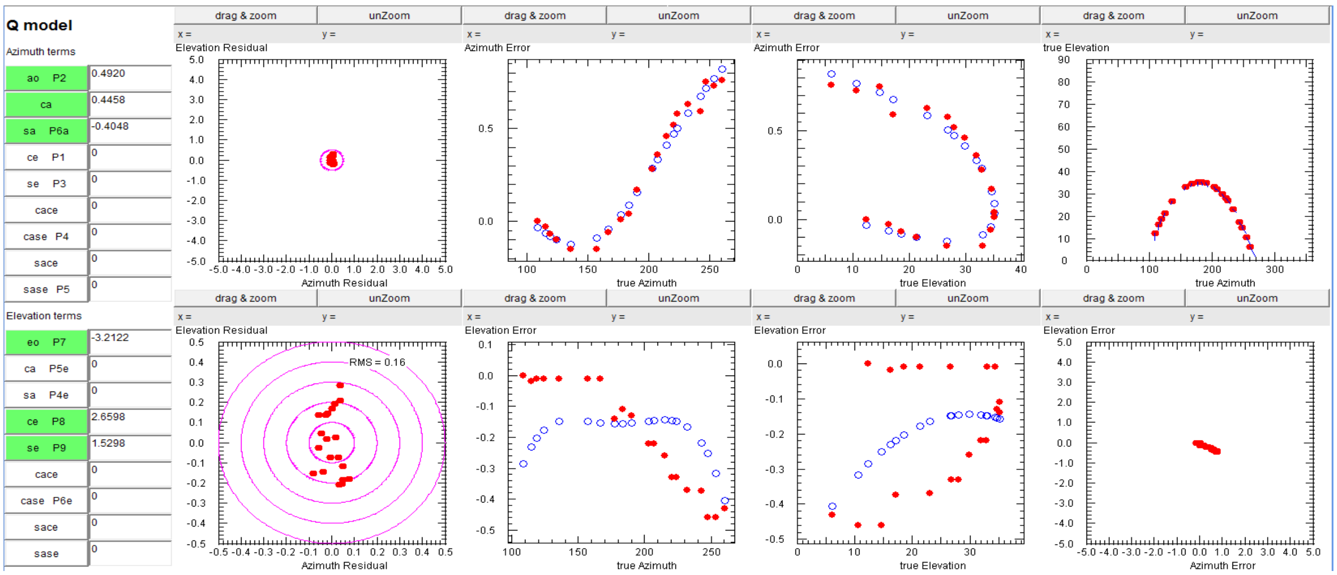

Fig. 6 *Fit with a table-like approach of δh = H(A) and δv = H(E) of solar observations with the DL0SHF 24 GHz antenna.*

Figure 6 shows that while the azimuth errors are rather well reproduced, for the elevation errors only a compromise average is found. The overall residual is 0.16°, which is less than one-half of the antenna's main lobe width. The fit in azimuth error is much better as that found by the Bodenschief model, because the latter lacks the correction P2 for collimation error, which apparently is important for the 24 GHz antenna. The azimuth error does not require any additional elevation-dependent correction. However, the elevation correction is very poorly represented in both azimuth and elevation dependence, which indicates the importance of the tilt corrections, which are not taken into account.

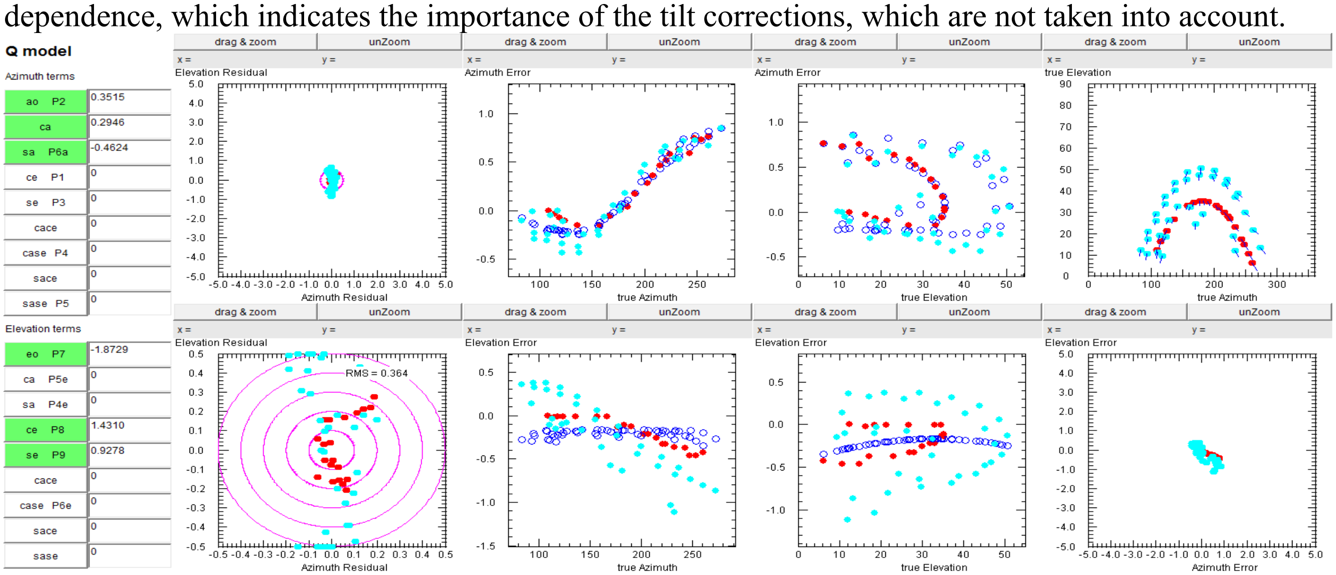

Fig. 7 *As Fig.6, but for the entire data of Sun and Moon with the DL0SHF 24 GHz antenna.*

The same statements apply also for the entire data set of solar and lunar position observations (Fig.7): While the azimuth correction is more or less acceptable, the elevation errors are very poorly represented by this simple approach. The overall r.m.s. residual is only 0.36°, about the width of the antenna main lobe, or a third of the Moon's angular diameter.

Conclusions and Recommendations

Experiments with Bodenschief showed

- The basic approach is sound and quite reliable
- As the optimization with the simplex method depends on a good choice of the initial parameters. In the present implementation the method is called up only once, and thus it is possible that the user may miss the true optimum. This could be improved by repeatedly applying the method to parameters slightly and randomly displaced from the last optimal set, and accepting a new result only if there is an improvement of the fit.
- The EL Sag2 parameter – which is often set to zero – is indeed not overly important. A formulation like in the P-model seemed to be more effective.

From these measurements and experiments with the data interpretation I can draw these conclusions

- The principal limitation of the Bodenschief model is the lack of the P2 and P3 terms for collimation error and elevation axis tilt.
- The current model could easily be improved by adding the other terms from the P-model. This would already give a substantially better match of the observed position errors.
- Likewise, the Q10- or even the Q18-model could be implemented without changes of the structure of the code.
- Combination of solar and lunar position observations seems quite successful for the determination of a global position correction model, as they can cover a large range in declinations (max. 46°). Measurements can be completed during about two weeks any time of the year.

About the 24 GHz antenna I conclude

- The combined solar and lunar position data obtained so far seems to be still limited in accuracy, thus allowing a best fit with a r.m.s. residual of only 0.16°. As the observations constitute something like a first test, the method of lunar observations by maps done in batch operations needs more improvements, especially for this narrow-beam antenna.
- The antenna needs corrections for collimation error (P2) and elevation axis tilt (P3)
- nothing else seems to be lacking or odd

References

- A.Greve, J.-F.Panis, C.Thum, 1996: *The Pointing of the IRAM 30-m telescope*, Astronomy & Astrophysics Supplement Series, **115**, 379
- P.Stumpff, 1972: Kleinheubacher Berichte **15**, 431