How to Improve the Position Measurements for Bodensschief

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The Results from December 2014

The position measurements collected for the 10 GHz antenna with the Moon and Sun during early december 2014 turn out to be not completely satisfying. Albeit the fit with the Bodenschief model arrives at a reasonable solution, there are several measurements which are in gross conflict with the others, as seen in Fig.1.

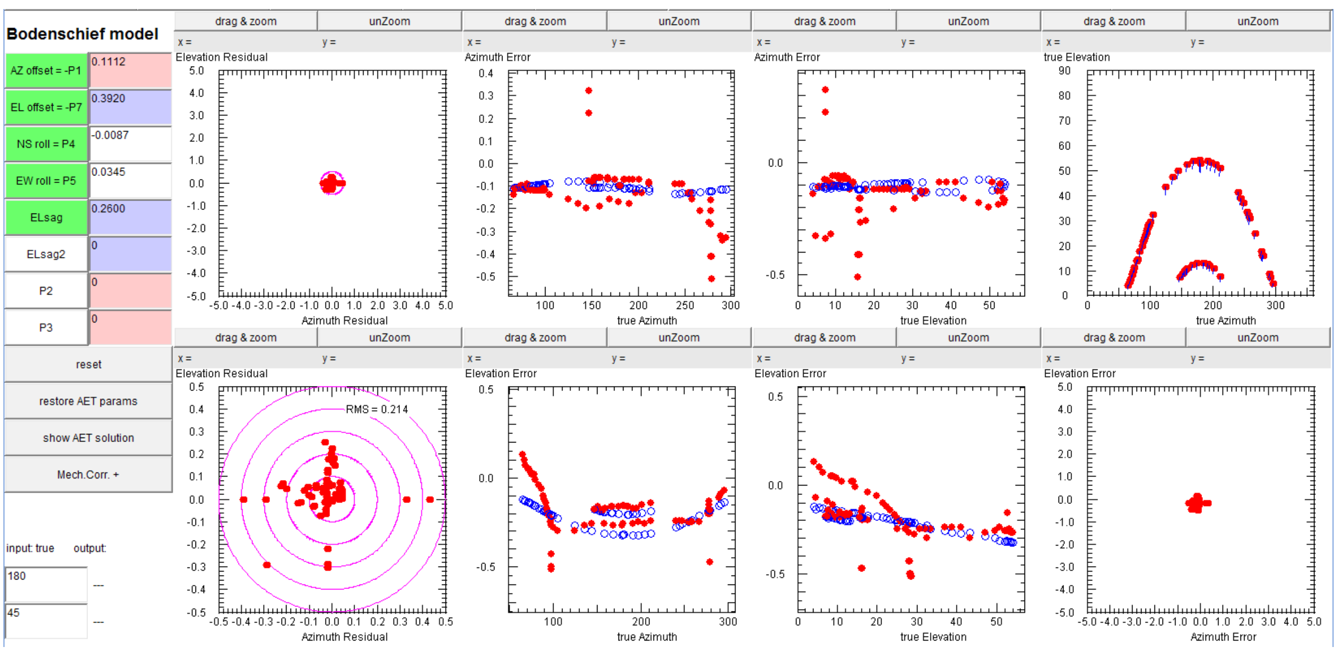


Fig.1 *The best fit with the Bodenschief model, using all data obtained between 6 and 9 dec. The red dots are measurements, the blue open circles are the model values for these positions.*

First of all, the overall r.m.s. residual is a rather poor 0.215°! Several measurements deviate strongly from the bulk of the data:

- azimuth deviations of -0.7° and -0.8° are found near Az = 150°, and of +0.4° and +0.5° near Az = 280°
- elevation deviations of +0.5° occur near Az = 100° and 280°

There are also other, less extreme, deviations which the Bodenschief model cannot reconcile, such as the train of elevation values for Az = 50° … 120° (corresponding to El = 4° … 30°)

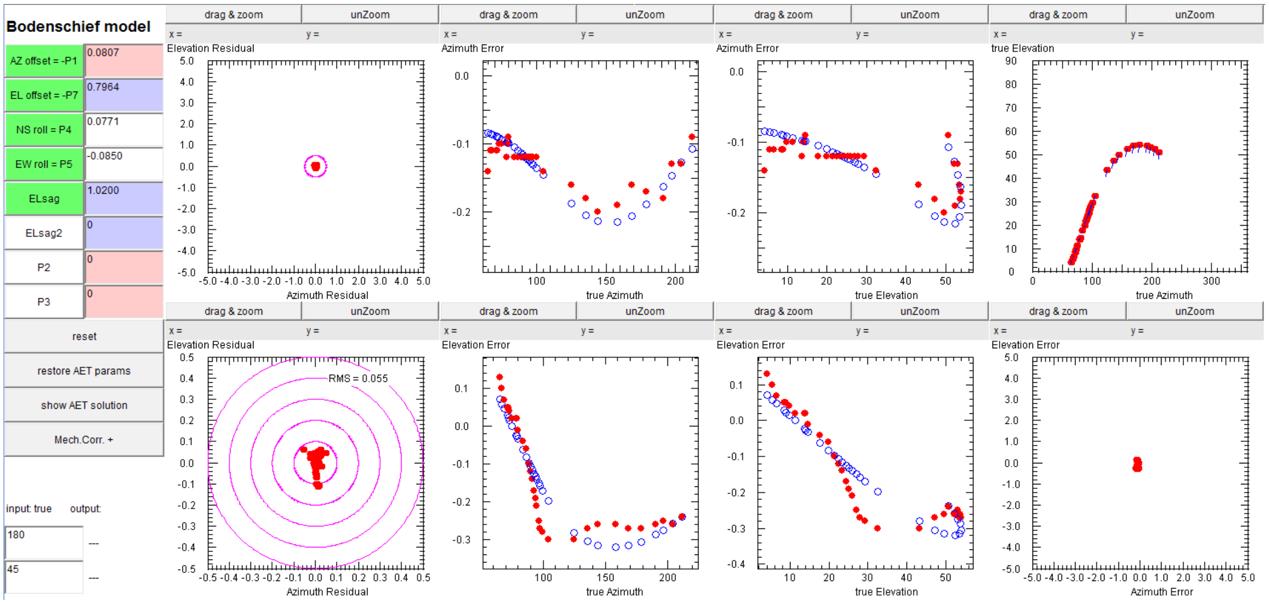


Fig.2 *As Fig.1, but using only the data obtained in the first half of the night of 6/7 dec.*

Let us look at the data taken in the first part of the night 6/7 dec (Fig.2): The overall r.m.s. residual is only 0.055°. This is only twice the accuracy of 0.02° of the tracking system, and thus represents a most satisfying result! In the azimuth deviations one notes that for Az = 80° … 100° (and El = 15° … 30°) there is no change in the measurements, while the model values show a systematic increase by 0.05°. As the measurements do not have any scatter, the azimuth correction evidently is left untouched, and no attempt is made to remeasure them. While the elevation deviations between El = 5°... 30° show the systematic increase with some scatter and are in good agreement with the model, the values taken between El = 20° … 40° steadily increase, overshoot the model values, and at El = 40° come below the model values.

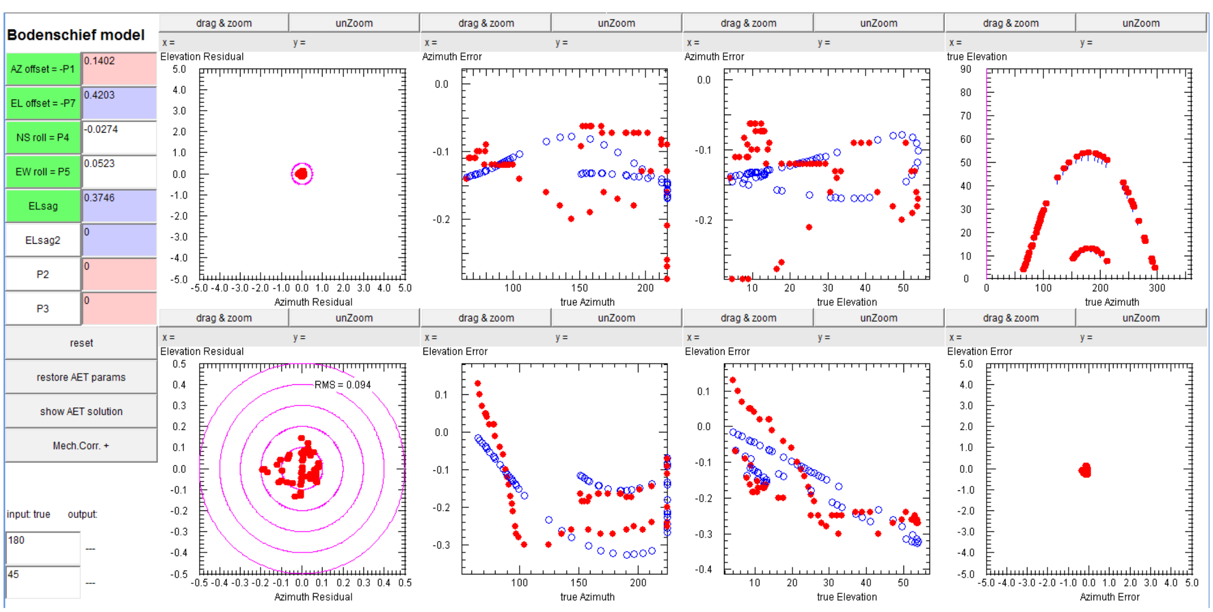


Fig.3 *As Fig.1, but using only the lunar data from the night of 6/7 dec and the solar data from 7 dec.*

Combining the data taken until sunset on 7 dec, viz. with the Moon and the Sun (Fig.3), one gets a very satisfactory fit: The overall r.m.s. residual is 0.094°, which is twice worse than Fig.2, but still substantially better than the entire data set (Fig.1). The combination of data obtained for the two objects high and low in the sky would certainly imply an increase of the r.m.s. value.
One also notes that the descending path of the Moon shows up with remarkably strong deviations in azimuth: between Az = 250° … 300° the deviation increases from +0.1° to +0.3°. This cannot be matched neither by the Bodenschief model nor with the P-model (r.m.s. 0.087°) or the Q10-model (r.m.s. 0.065°) although these give an improved match. Its greater freedom allows the Q18 model to yield a most satisfactory fit, with r.m.s. residual of 0.034° (Fig.4). It is also capable to account for the 'overshoot' in elevation deviation near Az = 120°, El = 40° (cf. Fig.2)

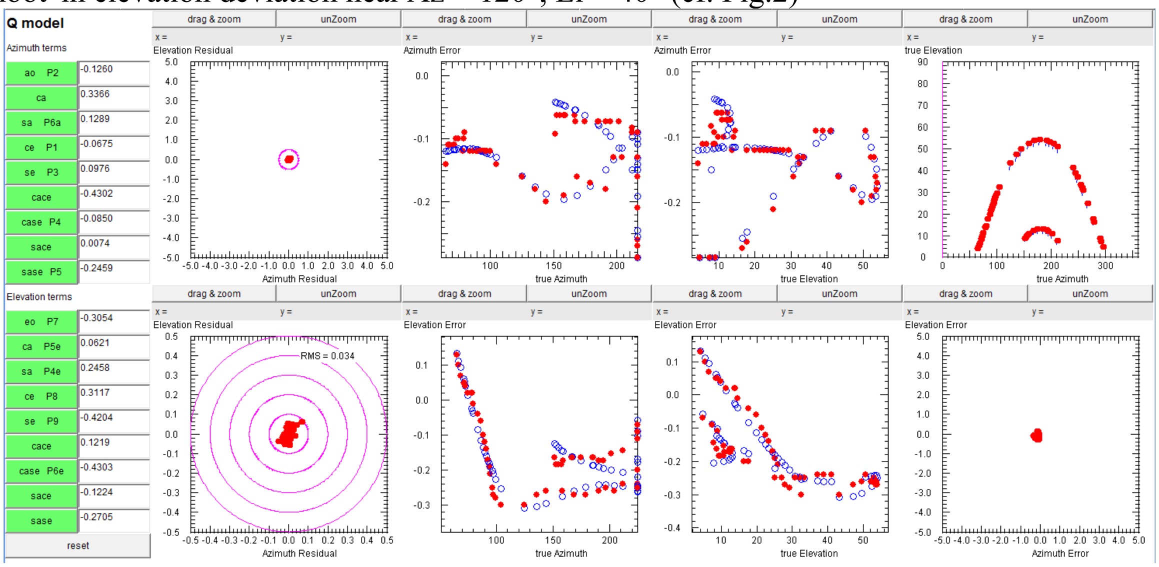


Fig.4 *As Fig.3, but using the full Q18 model.*

The Short Measurements

The data which show up as strong differences to the main part of the measurements are taken at various times on 7 to 9 dec within a few minutes. They are individual test measurements for certain sky positions.

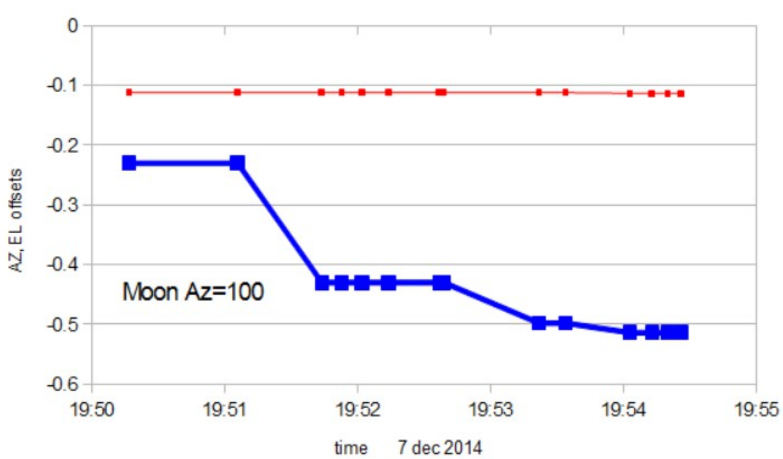


Fig.5 *Lunar measurements in the evening of 7 dec. The blue curve depicts the offsets in elevation, the red curve in azimuth.*

The first group is from the evening of 7 dec (Fig.5) : The elevation offset increases from -0.2° to -0.5°, i.e. by 0.3° within 4 minutes, while the moon moves in the sky by only 1 deg. As one can safely rule out that the antenna changed its elevation within these 4 minutes, it simply means that during this time a higher maximum signal is found. The data from the previous night show that at this sky position the offsets were -0.1° and -0.3° in Az and El, respectively. Hence the first two measurements are quite close, but why do the later measurements yield much higher elevation offsets?

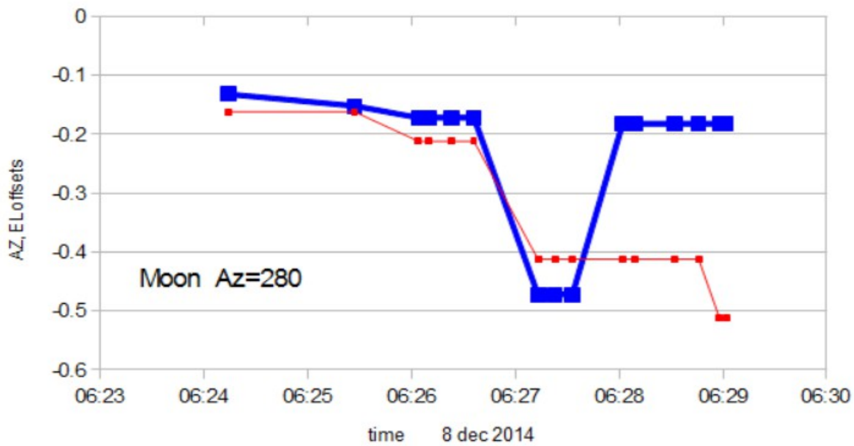


Fig.6 *Lunar measurements in the morning of 8 dec.*

The measurements of the setting Moon (Fig.6) show perhaps that during these observations a better maximum seems to have been found at -0.5° in elevation, but then it is realized that the initially found lower value of -0.1°...-0.2° is the true one. This is corroborated by the previous morning's data giving offsets of -0.1°.But the azimuth offset is changed by 0.4°, the previous value is around -0.3°.

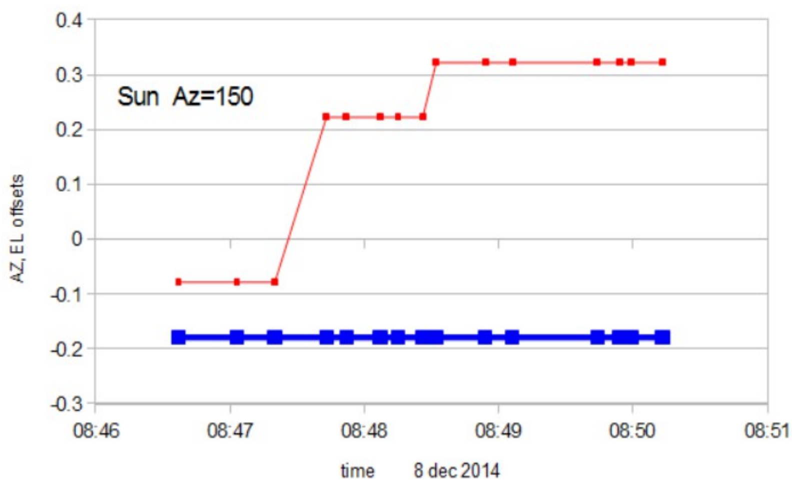


Fig.7 *Solar measurements in the morning of 8 dec.*

Figure 7 shows a subsequent measurement with the Sun. The elevation offset is found to be constant, near -0.2° and agrees well with the measurement from the previous morning. For the azimuth deviation one notes a strong change, ending up at +0.3° which is in disagreement with the previous value of -0.1°. Evidently, one is distracted from the initial value – which probably is the correct one!?

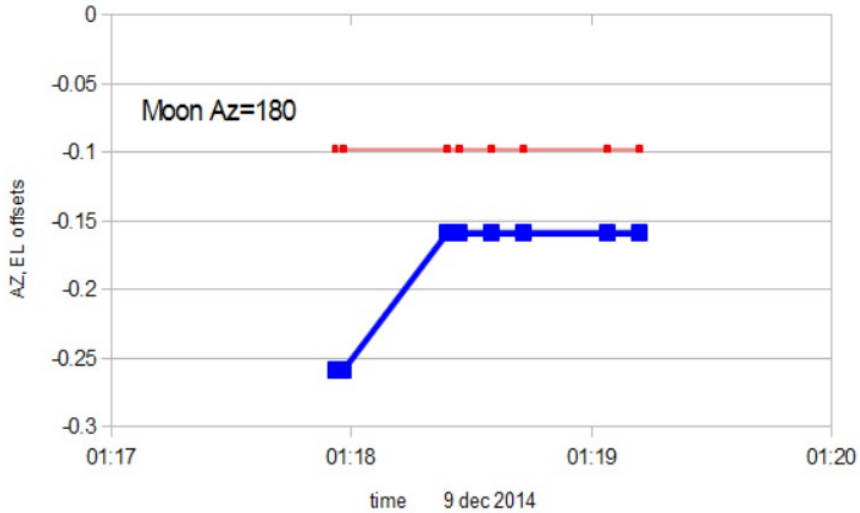


Fig.8 *Lunar measurements in the night of 9 dec.*

The subsequent observation of the meridian passage of the Moon (Fig.8) gives an azimuth offset of -0.1°, which agrees well with the 6/7 dec data. However, the elevation deviation is found to be -0.15° rather than the previous value of -0.27°.

In summary, the short measurements give disappointingly large deviations from the previous systematic measurements. However, the differences are not systematic but rather indicate that random errors seem to dominate. As the discrepancies remain below 0.5°, the angular diameter of Moon and Sun, which determine the angular variation of the signal power, it seems very likely that the short measurements suffer from the difficulties finding the true maximum in a rather broad distribution.

Measurements of 2 and 3 feb 2015

The data secured so far are not complete: The Moon is observed only during a high path in the sky, and the Sun covers a rather low path. For a proper position correction scheme it is necessary to observe the paths of intermediate elevation.

During the night of 2/3 feb 2015 a rather complete set of lunar measurements are taken, followed by solar measurements during the day and the ascending path of the Moon in the evening of 3 feb. During these observations great care is taken to obtain measurements as accurate as possible, using similar techniques previously used on 24 GHz, but also to try out methods to assure that the true maximum is observed – this will be described in later sections.

Overall, the measured offsets agree very well with those from 6/7 dec. No systematic differences are found. Thus one can combine all lunar and solar data, excepting the short measurements. The fit with the Bodenschief model is quite satisfactory with a r.m.s. residual of 0.091°, as shown in Fig.9. It is remarkable that the data points show a random scatter around the relation predicted by this best model. However, some of the data deviate by as much as 0.1° from the model, which is more than the tracking accuracy. This indicates that some of the data must be view with some caution, as it might be less reliable.

Similarly, the residuals are 0.083 and 0.057 with the Q10 and Q18 models (not shown).

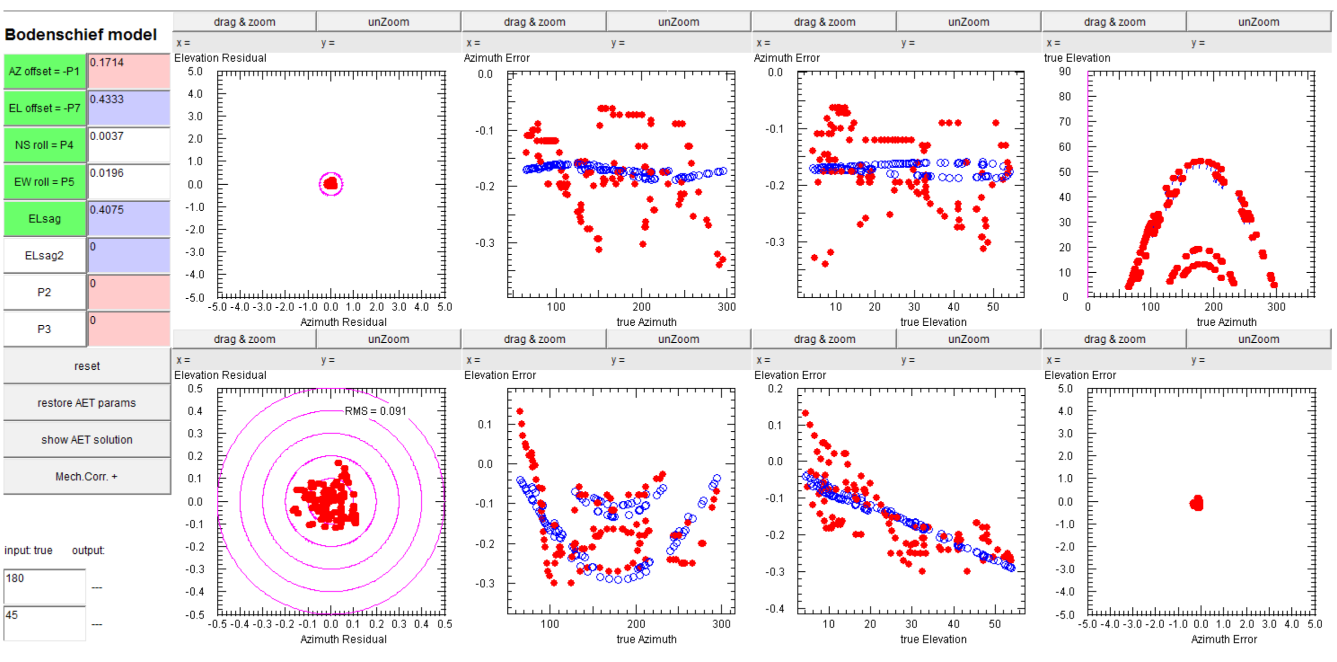


Fig.9 *Bodenschief analysis of the combined lunar and solar data of 6/7 dec and 2/3 feb.*

During the second set of measurements it is also found that the sky conditions do not affect the accuracy to distinguish the maximum position. The signal level may quite a bit, but it does so on longer time scales, and therefore never poses a serious problem. Figure 10 traces the signal variation during the solar observations. The numerous sharp dips in signal level are caused by moving the antenna well away from the current position, before starting a fresh search for the maximum position.

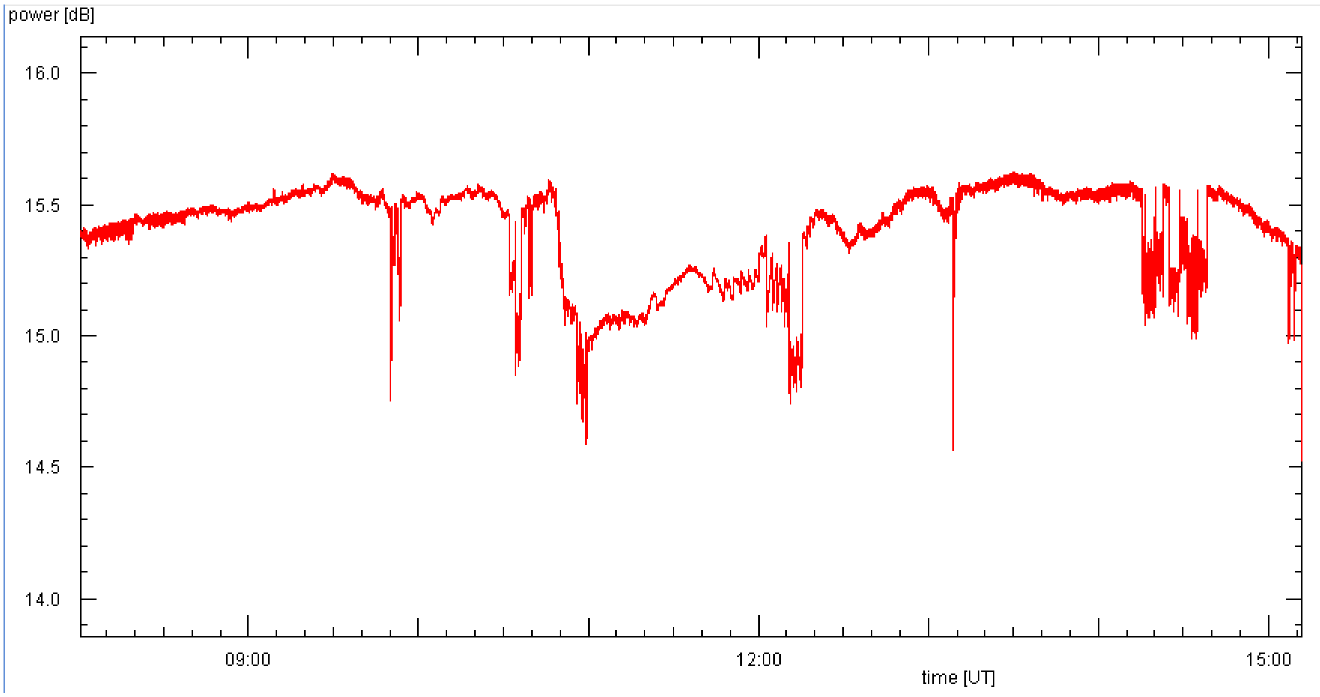


Fig.10 *Variation of the signal level during the solar measurements on 3 feb.*

How can one find the maximum signal?

Since the antenna's angular response closely resembles a Gaussian function, this presents a problem when one wants to find the source's position by searching for the maximum signal. Close to the centre of the beam the signal does not change much. Any fluctuations from receiver noise will add further difficulties to find the true maximum. Having to find the maximum in two dimensions – in azimuth and elevation – renders this task even more difficult.

For the 10 GHz and 24 GHz antennas the beam is narrower than the Sun or Moon. Thus the determining width is the source angular diameter of about 0.5°. Figures 11 and 12 show the expected relation of signal level and position offset (expressed in time during a drift scan), for the Moon and the 10 GHz antenna, for which the Moon is 3 dB above the background level.

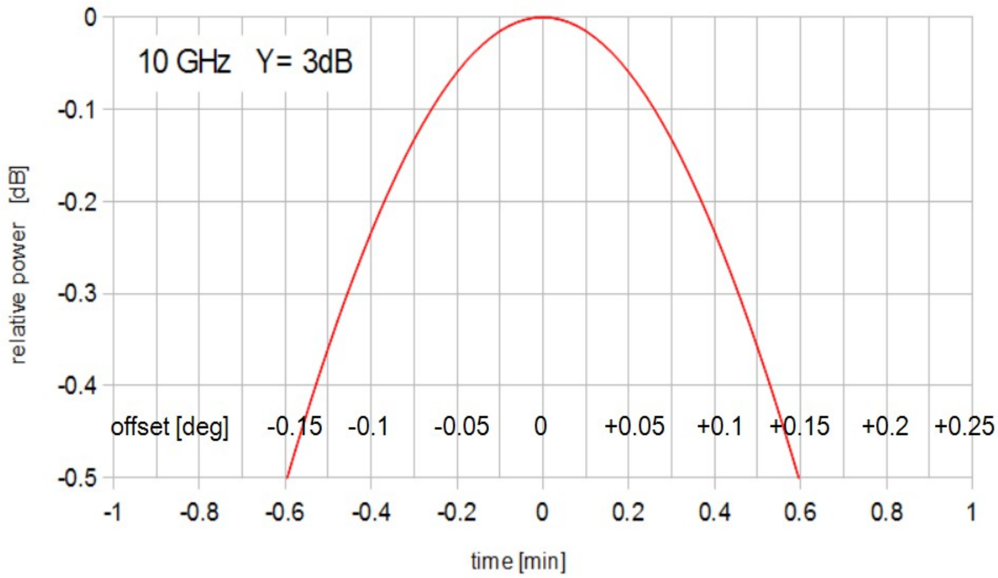


Fig.11 *Expected dependence of signal level with time for the Moon passing through the stationary antenna beam.*

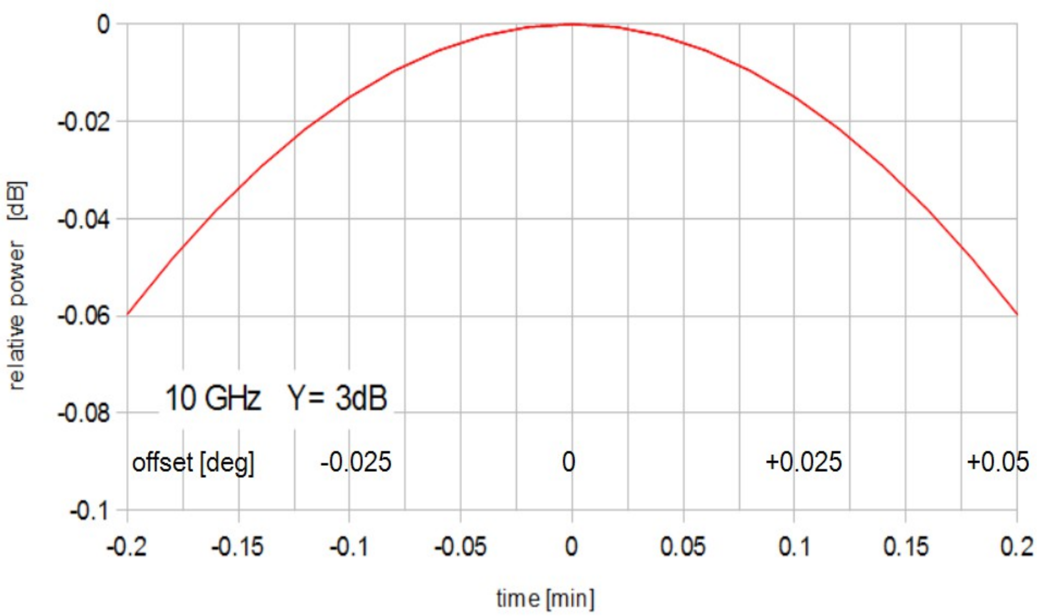


Fig.12 *As Fig.11, but a more detailed view.*

If one moves 0.1° from the maximum, the signal drops by 0.2 dB, which is far above the level of the remaining fluctuations in the HP437B data (about 0.002 dB for the 10 GHz antenna). It is thus not easy to explain how offsets differences of 0.1..0.4° might have occurred.

There are two possibilities to verify that a position is the true maximum:
Bracketing: if the signal level at positions 0.1° to the left and the right of the maximum drops by the same amount – about 0.2 dB – one has found the true azimuth of the maximum. Similarly, checks at 0.1° higher and lower ascertain the elevation value. This will be discussed below.

Continuous Monitoring: Since the tracking motors acts only if the position differs by more than 0.02° in azimuth or elevation, this gives a very useful control of the positioning:
Suppose the source is somewhat to the West of the beam centre, i.e. it is ahead of the beam. During the time the tracking is waiting for the next update, the source will drift further West and out of the beam. The signal level drops. Then the tracking is updated, and the source is brought back to its previous position relative to the beam: the signal jumps up. In this way, the signal level makes a sawtooth curve, with a slowly falling part and a sharp increase.
Analogously, if the source is somewhat to the East of the beam centre, therefore trailing the beam, the signal will be a sawtooth with a slowly rising part.

In Figs.11 and 12 the minimum tracking difference of 0.02° corresponds to about one of the vertical tick marks. Thus, one may estimate that a source at an offset of -0.05° will be allowed to drift to -0.075° and thus the signal drops from -0.05 to -0.13 dB, giving a sawtooth amplitude of 0.07 dB. Correspondingly, a source right at the centre can drift to -0.025°, with a signal drop of 0.01 dB which would be just noticeable.

If the antenna is at a position where the signal remains maximal with minimal variations of the order of 0.02 dB, one is sure that the source's position is within 0.02° of the maximum. An example is shown in Fig. 13. The rising slow part of the sawtooth indicates that the Moon is slightly to the East of the antenna beam, and thus drifts toward the beam centre in the intervals between tracking updates. The sawtooth amplitude of 0.02 dB indicates a position error of about 0.03°.

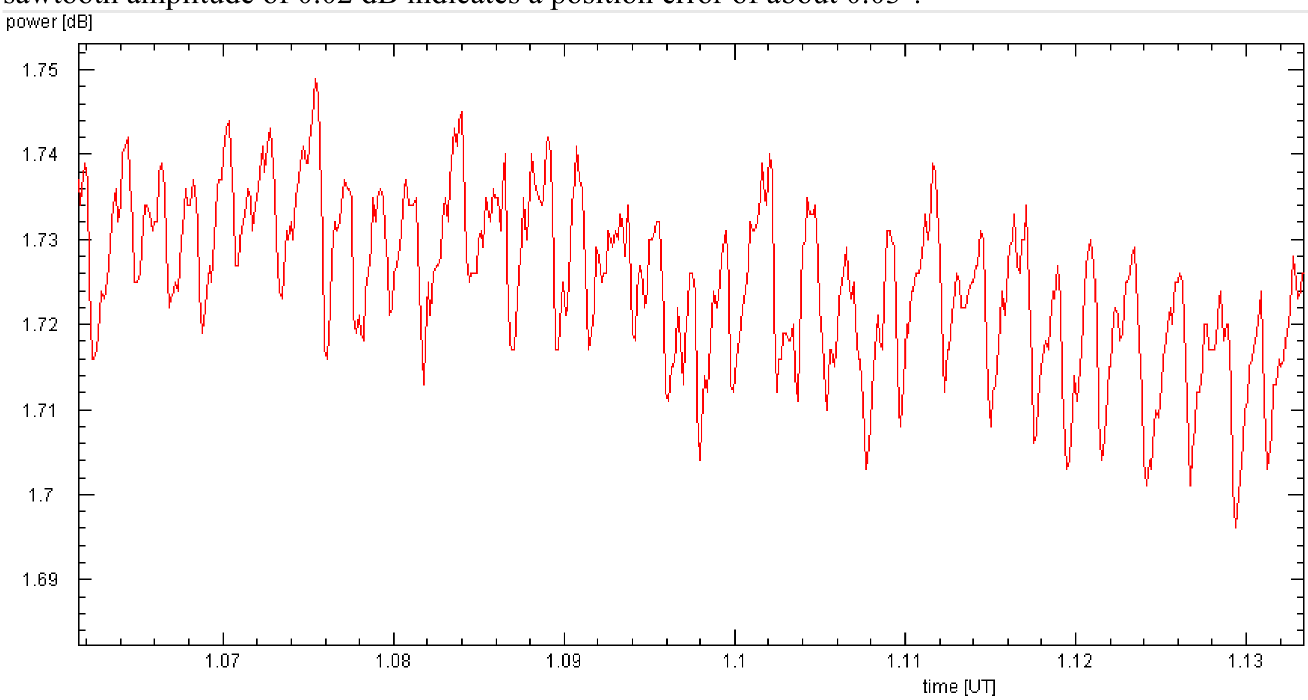


Fig.13 *Example of the sawtooth pattern of the signal level, from the Moon observations of 3 feb. Note the small fluctuations of 0.002 dB from noise in the power measuring apparatus.*

Bracketing

Since a position is the true maximum only if the signal level drops in by the same amount if one measures at the same offset – say 0.1° – in any direction, by these additional measurements one can confirm whether one really found the true maximum. Any differences in the signal drops will indicate in which direction the antenna position should be corrected.
As the tracking is updated only when the position differs by more than 0.02°, the measurements at these test positions also show the sawtooth signature, which can be used as further information about the true source position.

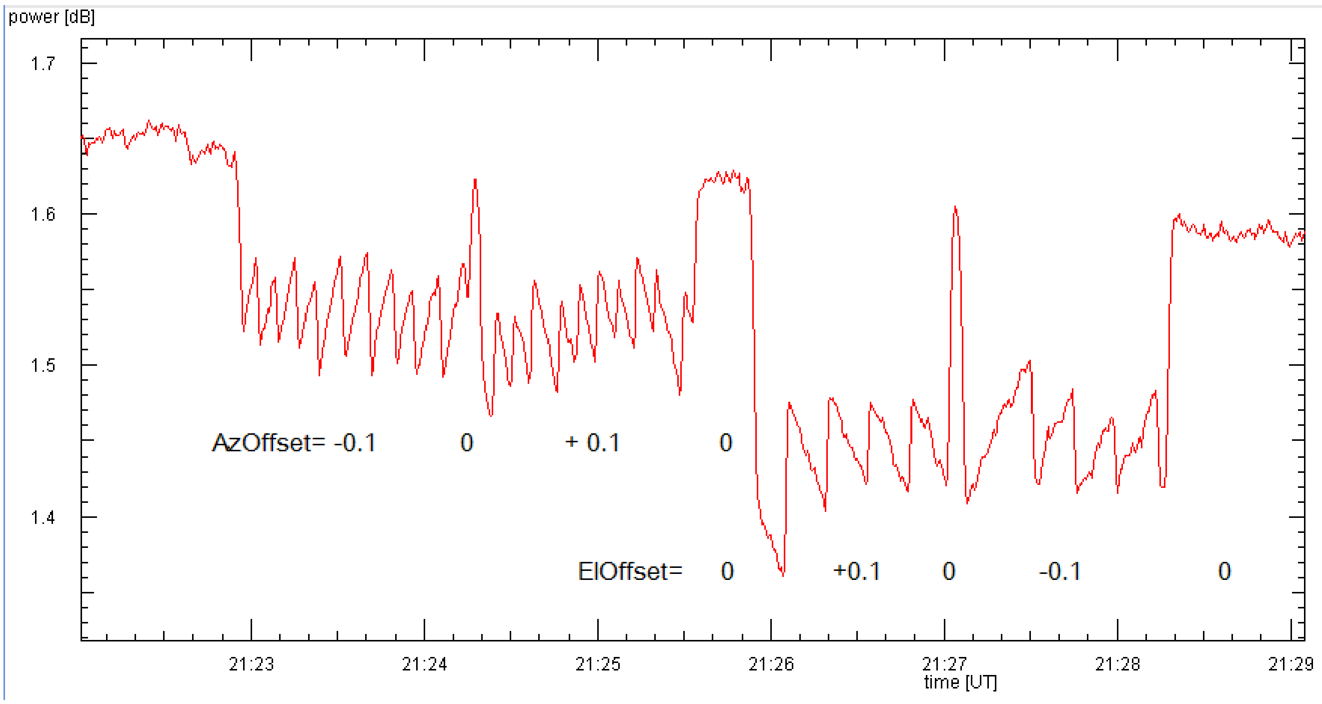


Fig.14 *Bracketing a position of the Moon: First, the antenna is moved by 0.1° to the East, then to the West, then by the same amount above and below the maximum position.*

Figure.14 gives an example of a well-determined maximum position. When the antenna is pointed more to the East, a rising sawtooth pattern is observed, and when it is more to the West, a falling pattern results, as one should expect. The average levels are nearly equal, which is another proof that the position is indeed the true maximum. The following tests in vertical direction confirm that also the proper elevation has been found.

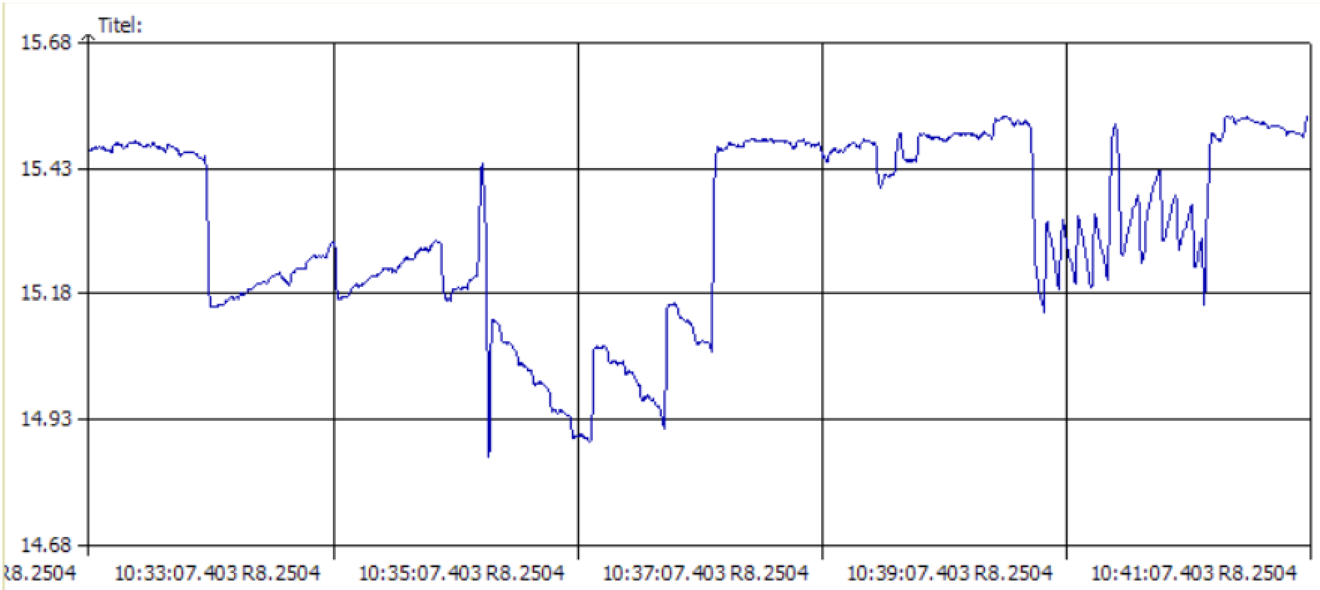
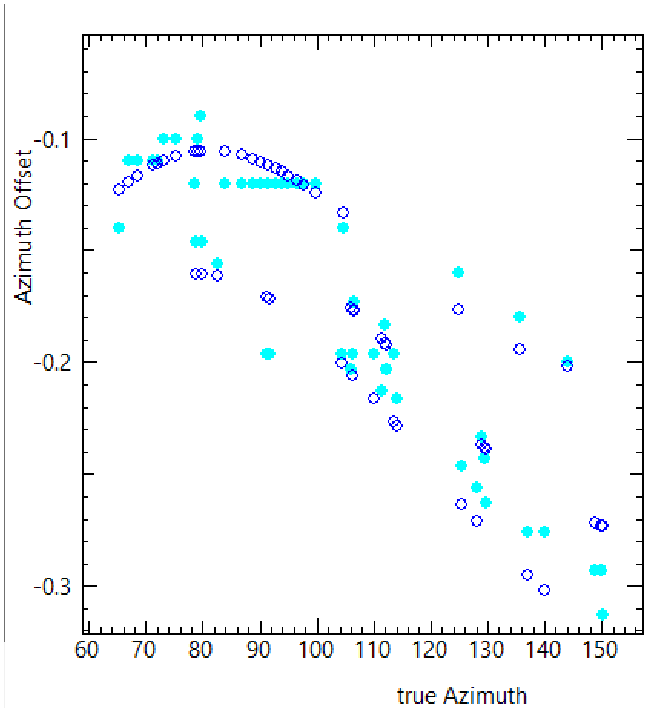


Fig.15 *Similar to Fig.14, but from a screen shot of the HP437B program. The offsets are El=-0.1,+0.1 then Az=+0.1, -0.1°*

Independent Measurements

Another important ingredient for accurate measurements is that each measurement must be done independent of the previous one. Position measurements require to optimize the signal both in azimuth and elevation. Sometimes, the additional trouble of searching in both directions is avoided by making adjustments in one dimension only – especially if it appears obvious that the other coordinate does not change much. In Fig.2 there is an example for this: for azimuths between 80 and 105° the azimuth offset is kept constant, while the elevation offset goes over a large range. However, this approach has also drawbacks, as seen in Fig. 16a, b: A constancy of the azimuth offset would not be matched by a realistic position correction model. As the deviations remain near the tracking accuracy of 0.02°, this is not a significant problem. However, in elevation one notes that the offsets increase rather rapidly near Az=95° and appear to be be overestimated for Az=98..105°. A reasonable model would not be able to account for such a strong change in the offset. The corresponding elevation residuals show an apparent evolution from 0.05° to -0.05° between Az=90 to 100°. Albeit this is not a major problem, it does add to the overall error of the fit.



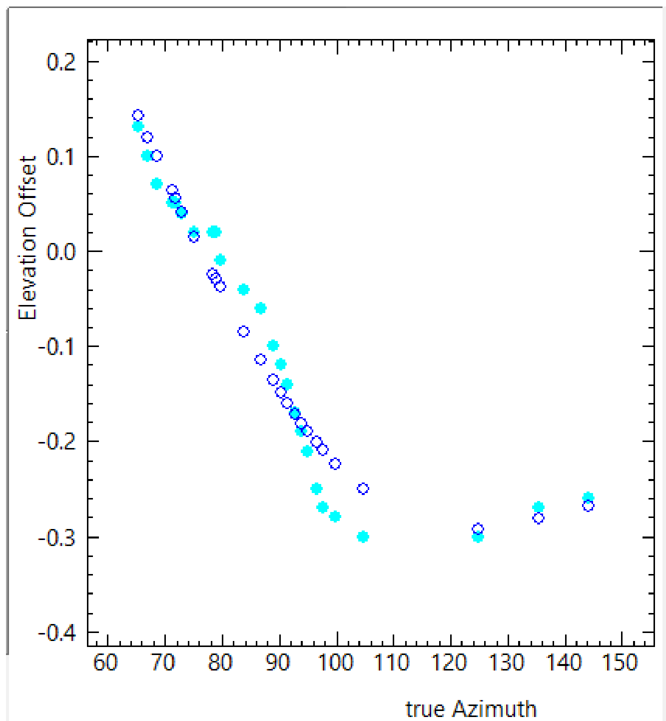


Fig.16a *The azimuth offsets for the rising branch of the lunar path, from the december and february observations. Filled dots are the measurements, blue circles the predictions from a best-fit Q18 model.*

Fig.16b *Similar to Fig.16a, but for the elevation offset and for the dec 6 data only.*

Much more reliable results are obtained if one moves in both directions well off the lastly measured position, and starts a completely fresh search for the maximum, preferably in a different way than the previous time. In this way, one gets independent measures, whose differences would reveal the random errors of the measurement process and the apparatus.

Multiple Measurements

As the old saying goes "Eine Messung ist keine Messung", it is better to take multiple measurements. in order to suppress any outliers and whose scatter about the average indicates the measurement error. These measurements must be done independently of each other, to prevent that any leak of information from one to the next causes a bias in the results.

This technique is explored with the 24 GHz antenna during the night of 6/7 dec in the following way. Before every individual measurement the antenna is moved well away – perhaps 0.5 or 1° – so that the signal dropped by perhaps 0.5 dB and in arbitrary direction. Then the search for highest signal level is started afresh, and in a way different from the previous attempts, e.g. first in azimuth then in elevation or vice versa. Figure 107shows that several examples of three measures each give very consistent results which show a scatter of the order of the tracking uncertainty of 0.02°.

The search itself usually involved a move beyond the maximum, and thus estimate the best position by comparing the two positions at the same lower signal level.

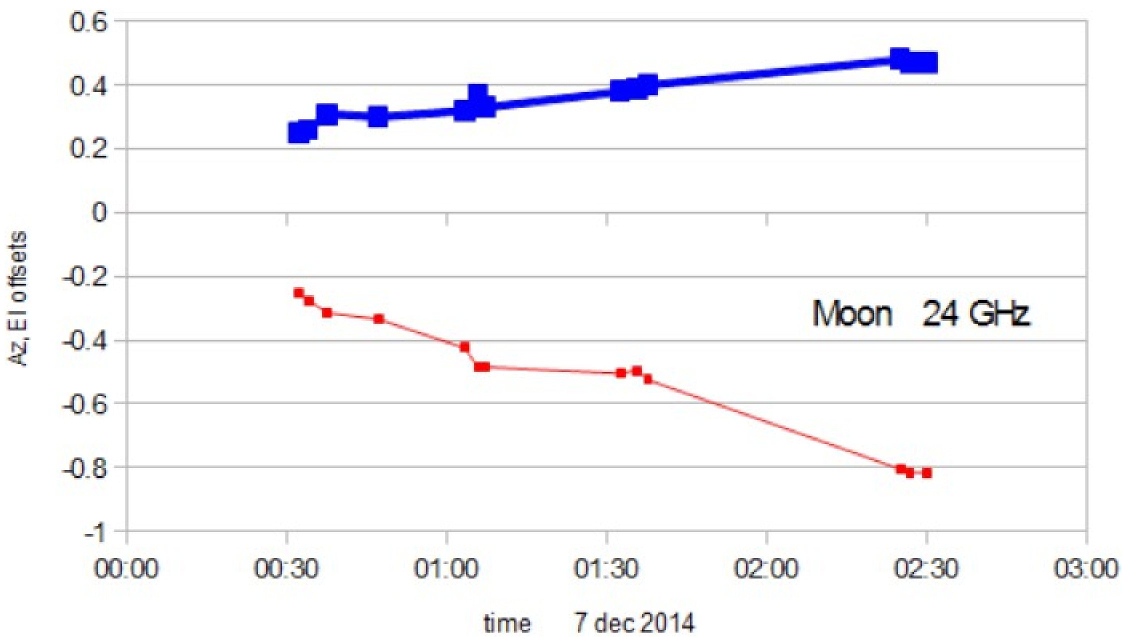


Fig.17 *Multiple measurements done with the 24 GHz antenna. Before each individual observation, the antenna is well offset from the last position, and a fresh search for the maximum signal is done.*

Some Finer Points

The accuracy of position correction measurements depends on the accuracy of the data for the true positions. Az/El Tracker's predicted positions are based on the data from the Horizons On-line Ephemeris System by NASA's Jet Propulsion Laboratory.

But it is worth to have a closer look, by comparing the true positions with the predictions of other programs, based on the formulae of Meeus (1991) or Montenbruck and Pfleger (1999), which are used in the RoenneRadioMeter and RoenneSpectroMeter programs and have an uncertainty of better than a few seconds of arc.

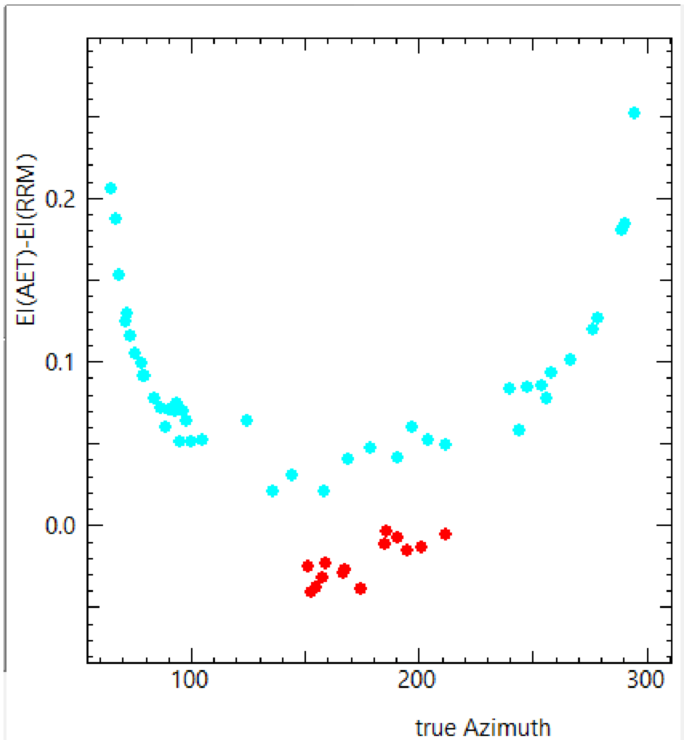


Fig.18 *Comparison of the elevations for Sun (red dots) and Moon (cyan dots) observed in december with the predictions based on the formulae from Montenbruck and Pfleger (1999).*

The comparison of the elevations, depicted in Fig.18, reveals differences

- the lunar elevations from JPL are higher than from Meeus, especially at moonrise and moonset, amounting to 0.2° at elevations below 10°. This is because the JPL data include the correction for tropospheric refraction.
- The solar elevations from JPL are slightly below the other predictions, and the difference becomes more positive with increasing azimuth.
- These differences are higher at moon set, i.e. in the West. Similar differences are also seen in the azimuths.

How could there be an E-W asymmetry in the predicted data? This hints to an error in the recorded times. If one assumes that the recorded time is 10 seconds fast with respect to the true time, perfectly symmetric results are obtained (Fig.19). One notes that with the combined data, there appear two distinct branches for the rising Moon, as the path in feb 2015 culminates at a lower elevation than the one in dec 2014. The figure also shows the solar data now form a cloud perfectly aligned horizontally.

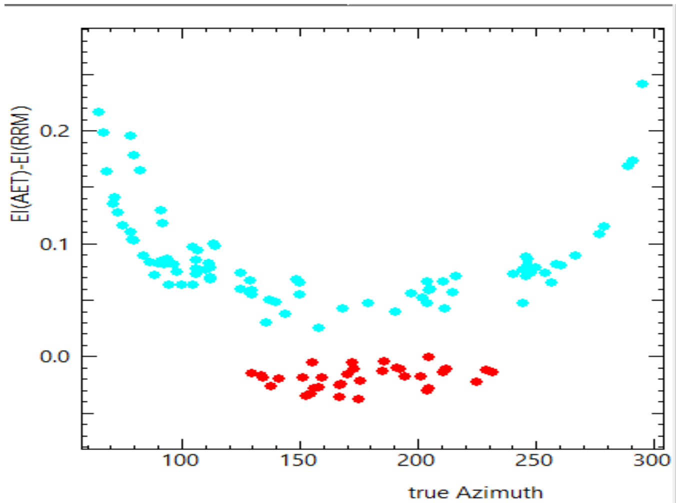


Fig.19 *Like Fig.18, but for the entire lunar and solar data from december and february, and assuming that the computer clock runs 10 sec fast*

This cannot be an error in the computer clock. Even if it was running fast or slow, the predicted positions would be correspondingly ahead or behind. Such an error would be noticeable in the offset positions. For example, a 10 second error in the computer clock would give a 150 arcsec position error, i.e. 0.042° which could be detectable.

Since the predictions used in RRM are without correction for atmospheric refraction, the relation of the elevation difference with the elevation reveals the refraction correction used in the JPL data (Fig.20). One notes that even at elevation 50° this correction is 0.05°, i.e. twice the tracking accuracy. The Horizons' program 'computes approximate refraction angles assuming yellow-light observations at 10 deg C sea level with pressure of 1010 millibars' (cf. Appendix). The data are well matched by the refraction correction for radio wavelengths, computed from the recommendations of Maddalena (1994).

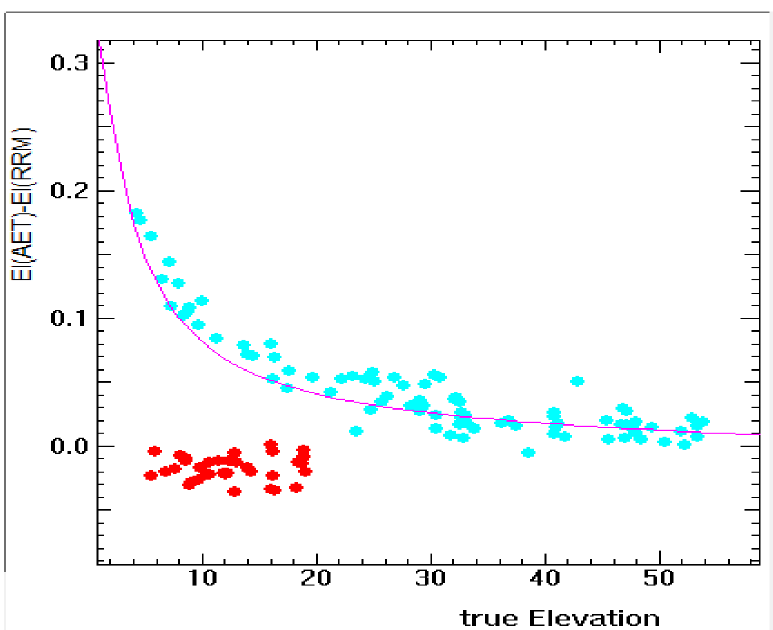


Fig.20 *Like Fig.19, but as a function of elevation. The magenta curve is the atmospheric refraction correction for dry air, computed from the formulae in Maddalena (1994).*

The recorded predicted solar positions are evidently not corrected for refraction, as in Fig.20 there is no tendency with elevation. This may cause a bias in the positions from Sun when combined with the lunar and other data.

In the solar elevations there is a scatter of about 0.01..0.02° (Figs.19 and 20). This shows that the errors in the interpolation of the JPL positions in Az/ElTracker are within the design limits. A good example is seen in solar data on 24 GHz from 16 dec (Fig.21) where the position error curiously alternates in successive measurements.

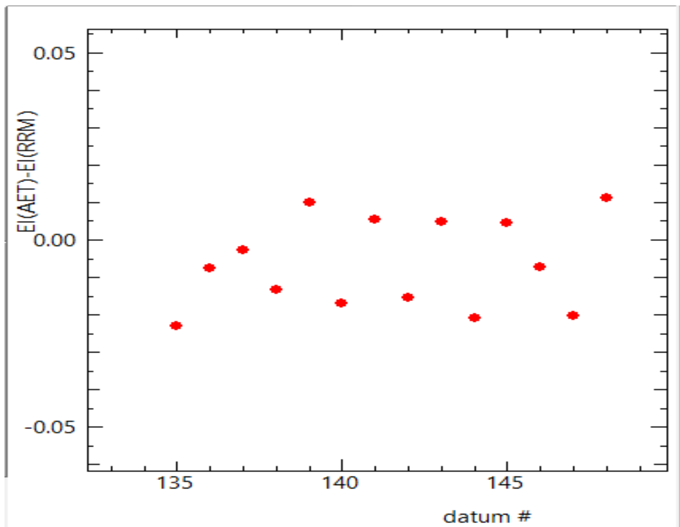


Fig.21 *The alternating deviations between recorded elevations and those computed from Meeus for solar data on 24 GHz indicate that the interpolation errors in Az/ElTracker are about ±0.01°.*

Since we compare predictions with each other, these differences must lie between the predictions. The lunar positions computed from either Meeus or Montenbruck/Pfleger agree with the JPL Horizons data better than 2 sec in right ascension and 15 arcsec in declination. Comparison of the file used by AZ/EL-Tracker shows for the 6 dec at UT 18:35:00. Here the refraction correction of 0.033° has been subtracted.

Model	Az	El (without refraction)
JPL	92.8522	24.1725
Meeus	92.8636	24.1760
Montenbruck & Pfleger	92.8626	24.1776

One notes an offset in azimuth of 0.01° which is larger than one should expect, but a perfect agreement in elevation. This same difference is also found in tests at other times. At this moment, there is no explanation.

If one compares for the record at UT 18:35:16 the recorded true position with the one interpolated linearly from the JPL data file of the neighbouring instants, one finds while the elevation agrees very well, there is an unexpected difference of 0.02° in azimuth:

	Az	El (with refraction)
JPL file: 18:35:00	92.8522	24.2055
recorded at 18:35:16	92.886	24.244
Interpolated for !8:35:16	**92.9052**	24.2433
JPL file: 18:36:00	93.8648	24.3472

At other times – at the full minute, when no interpolation is necessary – nonetheless differences between the JPL Horizons file and the recorded positions are still present. Usually they remain below about 0.01°, but occasionally 0.02° is found.

On the whole, one could thus expect in the recorded positions a scatter of less than 0.02° due to the interpolation from the JPL data. This would be equivalent to a time uncertainty of about 5 sec. As the comparison involved only predicted position, it thus seems that the E-W asymmetry in Fig.18 and the scatter in Fig.20 can only be an accumulation of small offsets or some errors in the calculations of the predicted positions. These uncertainties are comparable with the already achievable accuracy of the position measurements, and thus constitute a limit to the accuracy.

When taking measurements at elevations below 10° there is a substantial pickup of ground emission through the side lobes. This causes the signal level to increase towards the horizon, which will shift the position of the maximum signal towards low elevations. Figure 22 shows that a gradient of 0.3 dB over 0.25° in angle would cause a shift of 0.025° in the position of the maximum signal. As the shift is proportional to the gradient, it could become quite pronounced at very low elevations.

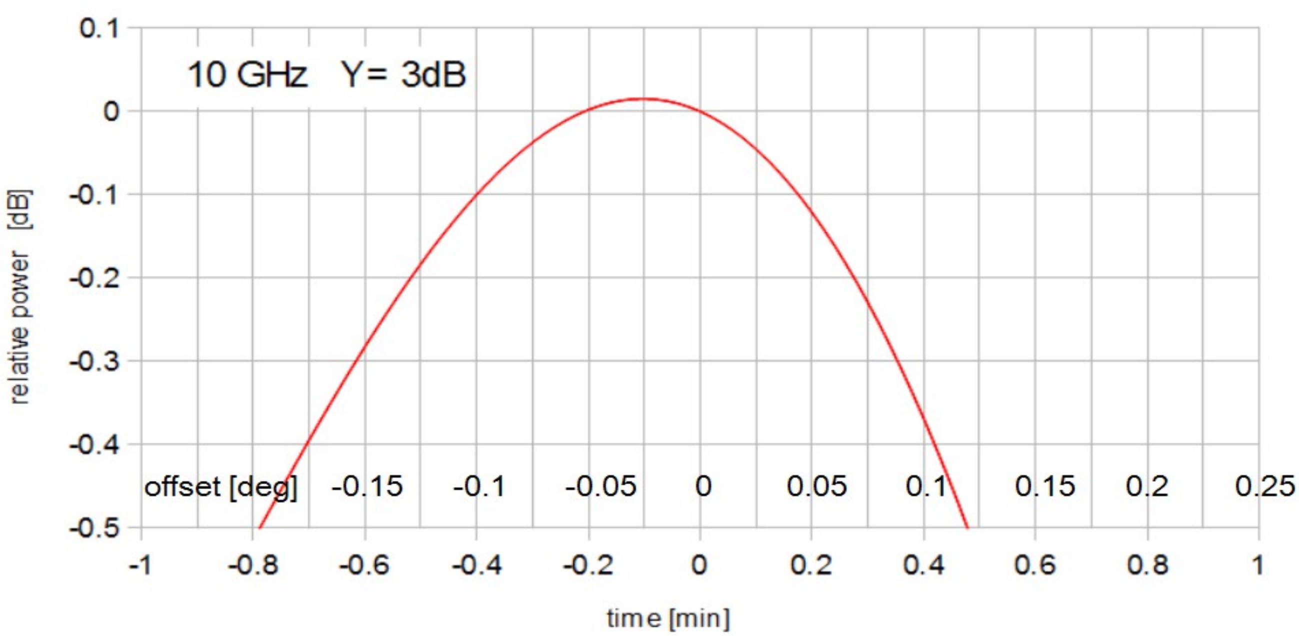


Fig.22 *Like Fig.11, but assuming that the signal level due to ground pick-up via the side lobes increases towards negative offsets by 0.3 dB over an angle of 0.25°.*

Conclusions and Recommendations

Careful inspection of the position measurements of dec 2014, and further lunar and solar measurements in feb 2015 show

- the data from both observation runs are in very good agreement with each other
- the data are sufficiently good to define reliable correction models, such as
  - Bodenschief (with r.m.s. residual 0.091°)
  - Q18 model (r.m.s. 0.057°)
- great care should be exercised if reliable position corrections are to be obtained

It is possible to achieve accuracies comparable with the tracking accuracy of 0.02° despite the fact that the widths of the signal distributions are as wide as 0.5°, viz. the angular diameters of Sun and Moon.

The accuracy of these measurements can be improved by

- seeking the maximum signal with fluctuations of less than 0.01 dB
- bracketing the position by inspections at say 0.1° left/right/above/below the 'best' one
- controlling the offsets so that the signal variations in the intervals between tracking updates are minimized (less than 0.01 dB)
- taking multiple and independent measures by searches in both azimuth and elevation, each one preceded by moving well away from the position of the last accepted measurement.
- making sure that before any measurements the computer clock is synchronized within 1 sec
- tropospheric refraction affects the data at low elevations, especially below about 10°. As it is weather-dependent, it deserves a closer inspection.
- operator fatigue – especially near the end of a long night – can contribute to noise in the data. Though the author has noticed this in some of his runs, this issue is not addressed in this report.

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Appendix: The Refraction Correction in JPL Horizons

The standard correction for refraction can be fit with a formula similar to the one proposed by von Hoerner (GBT Memo 110);

$$\Delta\varepsilon = 0.017° * \cos(\varepsilon_{obs}) / (\sin(\varepsilon_{obs}) + 0.00175*\cot(3.5° + \varepsilon_{obs}))$$

which for elevations above 10° is approximately $0.017° * \tan(90° - \varepsilon_{obs})$.

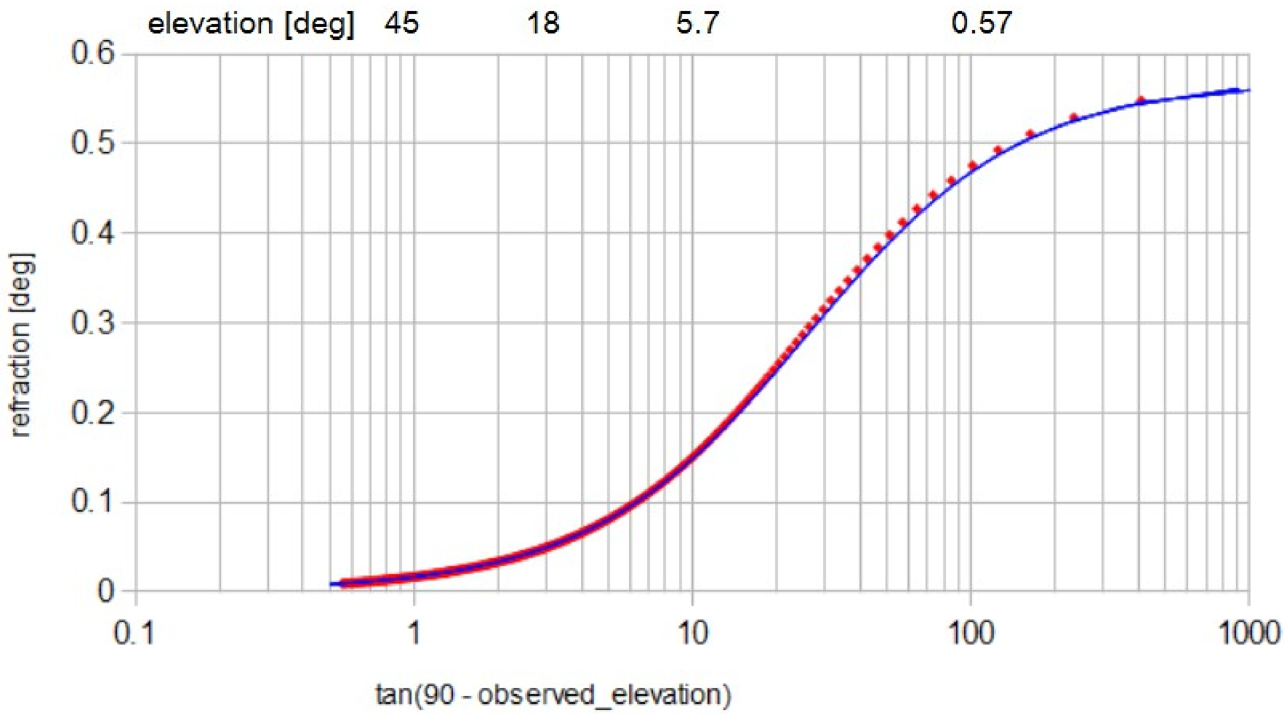

Fig.23 *The standard refraction corrections in JPL Horizons Ephemeris (red dots) compared with a simple fit formula (blue curve).*