Measurements at the DL0SHF 1GHz radio telescope

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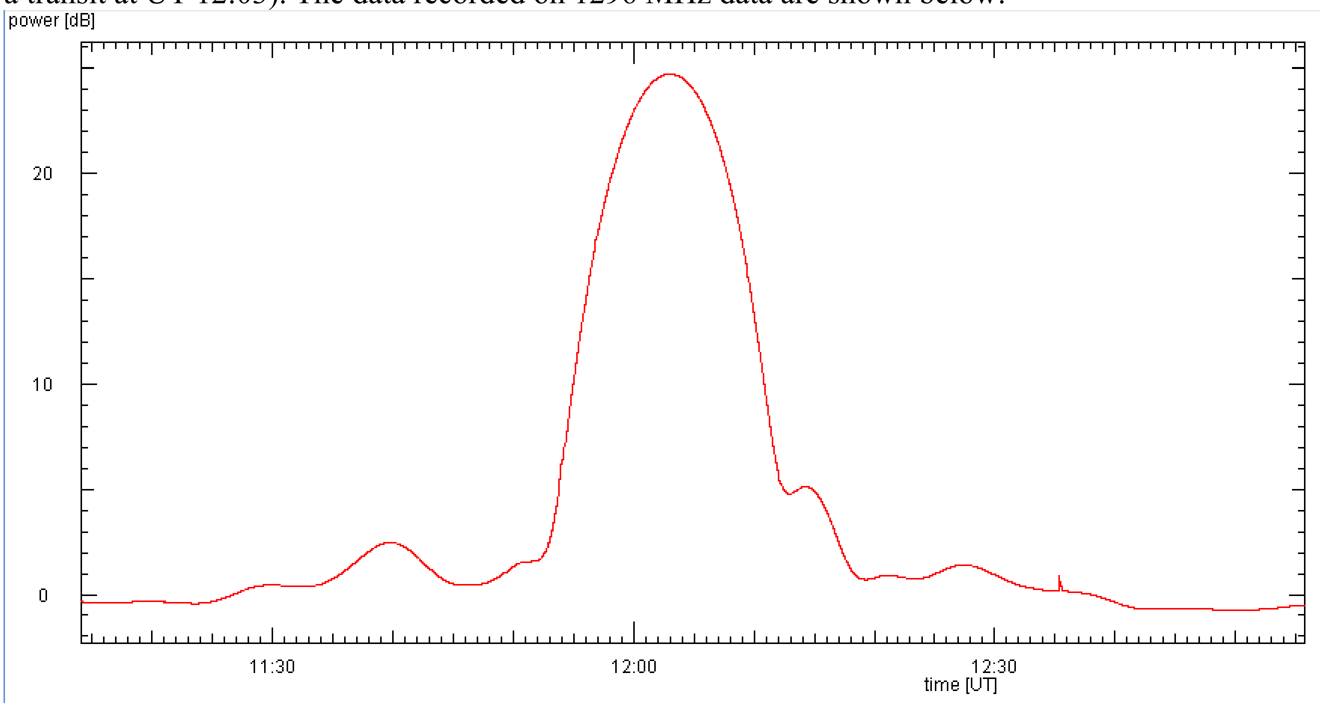
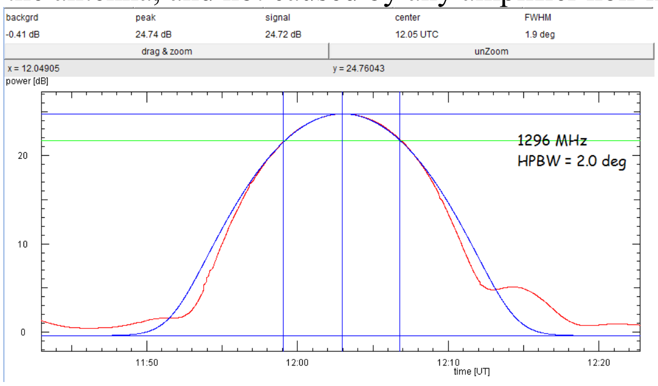
Horizontal Antenna Pattern and HPBW (1296 MHz)

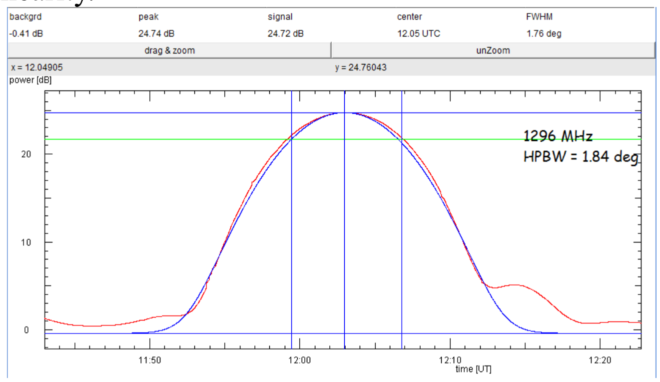
On 2 aug 2014, a long drift scan of the Sun is done at the position Az 194.83º El 52.73º (predicted for a transit at UT 12:03). The data recorded on 1296 MHz data are shown below:



The level of the main lobe peak is +24.83 dB, and of the nearly empty sky (at UT 12:50) is -0.72 dB. For this first measurement no data of the sky background profile or the grund calibrator is taken, nor any attempt is made to find the true maximum signal level. Nonetheless, a clean main lobe is seen, with sidelobes below 20 dB of the main lobe. Also, the peak occurs at UT 12:03:05, i.e. well on time, which implies that the positional error is negligible.

If one determines the half-power beam width (HPBW) by locating the -3dB points of the main lobe and applies the equatorial sky rotation rate of 15º/hr, one gets 1.9º. Correction for the actual solar declination (δ = 17.6º) gives 1.9º cos δ = 1.8º. This gives a good fit of the lobe centre (below left). However, if one wants to match the flanks of the main beam, a smaller HPBW of 1.75º (1.66º with correction, below right) is required. This weak flat-topping of the beam is most probably merely due to the antenna, and not caused by any amplifier non-linearity.

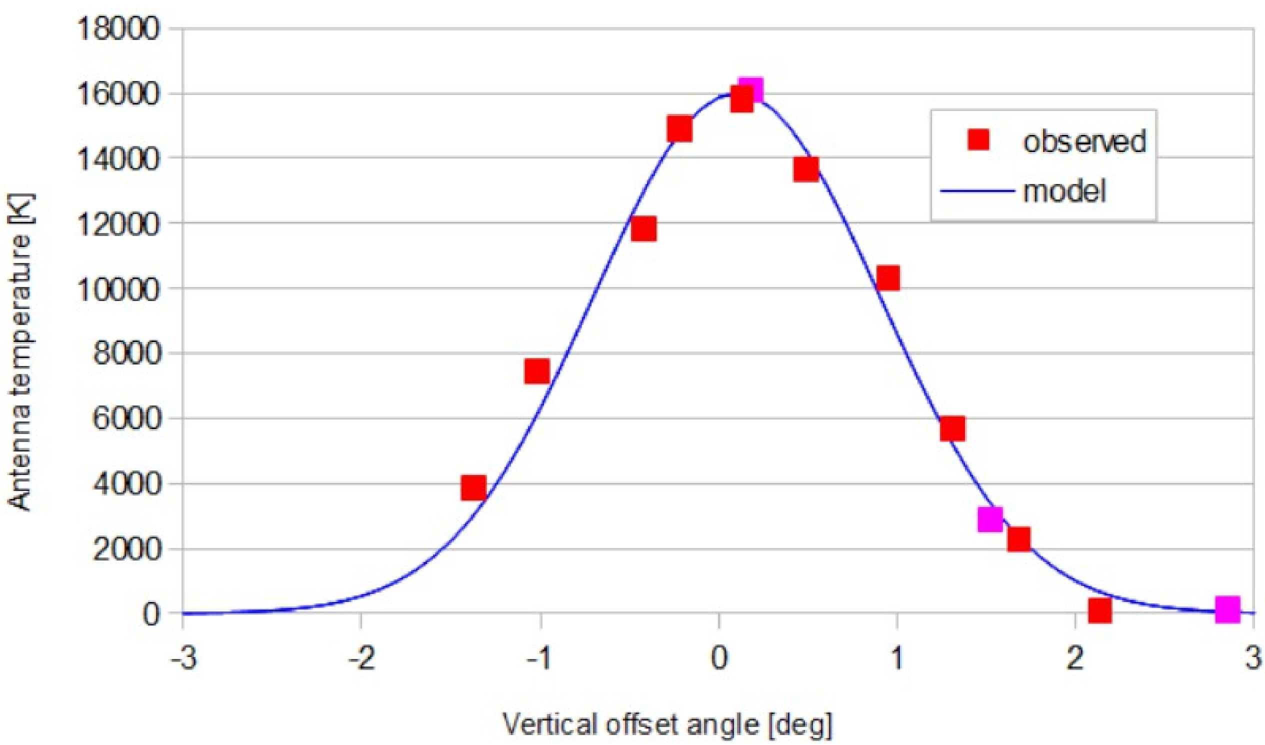




Thus, the HPBW is in the range of 1.8 .. 1.9º.

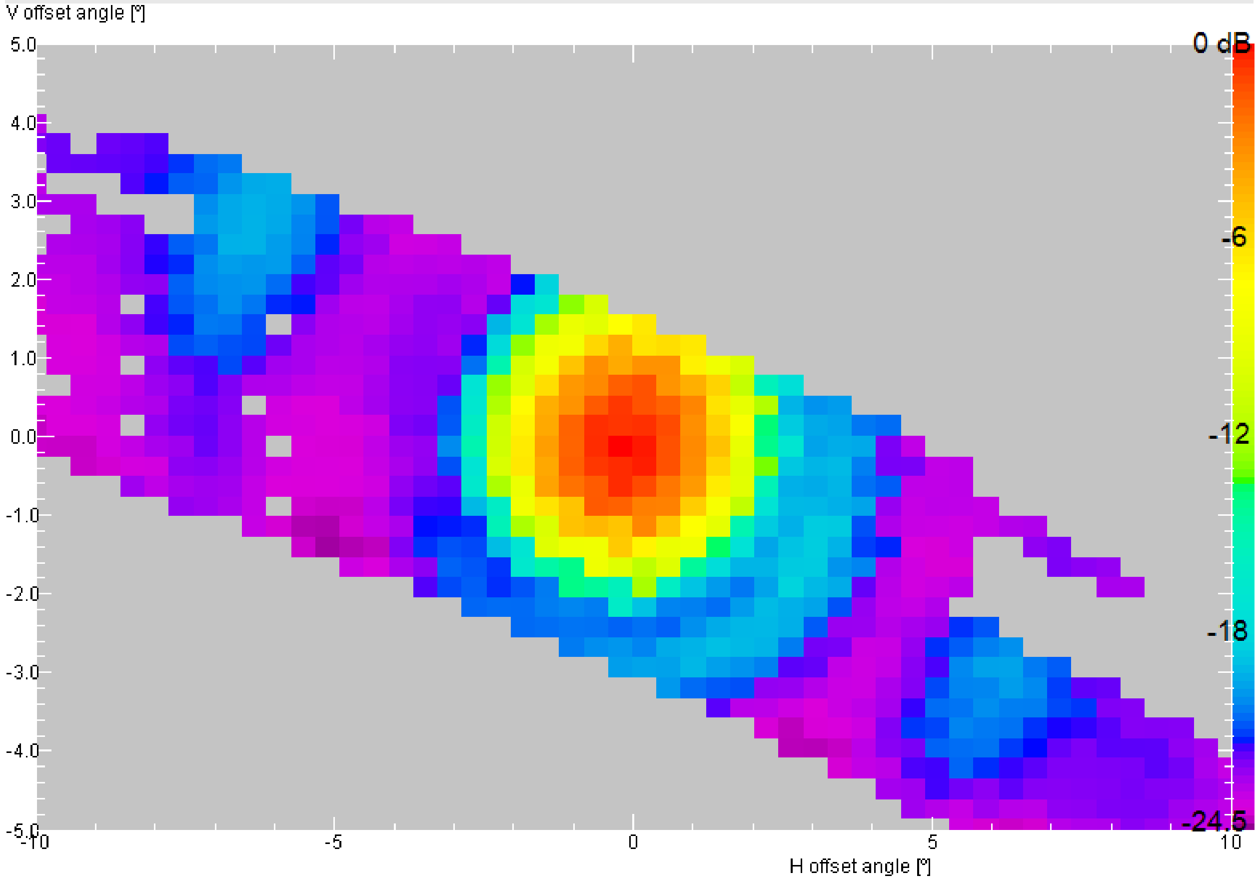
Vertical HPBW (1296 MHz)

In a series of daily solar drift scans executed at the same position (Az 220º El 39º) while the Sun comes down in declination during 20 aug to 4 sep the vertical beam width is confirmed to be 1.9º (model) with a slight vertical position error of +0.1º; in some parts a HPBW of 2º would be preferable:



Antenna Pattern (1296 MHz)

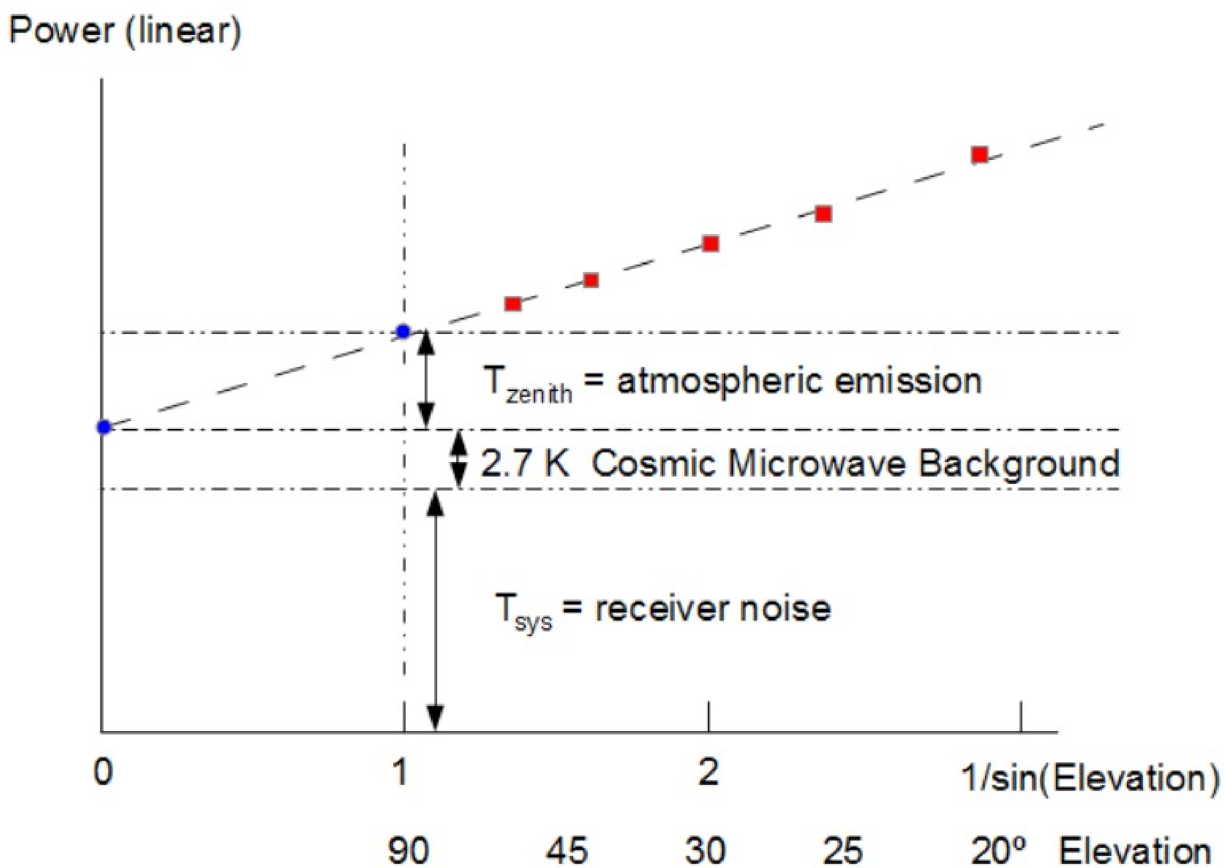
From the data of the daily solar drift scans a 2D representation of the antenna pattern is obtained. The colour scale at right goes from 0 dB (red) to -24.5 dB (violet).The main beam is sharp and clean, with the first sidelobe being stronger in the north-eastern side, and an extended ring of second (or third) sidelobe with maxima in the north-east and south-west.



System Temperature and the Profile of the Sky Background (1296 MHz)

Because of the low system temperature of this instrument the observed background level requires a correction for the emission of the Earth atmosphere. This is done by measuring the 'empty' sky at a number of elevations, and comparing with a plane-parallel atmosphere which predicts that the signal level increases with 1/sin(elevation). Thus, in a plot of (linear) power against 1/sin(el) the model is represented by a straight line:

p(el) = offset + slope / sin(el)



A linear regression fit of the data then yields the slope and the vertical offset. Note that in order to obtain a reliable fit, it is best to space the elevations in such a way that the data points are equally spaced in 1/sin(elevation).

The power data are in some arbitrary units determined by the receiver and software. To express them in terms of 'antenna' temperatures, we need to determine the factor 'a' of proportionality:

$$p(source) = a\,(T_{source} + T_{sys} + T_{CMB})$$

This is done by pointing the telescope at the nearby dense grove of trees, which is a very good approximation for a blackbody whose thermal emission fills the main beam completely. Hence the antenna temperature is equal to the physical temperature of the trees, about 290 K.

The vertical offset – which corresponds to an extrapolation of the data to the value 1/sin(el) = 0 which means in the absence of the Earth atmosphere – gives the level of noise from the receiver plus the emission of the Cosmic Microwave Background.:

$$\text{offset} = a\,(T_{sys} + T_{CMB})$$

When the telescope points at the calibrator, there is no CMB contribution:

$$p(\text{calibrator}) = a\,(T_{calibrator} + T_{sys})$$

As $T_{calibrator}$ =290 K is known, one can isolate $T_{sys} = p(\text{calibrator})/a - T_{calibrator}$, eliminate it in the previous equation, and determine the unknown constant a:

$$a = (p(\text{calibrator}) - \text{offset}) / (T_{calibrator} - T_{CMB})$$

It is worth noting that this may be approximated by

$$a = (p(\text{calibrator}) - p(\text{sky at high elevation}) / T_{calibrator}$$

which allows a first quick interpretation, for example.

This gives the system temperature:

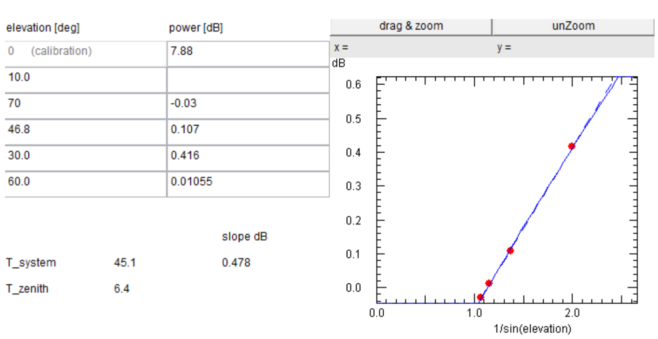
$$T_{sys} = 1/(p(\text{calibrator})/\text{offset} - 1) \; * \; (T_{calibrator} - T_{CMB}) \; - T_{CMB}$$

$$\approx T_{calibrator} \,/\, (p(\text{calibrator})/p(\text{sky at high elevation}) - 1)$$

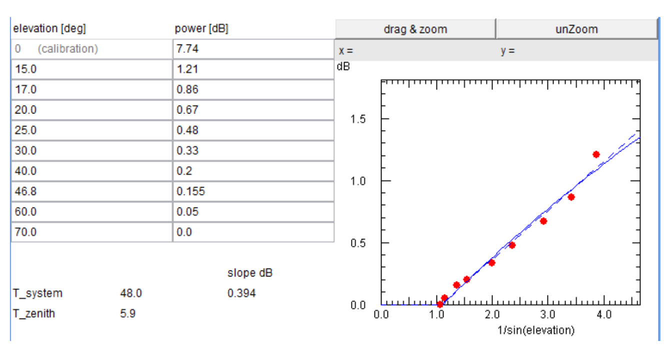
The slope of the fitting line is a measure of the emission of the Earth atmosphere. It is conveniently expressed as the antenna temperature of the zenith.

From $\quad p(\text{zenith}) = \text{offset} + \text{slope} = a\,(T_{zenith} + T_{sys} + T_{CMB}) \; = \; a\,(T_{zenith}) + \text{offset}$ one gets:

$$T_{zenith} = \text{slope} / a \; = \; \text{slope} * (T_{calibrator} - T_{CMB}) / (p(\text{calibrator}) - \text{offset})$$



23 aug: typical result with nearby Sun



2 sep: sky profile taken about one hour after solar transit. The datum at el=15° is obviously affected by emission of the nearby calibrator trees.

Due to this September's restrictions in azimuth travel, the sky profile measurements are done only at AZ 220 and with the Sun in the vicinity. Despite this limitation, the results appear quite robust and reliable, as shown in the analyses below:

day	T_{sys}	T_{zenith}
23 aug	45.1	6.4
25 aug	45.8	6.2
26 aug	49.4	4.3
27 aug	48.7	5
28 aug	49	4.4
29 aug	44.2	6.7
30 aug	47.2	5.4
31 aug	44.5	7.1
1 sep	45.8	6.7
2 sep, 'normal' obs.	47.6	6.8
2 sep, after sun transit	48	5.9
2 sep, without el=15º	49.5	5.2

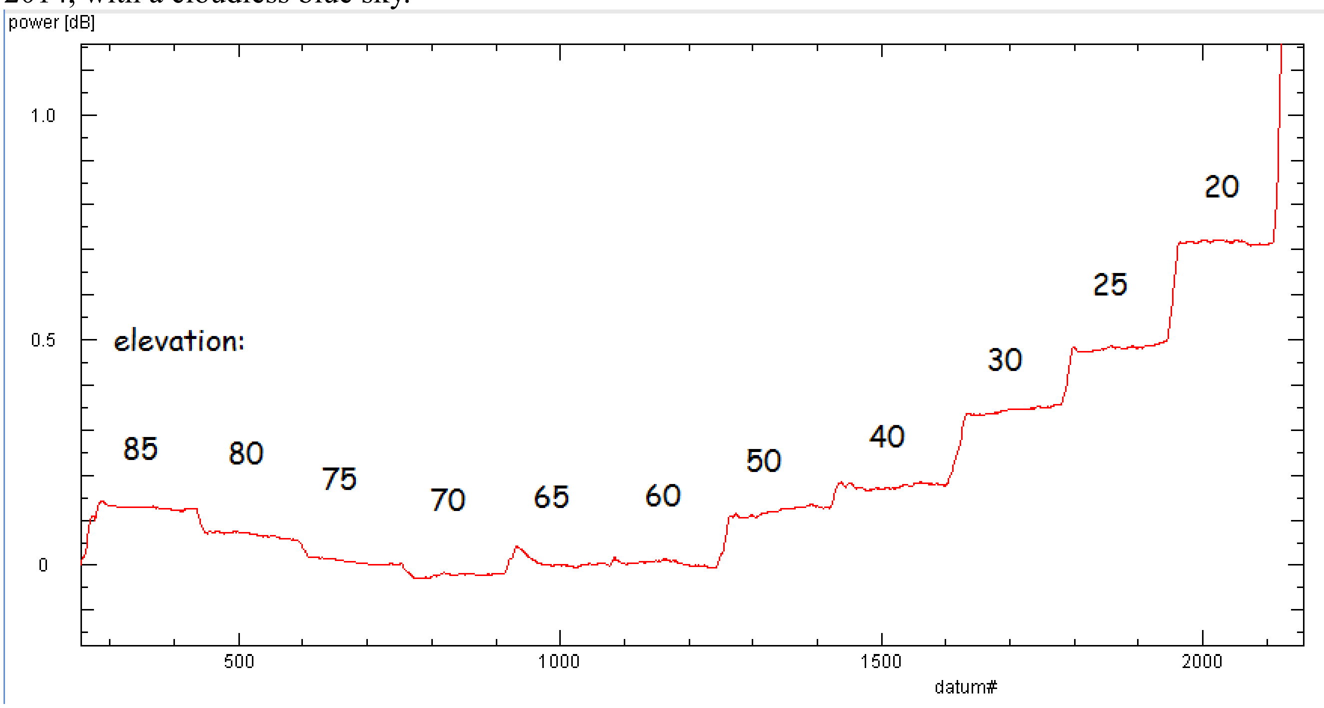
One notes a clear trend between larger zenith temperatures and lower system temperatures. This is because the data for intermediate elevations (20..30º) are affected by solar radiation picked up by the sidelobes, which may differ since each day a compromise had to be found for suitable positions.

On 2 sep. more careful measurements is done, with a larger separation from the Sun and with a larger number of positions (shown in the plot above right). These show an excellent agreement with the model, with the exception of 15º elevation where the sidelobe contribution from the calibrator (at elevation 0º) becomes noticeable.

From these results one may conclude that the system temperature at 1296 MHz is 50 K. The value might improve slightly, if an even better calibration position in the grove would be found.

Antenna spillover

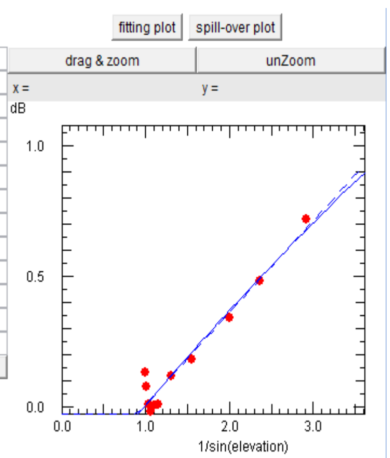
The antenna feed's pattern is designed to illuminate most of the parabolic reflector, but it is inevitable that it is also somewhat sensitive to directions just beyond the reflector's rim. Thus some radiation from directions almost perpendicular to the optical axis are picked up, whenever these directions point to the ground. When the antenna is pointed close to the zenith, this contribution is largest, about twice as much as when the antenna looks at a lower elevation. The sky profile measurements exhibit a rise in noise level for elevations larger than 70º, by about 0.2 dB, as seen in a complete profile taken on 12 sep 2014, with a cloudless blue sky.

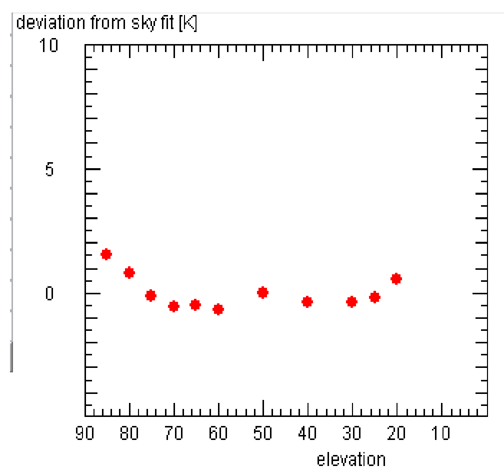


The analysis ...

elevation [deg]	power [dB]
0 (calibration)	8
15.0	(1.48)
20.0	0.72
25.0	0.48
30.0	0.34
40.0	0.18
50.0	0.12
60.0	0.01
65.0	0.003
70.0	-0.017
75.0	0.007
80.0	0.077
85.0	0.13

		slope dB
T_system	46.0	0.352
T_zenith	4.7	

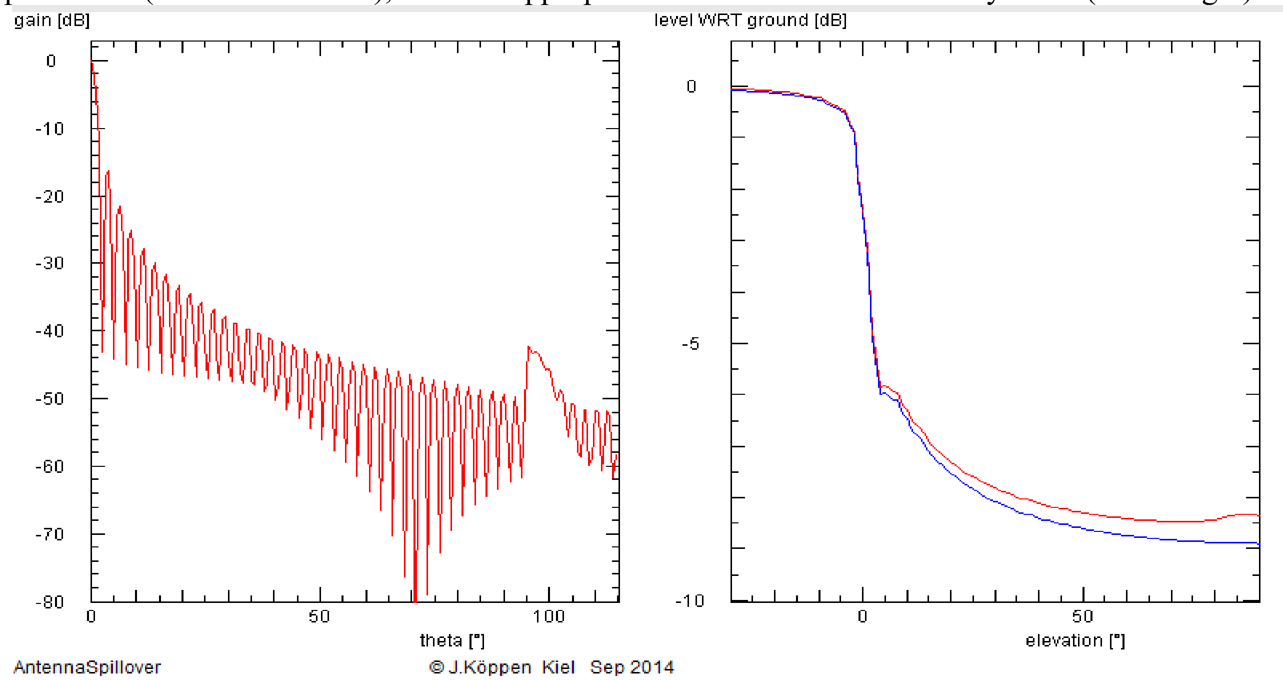


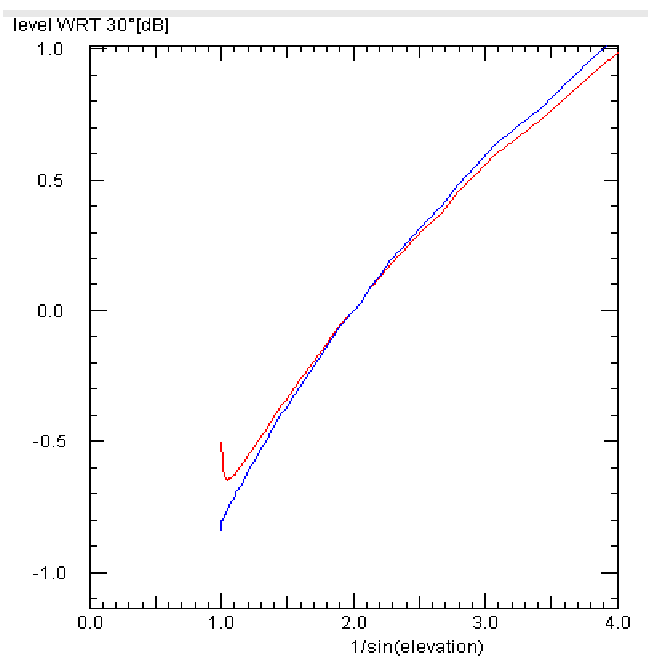


… gives a very good fit and values for system and zenith temperatures as before ... except for high elevations and for 15º (too close to the trees).

Elevations above 70º show excess noise which systematically increases to the zenith, to about 3 K or 0.2 dB.

The measured sky profile can well be reproduced with a simple model, in which one adds to a reasonable theoretical antenna pattern (HPBW = 1.9º) an adhoc spillover contribution from 95º off the optical axis (shown below left), and sets appropriate levels for receiver and sky noise (below right):





The resulting sky profile with spill-over (red) closely matches the observations. The concentration of the noise enhancement to within 20º of the zenith implies that the spill-over must come from the angles close to 95º off the optical axis.

The 'true' sky profile without spill-over (blue curve) deviates only slightly in slope from curve with spill-over. This implies that the true distribution of the sky noise can indeed be reliably determined without any correction from the measurements below 70º elevation.

Further measurements are being done to explore the influence of the weather and the cloud cover.

Antenna Gain (1296 MHz)

For a uniformly illuminated circular aperture the half-power beam width (HPBW) can be calculated from its diameter (antenna books by Heilmann, Kraus, Balanis):

$$\text{HPBW} = 58.8^\circ * \text{wavelength} / \text{diameter}$$

and its effective area is equal to the geometrical area

$$A_{eff} = \pi * \text{diameter}^2 / 4$$

From the fundamental relationship with the antenna beam's equivalent solid angle Ω

$$A_{eff} = \text{wavelength}^2 / \Omega$$

and the definition of the gain

$$\text{gain} * \Omega = 4\pi$$

one gets this relation

$$\text{gain} = (58.8^\circ * \pi/\text{HPBW})^2$$

With the measured value of HPBW = 1.8º or 1.9º one obtains a gain of +40.23 .. 39.76 dBi. With the wavelength of 0.23m the effective area is

$$A_{eff} = 44.91 .. 40.31\ m^2$$

which yields an effective diameter of 7.56 ..7.16 m. Since the geometrical diameter of the antenna is 9 m, we get an antenna efficiency of 71..63%.

The sensitivity of the telescope is $T_{ant}/\text{Flux} = A_{eff}/2780 = 16.3 .. 14.6$ mK/Jy

On 29 aug the Sun is observed t 1320 UT with a negligible offset of 0.13º with a peak signal of 24.6 dB, with sky background level at El 70º of 0.055 dB, and the calibrator level of 8.07 dB. From

$$p(\text{sun}) = a\,(T_{sun} + T_{sys} + T_{CMB})$$

and

$$p(\text{calibrator}) = a\,(T_{calibrator} + T_{sys})$$

one gets with y = p(sun)/p(calibrator) = 45.0

$$T_{sun} = y * (T_{calibrator} + T_{sys}) - (T_{sys} + T_{CMB}) = 15240\ K$$

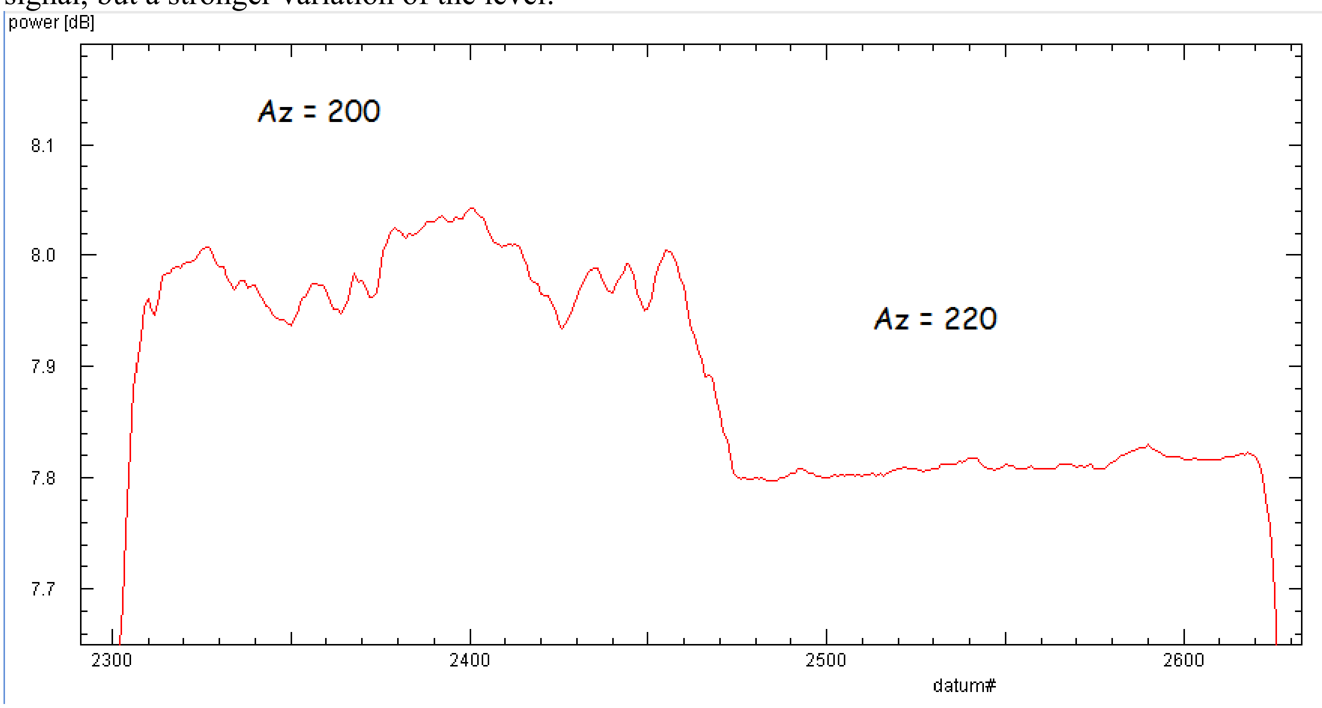
On this day the station San Vito Island measures a local noon flux of 111 SFU (solar flux unit = 10^4 Jy) at 1415 MHz (published by NOAA at http://www.swpc.noaa.gov/ftpmenu/lists/radio.html). A slight correction – with spectral index 0.5 – gives a flux at 1296 MHz of 1.06 MJy. This yields for the antenna temperature (for HPBW = 1.8 .. 1.9º):

T_{ant} = Flux*A_{eff}/2760 = 17124 .. 15370 K

This is slightly larger than our measurement:

$T_{measured}/T_{predicted}$ = 0.89..0.99 which corresponds to a deviation of 0.5 .. 0.04 dB

Hence, the directly measured HPBW of 1.9º gives a nearly perfect result. The figures also show the strong dependence of the results on the exact value. It is worth noting that for the predictions a uniformly illuminated telescope aperture is assumed. The currently used position (Az = 220º, El = 0º) for the flux calibration gives a very stable signal level.The position at Az = 200º gives a 0.2 dB higher signal, but a stronger variation of the level:

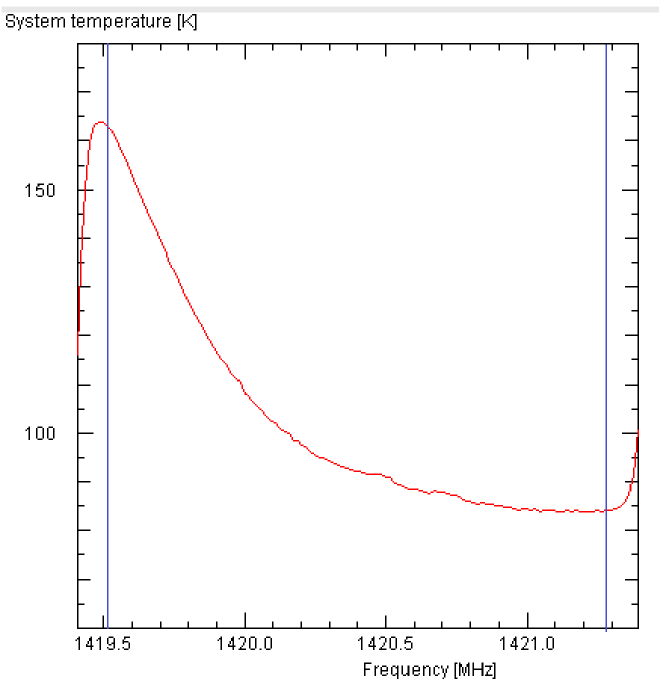


This is a minor issue, as neglecting an uncertainty of 0.2 dB in the calibrator level of 8 dB represents a relative error of only 5% in the values for antenna and system temperatures. Subsequent tests show that flux calibrations with this source yields very consistent results from the quantitative interpretation of observations with this antenna.

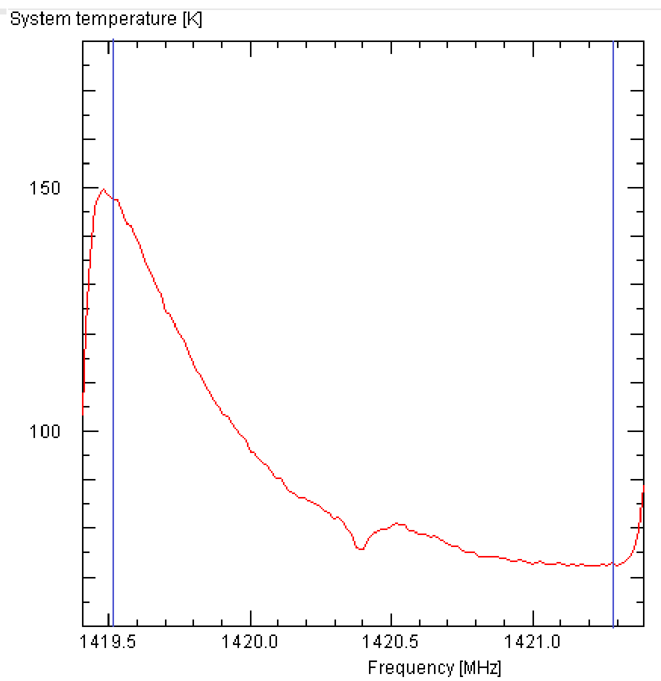
Frequency-dependent System Temperature (1420 MHz)

Simultaneous spectral observations in a 2 MHz wide band centered on 1420.406 MHz allow to compute the system temperature. A simplified determination, based on the spectra taken only at the flux calibrator and at elevation 70 º in the sky (left) gives higher values – by about 10 K – than the analysis of the complete skyprofile (right). As very consistent results are obtained throughout the observation period, it suffices to show results from 2 sep. Due to the limitations of the compensation for the frequency response of the Perseus receiver the rim portions are not reliable, i.e. outside the blue lines.

The system temperature is significantly higher than on 1296 MHz – although this does not constitute a serious limitation for astronomical observations. For Milky Way observations one has about 90 K. There is a strong frequency dependence, with the noise level going up towards low frequencies.



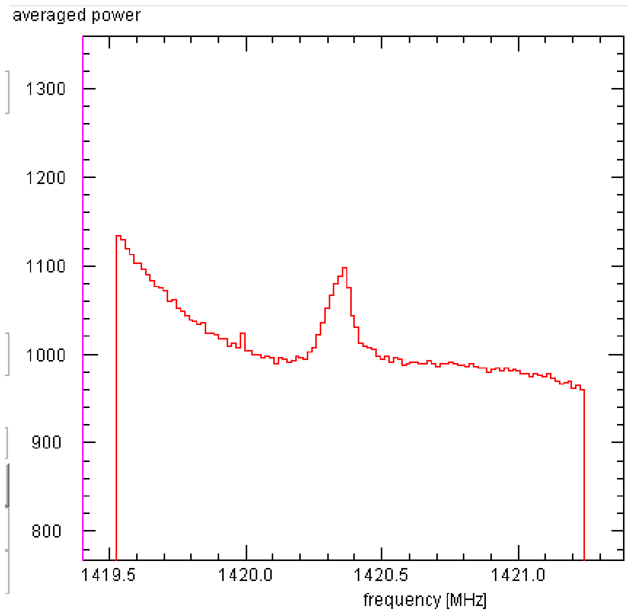
Simplified analysis using sky background at 70º

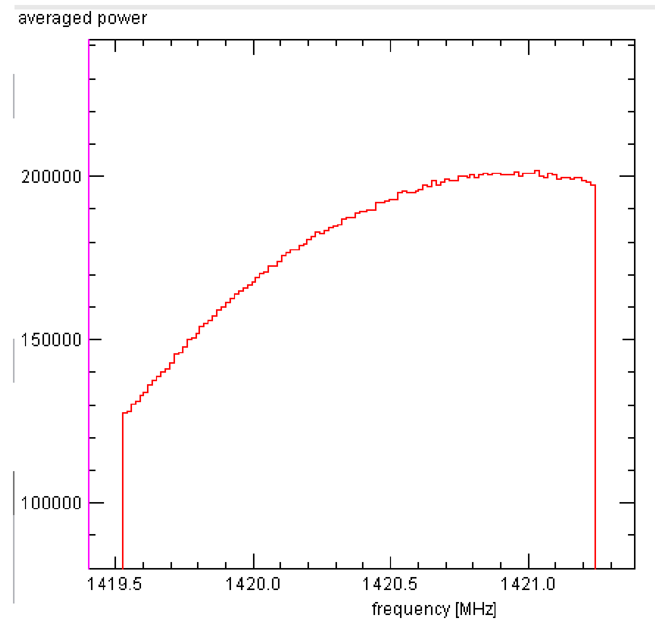


Complete skyprofile (15,25,30,46.8,60,70º)

Changes of the Spectrum during Solar Drift Scans (1420 MHz)

During the solar drift scan of 2 aug it is quite surprising to see that the spectrum changes rather dramatically from a downward slope (negative spectral index) at the empty sky (at left. Note the Milky Way emission and the birdie at 1420.0 MHz) are no longer visible when the sun is in the beam centre (right); the spectrum has a positive slope:





At first sight, one might think of the fact that the true spectral index of the Milky Way continuum - due to its synchotron component – is negative (about –0.5) while that of the Sun's thermal emission is positive (about +0.5 at 1420 MHz). However, the span in frequency of 2 MHz is far too small to provide any evidence for this: the variation of the flux would be ±0.003 dB for a spectral index of ±1.

Since the spectrum shape seems to correlate with the signal level, one might think of non-linearities in the receiving system. However, neither are these present in the data reduction (FFT) and the Perseus receiver nor are the signal levels in front of the Perseus sufficiently high for this possibility: The Sun produces a signal level of about –76 dBm/bin at the input of Perseus, which amounts to –53 dB integrated over the whole spectral range. Likewise, the Sun provides –157 dBm/Hz to the first preamplifier, or about –60 dBm integrated over an assumed bandwidth of 50 MHz and an assumed total preamp gain of +40 dB. This is corroborated by the measured antenna pattern which shows no evidence for a gain flattening at the centre.

It turns out that there are two effects that contribute to the observed behaviour:

- the antenna squints: the main lobe's direction changes with frequency.
- the frequency-dependence of the gain of preamplifiers and filters preceeding the AR5000 and Perseus receivers

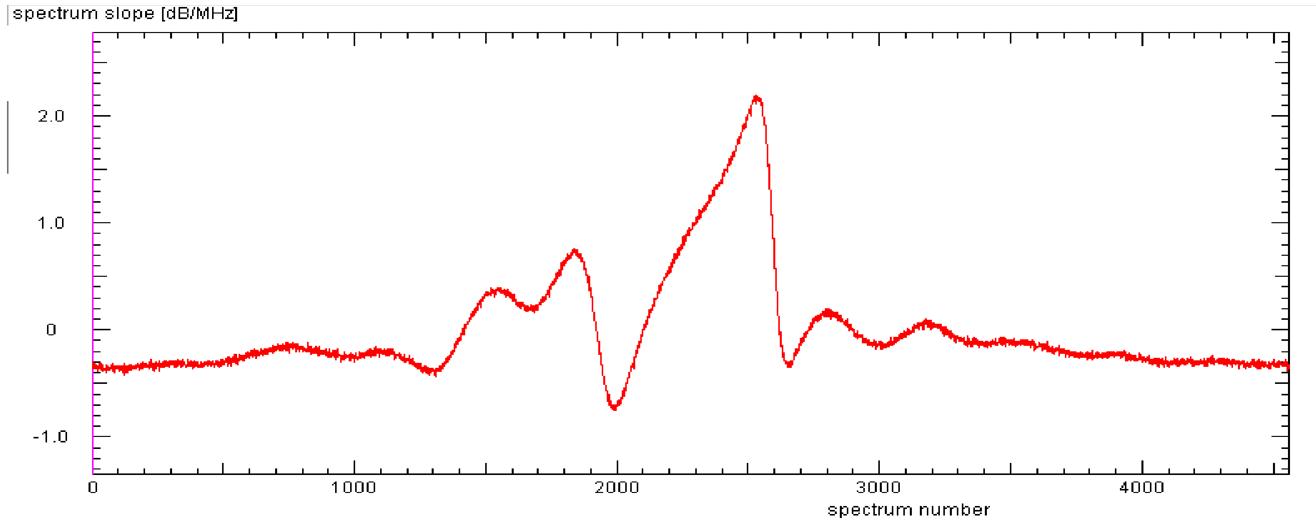
These points are discussed in the following in more detail.

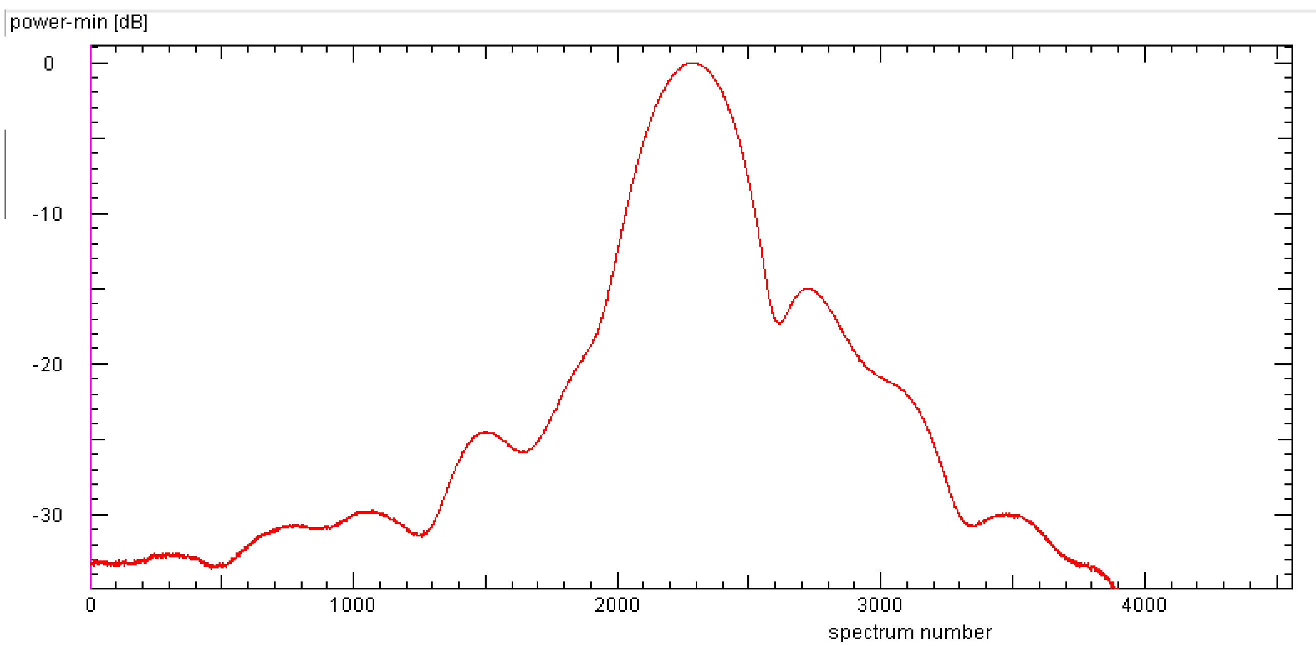
Squinting of the Antenna

To characterize the spectra it is useful to define a spectral slope from the powers at the low and high end of the spectrum

$$slope = 10 * \log10(p(f2)/p(f1) / (f2-f1)$$

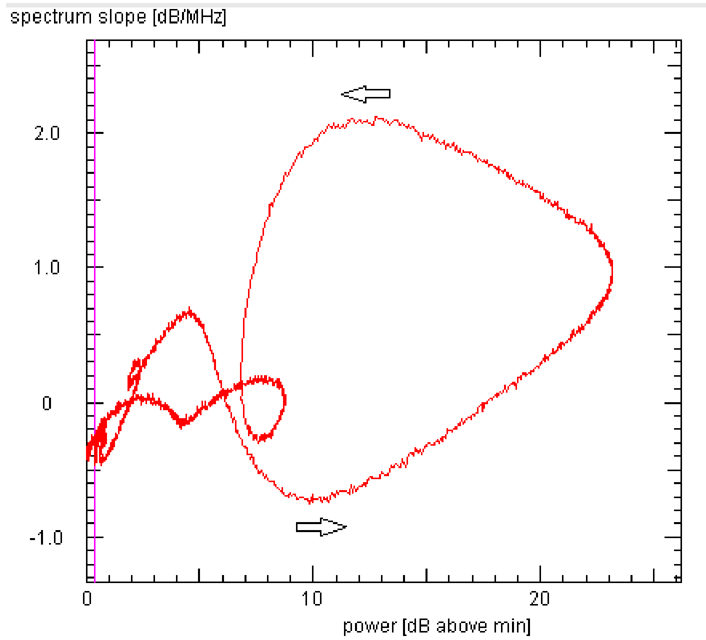
which is in convenient units of dB/MHz. Comparing the slope with the signal power shows that during the Sun's travel across the antenna beam the slope goes from negative to positive values. It also varies while the Sun passes through the sidelobes:





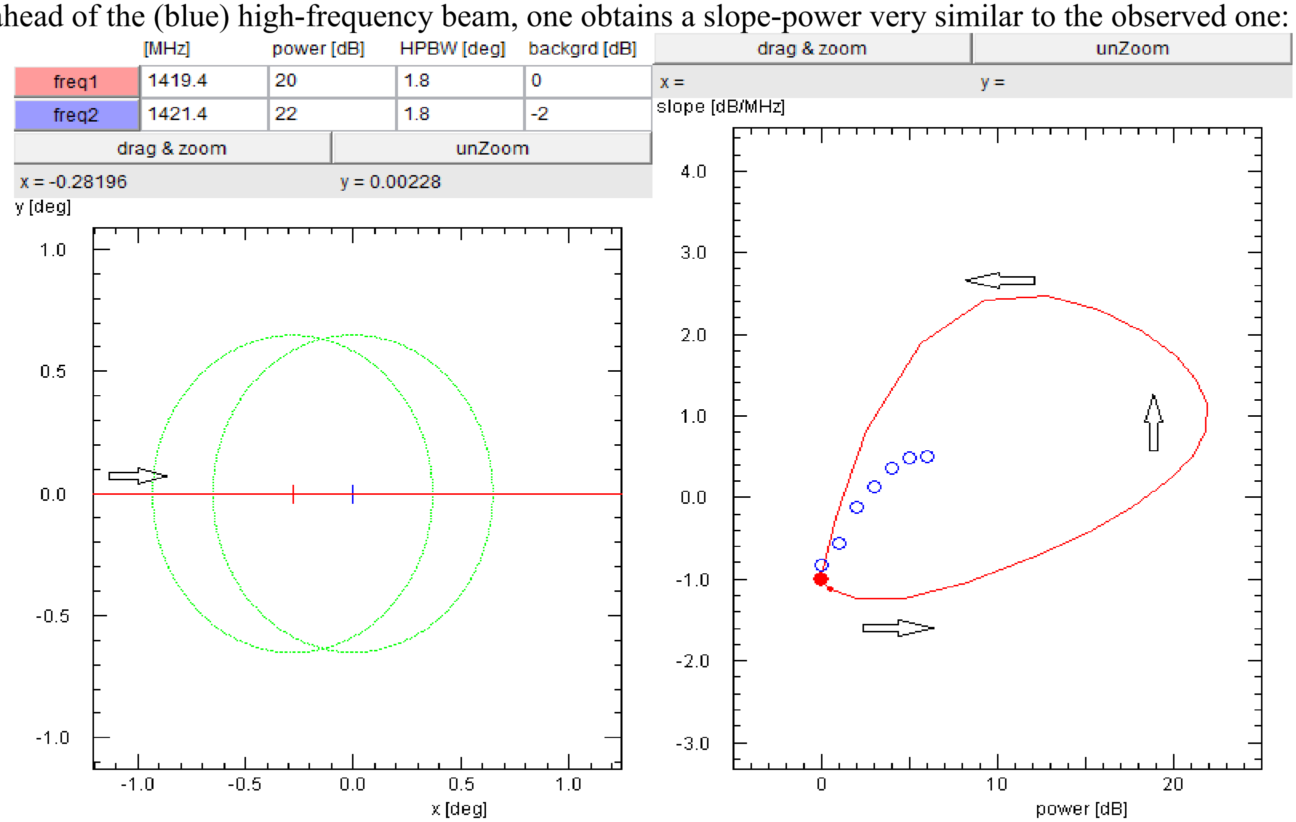
That the slope during the incoming side is different from that of the outgoing side shows that the slope is not related to the power level – as would be an indication for non-linearities – but it is related to the antenna pattern, which is sampled by the Sun.

This is nicely shown by plotting the slope versus the signal power (the arrows indicate the flow of time):



Since the slope increases during the solar transit, the signal at the lower frequency rises before the high-frequency signal. The antenna beam at low frequency points closer to the approaching Sun than the beam at higher frequencies … The antenna squints!

This can easily be modeled by considering two Gaussian-shaped beams pointing at slightly different positions relative to the Sun's path, as shown below. If the low frequency beam (red cross) points 0.3º ahead of the (blue) high-frequency beam, one obtains a slope-power very similar to the observed one:

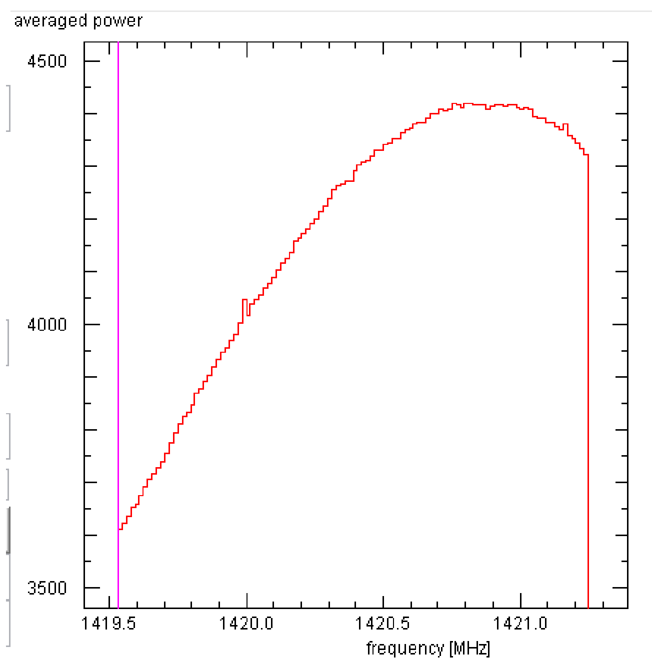


However one notes that the curve from the observations is more strongly pointed. Changing the various parameters of the model does not allow to get a better reproduction of the curve shape. The reason for this pointed shape is not yet known.

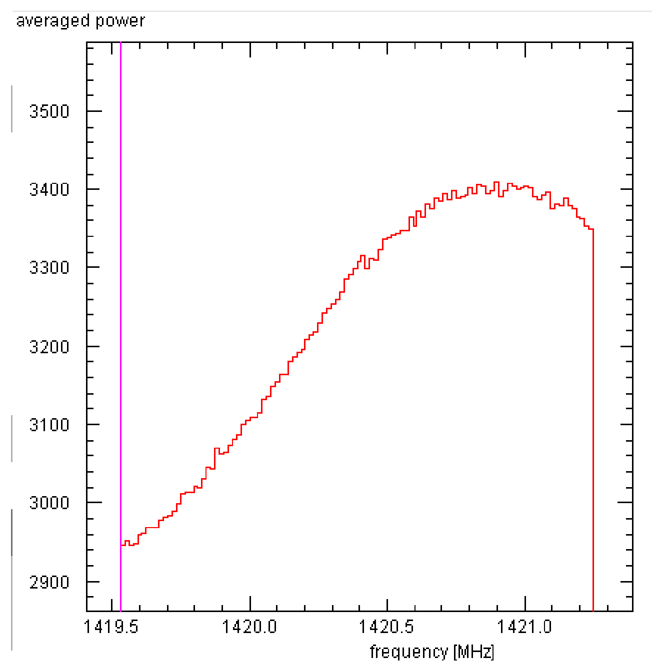
This simple model permits to determine well the difference in the beam positions parallel to the Sun's trajectory, which implies here that the beams must still be strongly overlapping. Unfortunately, no constraint can be obtained on the position difference perpendicularly to the solar path. As long as the beams overlap as strongly as shown above, the power-slope curve retains its shape. Perhaps by more precise data or different data this could be done …

Frequency Dependence of the Gain (1420 MHz)

The explanation of a squinting antenna fails to account for another observation: The spectrum of the flux calibrator also has a positive slope and even a curvature like that of the Sun (below left). The emission by the calibrator fills completely the beam, thus antenna squint cannot contribute. Furthermore the spectrum of DK7LJ working in front of the antenna feed has the same characteristics (below right). Of course, the spectrum of the empty sky (above) also is not affected by any squinting!

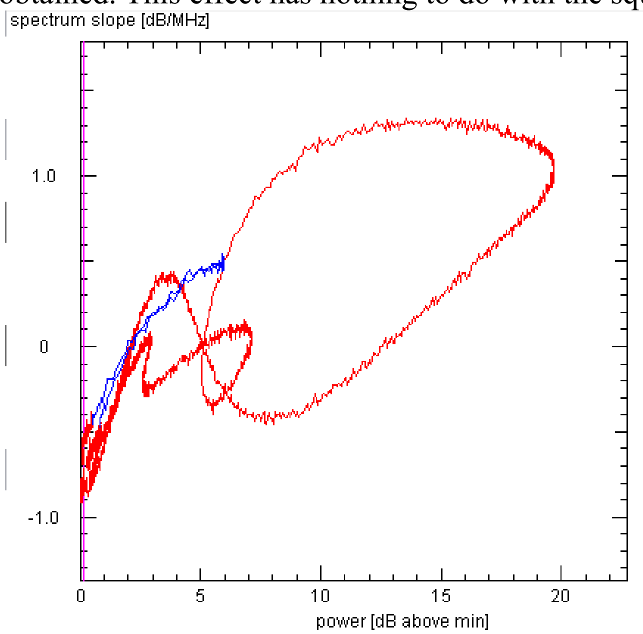


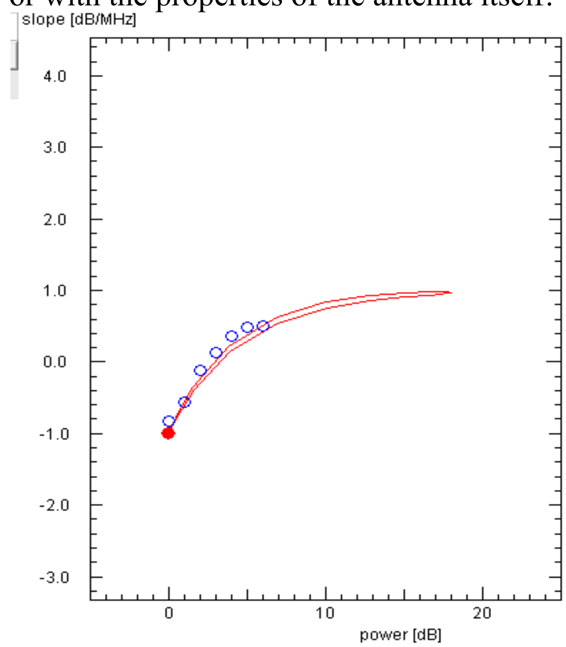
Spectrum of the flux calibrator



Spectrum of DK7LJ in front of antenna feed

Thus the antenna system provides different spectra, even if the entire beam is filled with this emission, the only difference being the power level. But there is another important information: when the antenna turns down to the flux calibrator, the signal gradually increases, as more and more of the trees enter the beam; but also the slope gradually increases, as shown by the blue curve in the plot below left. Even more significant is the fact that when the antenna is moved away from the calibrator, power and slope decrease gradually, but in the same way as they had increased before. The same curve is repeatedly obtained. This effect has nothing to do with the squint, or with the properties of the antenna itself!

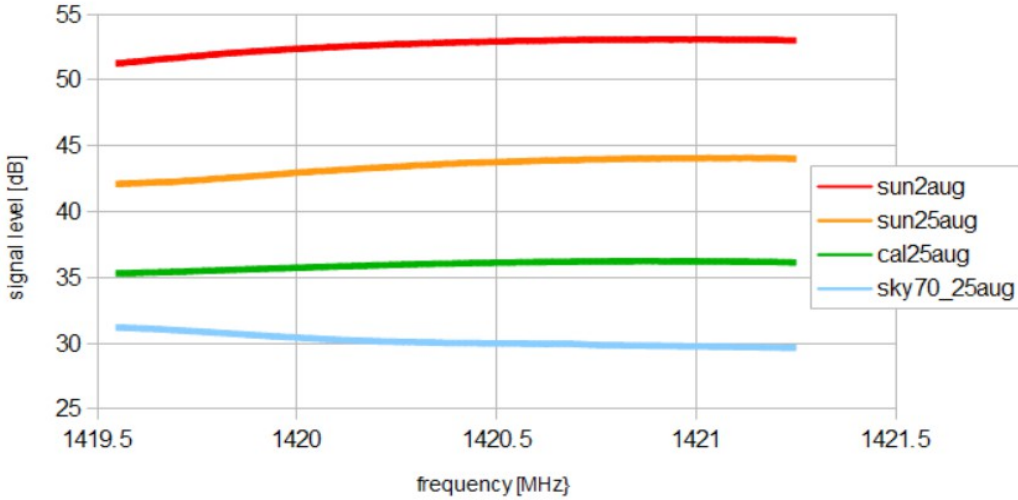




The explanation is very simple: The gain of the receiving system varies across the frequency band: At above right, the observed relation (blue circles) is well reproduced for the two antenna beams (as modeled before) coinciding exactly, but if at the lower frequency the noise level is 2 dB higher and the gain 2 dB lower than at the higher frequency.

The modeling for the antenna squint, discussed earlier, includes this gain and background variation with frequency.

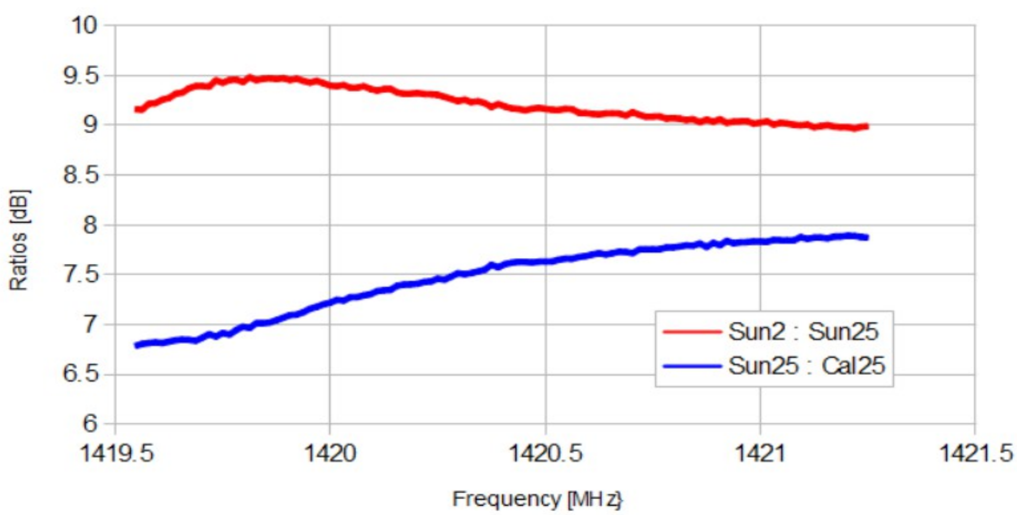
The simple modeling is extended in the following manner: Let us compare spectra of the Sun taken on 2 aug (Sun passing through beam centre), 25 aug (Sun 1.4º offset from centre), the sky and the calibrator:



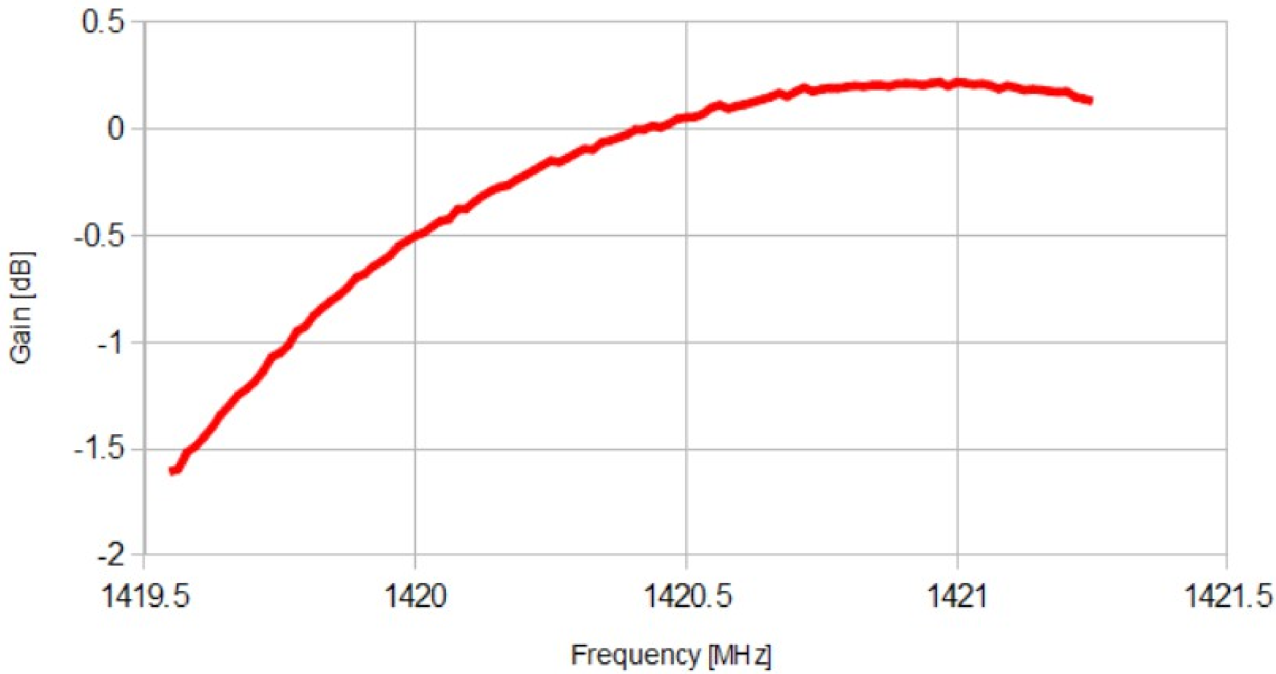
While the sky spectrum slopes down, the other spectra have positive slope. The latters differ in relation of the signal level, because any spectrum is the sum of the background noise (essentially seen in the sky spectrum) and the source signal. From the determination of the frequency-dependent system temperature it is known that the receiver noise increases to lower frequencies.

Because of the small frequency range (2MHz at 1420 MHz: less than 0.2%) one can safely assume that the true spectra of Sun and calibrator are flat, i.e. with zero slope. Thus, any frequency-dependence seen in the receiver output from a source much stronger than the receiver noise level, simply is the frequency characteristic of the receiver system.

Despite their large difference in level, the solar spectra from 2 aug and 25 aug agree within 0.5 dB. The much lower spectrum from the calibrator shows a 1.5 dB variation in comparison with the solar spectrum:

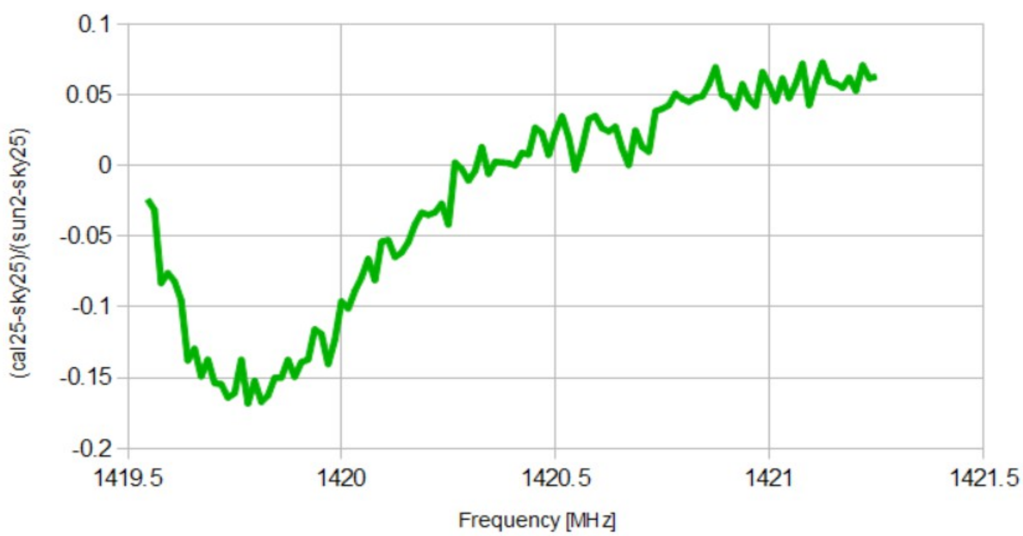


Taking the data from 2 aug, one obtains the dependence of the receiver gain on frequency:

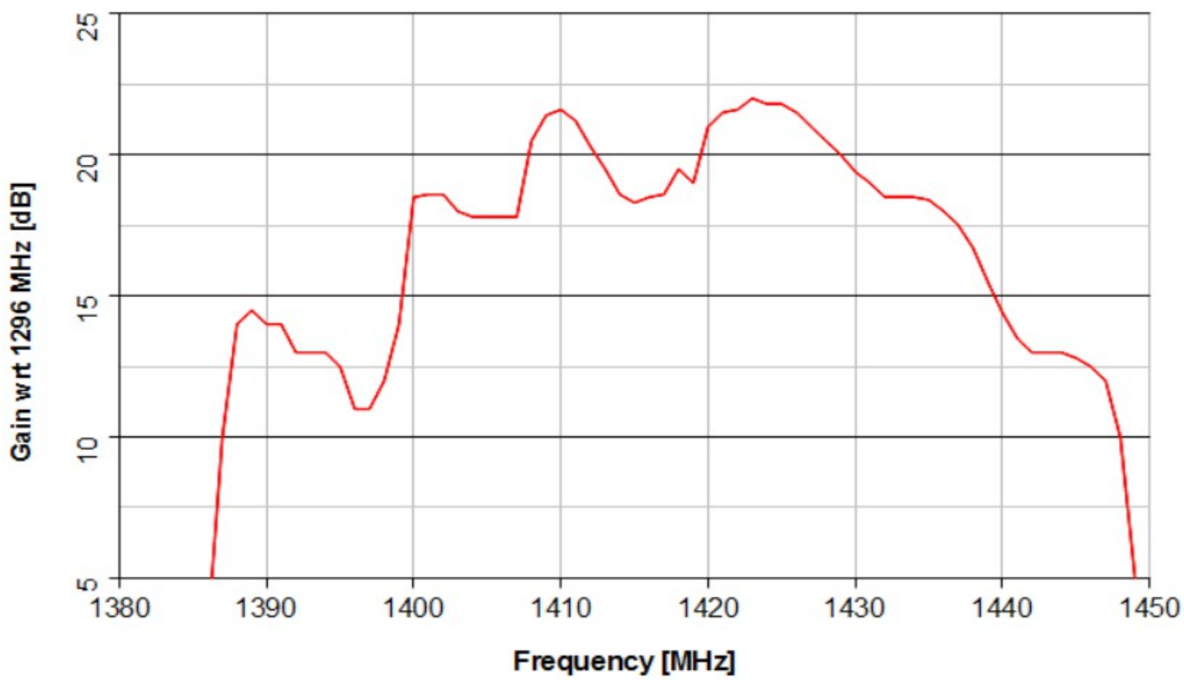


This could be due to the ripple in the frequency response of the 1420 MHz interdigital filteror in the passband of the preamplifiers.

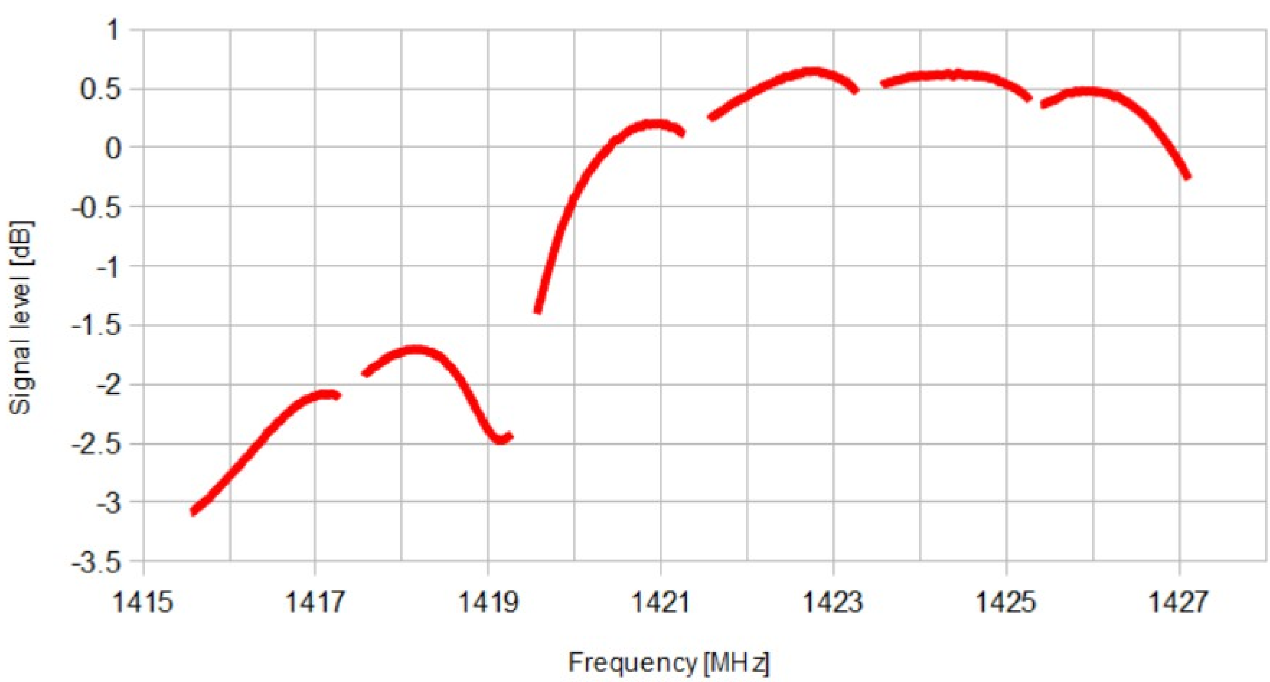
Instead of the Sun one can also use the always available signal from the calibrator, if the sky background spectrum is subtracted, which can be taken as an approximation for the contribution of the receiver noise. The error in the frequency reponse is probablycomparable to the overall accuracy of this procedure:



The frequency response has been measured over a larger bandwidth, using the Sun as a source. The coarse response, obtained by DF5DU from measurements every 1 MHz, shows the presence of six maxima of the interdigital filter between 1390 and 1445 MHz, and that 1420 MHz is placed near the low-frequency flank of one of them:

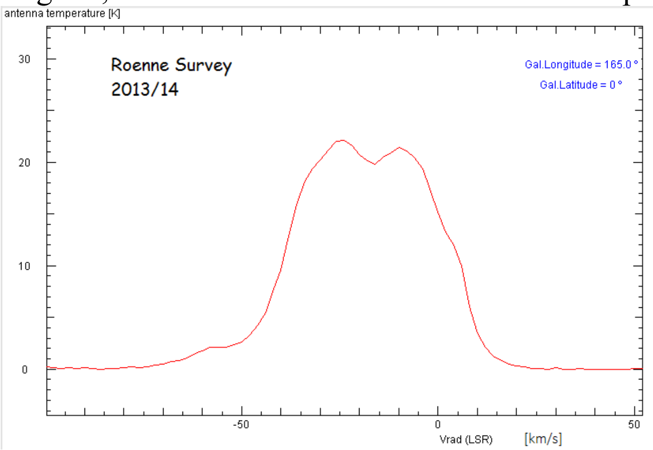


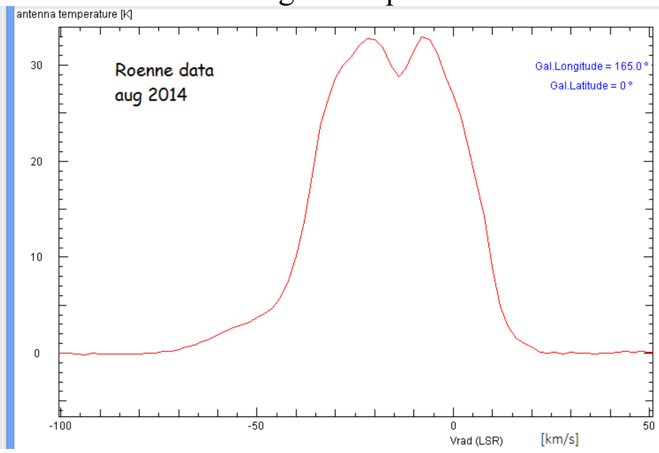
By taking 2 MHz wide spectra centered every 2 MHz, a more detailed view of the frequency response is secured. It shows that the rather flat portion between 1421 and 1427 MHz has a rather steep flank at 1420 MHz. Since all spectral portions exhibit a marked decrease at the high frequency end, this indicates a slight low-pass response by another filter, between AR5000 and Perseus.



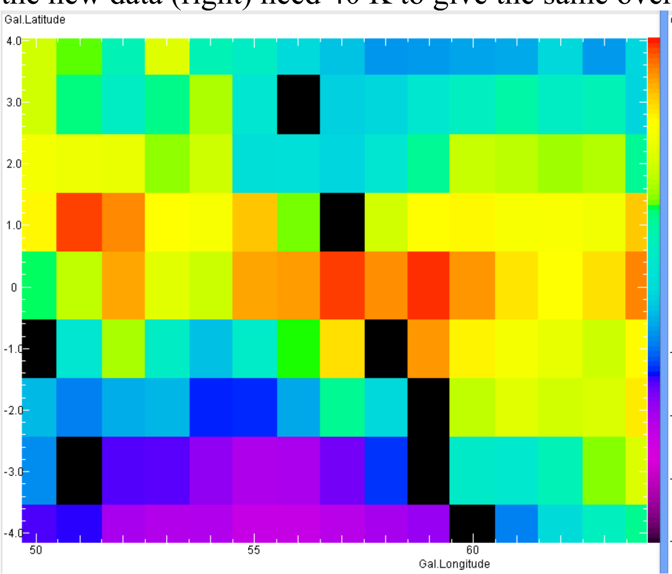
Comparison of Performance Before and After Relocation (1420 MHz)

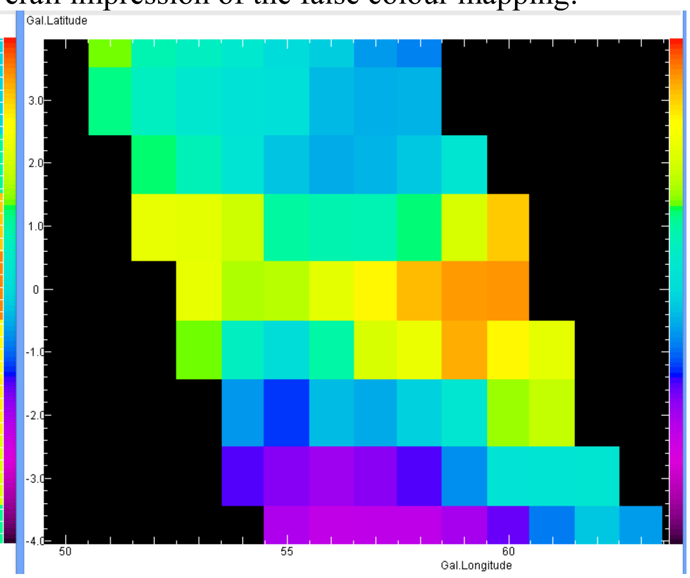
In the ongoing survey of Galactic Hydrogen it is noticed that the data taken on the new location of the antenna is markedly better than the data taken before. While in the data reduction the same ystem temperature (50 K) is assumed, the emission features in the new data are on the average by about 30 % brighter, i.e. about 1 dB. This can be seen from spectra taken at the same galactic position:





as well as from the intensity maps of the same region. The old data (left) require a range of 30 K but the new data (right) need 40 K to give the same overall impression of the false colour mapping:

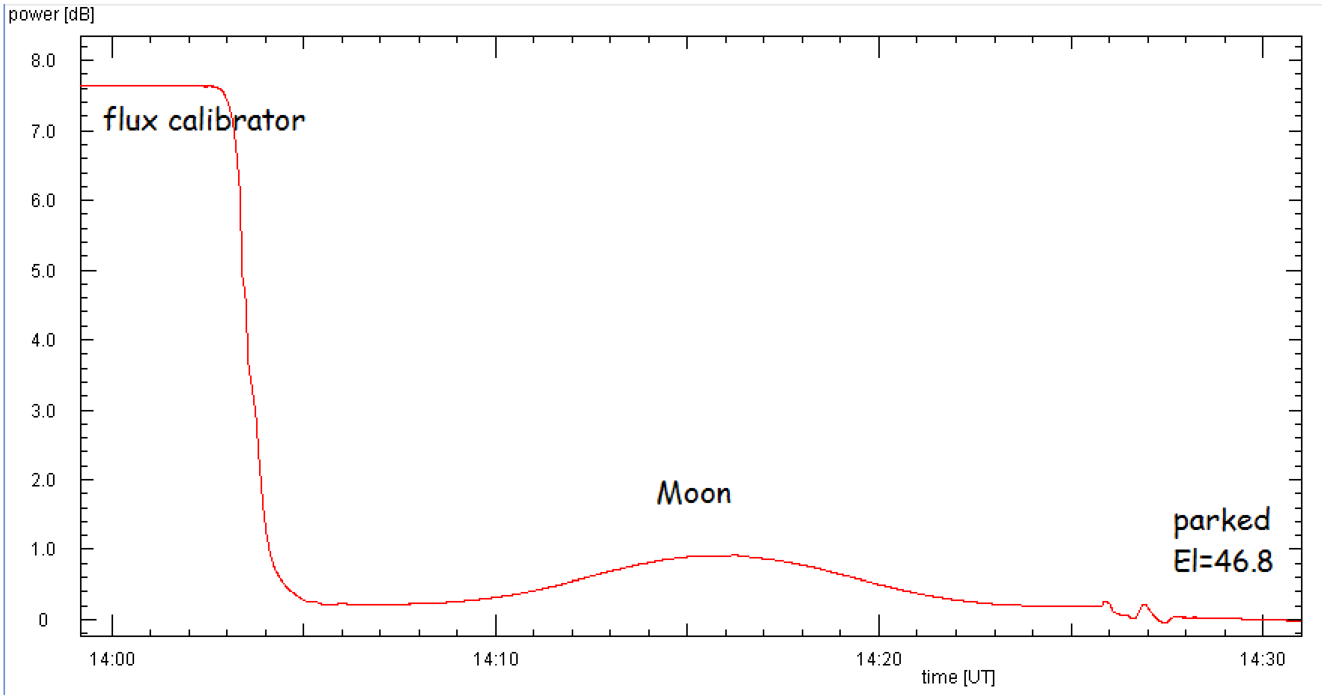




While there is a fair amount of variation of this enhancement factor, on the average the antenna appears to perform better by 1 dB at its new location.

Moon (1296 MHz)

A preliminary drift scan of the four-days-old Moon on 28 aug 2014 at AZ 220, El 29.6:



gives these results:

peak of the Moon signal: 0.914 dB
nearby sky background: varies from 0.215 to 0.187 dB during the transit. At the peak time it may assumed to be 0.20 dB.
This gives for the on/off ratio Y = 0.71 dB

The moon is a thermal emitter with an average temperature of 220 K with a monthly variation of ±20 K (cf. Monstein's determination on 10 GHz). This gives an average flux of

$$\text{Flux} = 2760 * T_{moon} / \text{wavelength}^2 * \Omega_{Moon} = 728 \text{ Jy}$$

with the Moon's solid angle $\Omega_{Moon} = \pi (R_{moon}/\text{distance})^2 = \pi (1738 \text{ km}/384401 \text{ km})^2 = 6.42\ 10^{-5}$ sr.

With the effective antenna area 45..40 m^2, determined by the solar observation,

$$T_{ant} = A_{eff} * \text{Flux} / 2760 = 11.9 .. 10.5 \text{ K}$$

The antenna temperature of the local sky background is

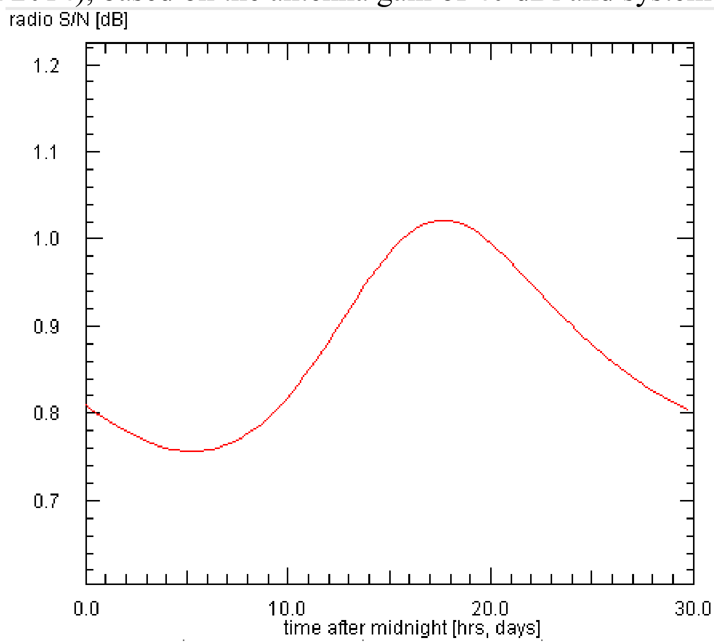
$$T_{background} = T_{sys} + T_{CMB} + T_{zenith}/\sin(\text{elevation}) = 48 + 2.7 + 5/0.5 = 60 \text{ K}$$

and the on/off ratio

$$Y = 1 + T_{ant} / T_{background} = 0.79 .. 0.70 \text{ dB}$$

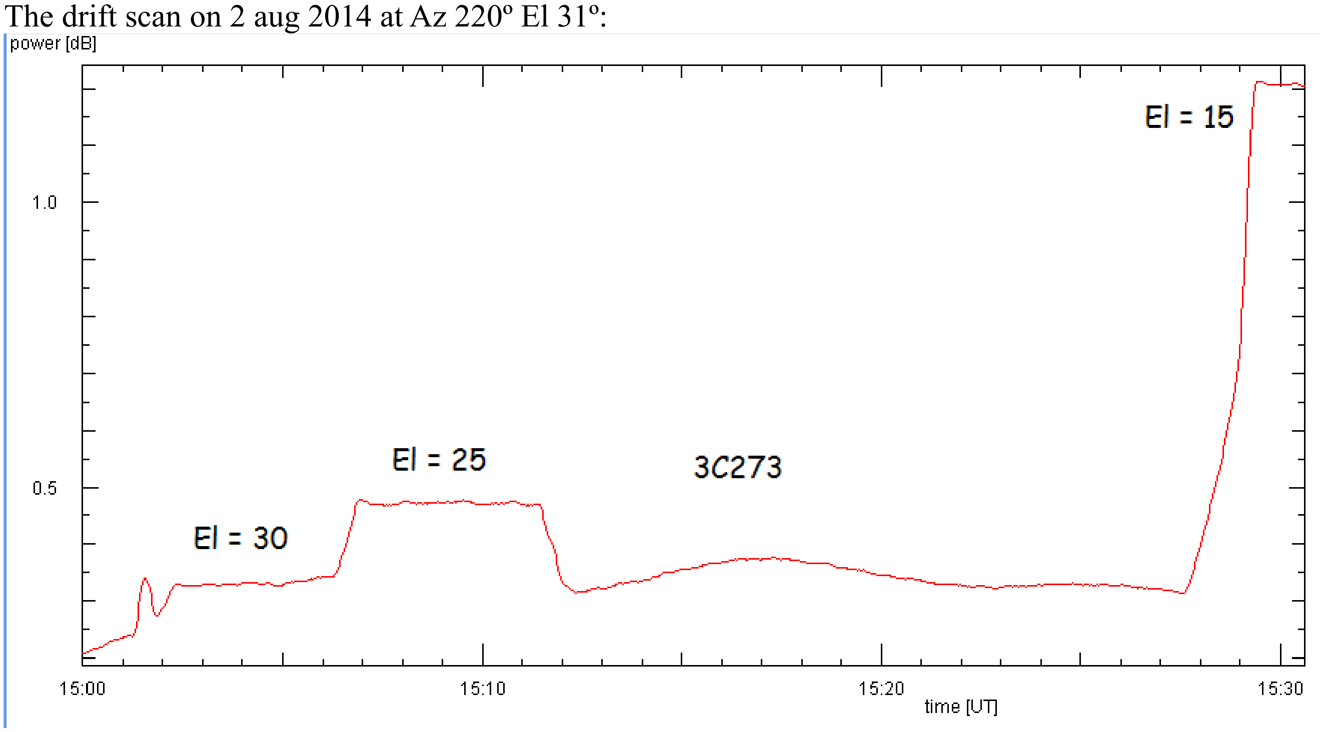
in agreement with the prediction (for the average values)

If one takes into account the monthly variation of the integrated lunar surface temperature and the variation of the actual lunar distance, one gets this prediction of the on/off ratio Y for the days starting with New Moon (27 jul 2014), based on the antenna gain of 40 dBi and system temperature 50 K:



Quasar 3C273 (1296 MHz)

The drift scan on 2 aug 2014 at Az 220º El 31º:



gives these data:

peak of 3C273: 0.374 dB
nearby sky background: 0.32 .. 0.324 dB
hence an on/off ratio Y = 0.05 dB

From the Geneva database (http://isdc.unige.ch) the average flux at 1.5 and 2.5 GHz is obtained:

Flux = 42 Jy

This yields with the effective area 45..40 m^2, determined by the solar observation,

$$T_{ant} = A_{eff} * Flux / 2760 = 0.68 .. 0.61 K$$

The antenna temperature of the local sky background is

$$T_{background} = T_{sys} + T_{CMB} + T_{zenith}/\sin(elevation) = 48 + 2.7 + 5/0.5 = 60 K$$

and the on/off ratio

$$Y = 1 + T_{ant} / T_{background} = 0.048 .. 0.043 dB$$

in very good agreement with the measurement.

Conclusions

- Very consistent results are obtained with the antenna parameters:
  HPBW = 1.8º
  gain = +39.8.. +40.2 dBi at 1296 MHz
  A_{eff} = 40..45 m^2
  System temperature: 45..50 K (1296 MHz) and about 80 K (1420.4 MHz)
- Day-to-day measurements give the impression that the system parameters are rather stable. Of course the system's performance needs to be monitored over a longer time span, and a larger range of environmental conditions such as ambient temperature and rainfall.
- The spillover amounts to about 0.2 dB at the zenith. This suggests a 10dB enhancement of the side-lobe level near 95º off the optical axis.
- The antenna has a squinting main lobe. This is not overly surprising, but it is quite remarkable that it varies strongly with frequency and amounts to about 0.3º between 1419 and 1421 MHz.
- The position at Az 200º El 0º provides a very stable flux calibration level.
- The receiving system for 1420 MHz has a gain variation of about 1.5 dB across the 2 MHz wide band. The system temperature is lowest and the gain highest near the upper frequency limit.
- This slight imperfection does not restrict the quality of any radio astronomical measurements. Eventally it can be remedied by tuning. But, as any changes in the receiving system would upset the ongoing Rönne Survey of Galactic Hydrogen, such action need not to be taken until the Survey is finished.