EME and Radio Astronomy

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With only three days a month with big EME activity, and maybe less than few hours a day when the effort and conditions not always the best, one big question may appear in our minds: What to do with the antennas in the remaining 26 nights?

The following article describes how to do radio astronomy experiments using our EME antenna set-ups. I also describe the additional equipment required for these observations.

New moon and apogee time will never be the same again!

Introduction

In the early 1930s, an engineer named Karl G. Jansky was working for the Bell Labs. (New Jersey), and was assigned to study the origin and direction of the static noise from thunderstorms. This was, at the time, very useful information for the antenna design for the transoceanic radio-telephone communication systems, especially if a predominant direction for the noise were found. In his research, Jansky used a vertical Bruce curtain antenna and operated at 20.5MHz. He was than able to identify several types of static, but one of them had unknown origin and its direction seemed to move as the earth rotated. Later, Jansky was able to calculate the position of this noise source to be a fixed point in the sky of about 18Hr of right ascension and -10° declination. This position is in fact (as far as he could resolve) the centre of our galaxy. Jansky had just become the very first Radio Astronomer.

After these crude experiments many new researchers came into action, building antennas and scanning the sky searching for new sources, and trying to see the universe from this entirely new perspective.

This new science, Radio Astronomy, has revealed important things like our position in the galaxy, and is the main support for the big-bang theory. In fact it has contributed more than 60% of the our present knowledge of the universe.

Radio telescopes, antennas, noise and noise temperature

A directional antenna, pointing to the sky, connected to a low noise receiver is the simplest description of a radio telescope we can imagine. Although it is simple, it is also a very correct definition, only requiring further to establish what is the directional antenna requirements and how low the noise of the receiver must be.

Nowadays, radio telescopes (RT) commonly employ dish antennas and make use of the lowest noise preamplifiers technology can produce. Useful antennas can be as small as a 3m dish or as large as a 300m dish (Arecibo RT).

When looking up in the skies the RT is receiving its own noise plus the noise coming from that direction in the sky. In most cases, sky noise is a small fraction of the receiver system noise. This fact forces the measurements to be made on a fraction of a dB, so most of the times this is not a very easy task.

To ease the comparison of signals, or to compare between systems and also to have some physical meaning, noise measurements are usually expressed in temperature or equivalent temperature, while the noise sources in the sky are expressed in power-flux density (normally in Jy, Jansky).

A resistor at temperature T will deliver at its terminals a power:

$$P = K . B . T \qquad \text{(eq. 1)}$$

where B is the bandwidth (Hz), T the temperature of the resistor (Kelvin) and K is the Boltzmann constant equal to 1.38 x 10^{-23} J/K (Joules/Kelvin)

An antenna pointing to a body at temperature T will receive exactly the same power as above, as long as all radiation pattern is filled with that body. Or it receives a fraction of that power corresponding to the fraction of solid angle covered by the body. In this case we are measuring a total temperature of:

$$T_{ant} = T_{src} \cdot \left(\frac{\Omega_{src}}{\Omega_{ant}} \right) \qquad \text{(eq. 2)}$$

where T_{ant} is the temperature that the antenna sees, T_{src} (source temperature) is the body equivalent temperature, Ω_{src} is the solid angle occupied by the body and Ω_{ant} is the total antenna solid angle.

In a real system we are measuring the source equivalent temperature added to the system equivalent temperature; therefore an accurate result is only possible by knowing well the characteristics of our system. We can calculate the source equivalent temperature by using a comparative measurement between the unknown source and a known source (that could be the empty, or cold, sky). The Y value is defined as:

$$Y = \frac{P}{P_0} \qquad \text{(eq. 3)}$$

where P is the total power received while pointing at the source while P_o is the power received pointing at the cold sky (or pointing to another known source).

It can be also represented in equivalent temperatures as:

$$Y = \frac{T_{sys} + T_{ant}}{T_{sys} + T_{cold}} \quad \text{or if } T_{cold} \text{ is small} \quad Y = \frac{T_{sys} + T_{ant}}{T_{sys}} \qquad \text{(eq. 4,5)}$$

where T_{sys} is the equivalent temperature of the RT equipment, T_{ant} is the equivalent temperature of the source sensed at our antenna and T_{cold} is the equivalent temperature of the cold sky (can be as low as 3K and neglected if T_{sys} or T_{ant} are much larger).

Y values are usually presented in dB and represent the value measured directly from a receiver (this is the relation behind the common statement of “having a moon noise of…” or “a sun noise of …”).

The power-flux density is the way to express the radiation of a source without the need to account for the specific characteristics of the measuring system such as antenna size or measurement bandwidth. The most common unit in radio astronomy is the Jy (Jansky) with $1 Jy = 10^{-26} W.m^{-2} Hz^{-1}$

Most of the tables containing radio sources express their strength in Jy at a specific wavelength.

Since the sources in the sky are relatively broad-band signals, their observation, from a power ratio point of view, is independent from the bandwidth employed. However the random fluctuations on the measured signals increase with the decreasing bandwidth and make the ability to resolve small variations difficult as the band gets narrower (remember we are measuring noise).

The resolution (or the ability to resolve the minimum signal variations) is calculated by the “Dicke” expression, equation 6, or as the minimum measurable temperature increase, equation 7.

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{B.\tau}} \qquad T_{\min} = \frac{T_{sys}}{\sqrt{B.\tau}} \qquad \text{(eq. 6,7)}$$

where B is the bandwidth and τ is the measurement integration time. (This expression corresponds to a total power measuring system.)

From the above equation is easy to understand that we would require a large bandwidth and integration time as long as possible, in order to resolve the smallest possible temperature increase.

These parameters are limited by practical reasons such as the bandwidth free of interference (this was not a problem in the early RA days) and also the integration time must be a practical value (up to some hundreds of seconds).

The overall system sensitivity must include also the antenna size (or gain), that is, how much power it can receive. The effective aperture size is the determinant parameter to know how much power flux is intercepted. The antenna effective aperture can be calculated as:

$$A_{eff} = \frac{G_i . \lambda^2}{4\pi} \qquad \text{(eq. 8)}$$

where G_i is the isotropic gain of the antenna and λ is the working wavelength.

The antenna temperature increase when pointing at a source with a flux density of *S* can be calculated as:

$$T_{ant} = \frac{S.A_{eff}}{K} \qquad \text{(eq. 9)}$$

S is the source flux density (in SI units, x10^{-26} Jy), A_{eff} is the antenna effective aperture and K is the Boltzmann constant equal to 1.38 x 10^{-23} J/K (Joules/Kelvin).

The G/T parameter, often used to evaluate the system performance, can be also calculated from the above equations. We want to know G_i/T_{sys}; therefore we make use of equation 5 to obtain T_{sys} and from equations 8 and 9 we can get G_i resulting in:

$$\frac{Gi}{T_{sys}} = \frac{4.\pi.K(Y-1)}{\lambda^2.S} \qquad \text{(eq.10)}$$

Note that Y values are in linear form and flux densities are in W m^{-2} Hz^{-1}. This expression allows you to calculate a system performance using a known source in the sky.

Most of amateur EME (or RA) stations are capable of resolving far below 1K and also capable of detecting and measure many individual sources.

The use of sky sources for the EME system calibration and optimisation is far more accurate than the use of the Sun or Moon as their signals are not constant in time. One of the best references in the sky is M1 (Taurus A or the Crab Nebula), for which the flux is very stable and accurately known.

Radio sources in the Sky

Up to now, thousands of radio sources have been discovered in the skies. Some of them correspond to extremely far away objects on the very edge of the universe (or at least on our observable limit). For the size of antennas we have (EME stations have from 3 to 15m dishes) some very distant objects can be also detected.

The following table presents a selection (organised by type of object[1]) of some strong sources in the sky. Most of them are detectable by amateur systems.

Supernova remnants (SNR)

Name	**RA h:m**	**Dec °:m**	**Flux Jy (2)**	**Comments / (Y at DMK's) (3)**
3C10	00:22.6	+63:52	44	Tychos from 1572dc
3C144	05:31.5	+21:59	875	Taurus A,1054dc/ (0.08dB)
3C157	06:14.3	+22:36	190	/ (0.025dB)
W41	18:31.6	-08:57	75	
3C392	18:53.6	+01:15	171	W44
W78	20:48.2	+29:30	90	Cygnus loop
3C461	23:21.1	+58:33	2480	Cassiopeia A

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[1] - Types of sources: **Thermal radiators**, the ones in which the physical temperature resembles the noise temperature measured, are the planets. The easiest one to measure is the Moon (exception must be made to Jupiter at certain wavelengths where it is not a thermal radiator). **Stars** radiate in several ways, although the Sun is the only one detectable by RA. It exhibits a turbulent behaviour and signals may fluctuate orders of magnitude. **Supernova remnants** (SNR) are gigantic plasma clouds that remained after a supernova explosion. These are some of the strongest sources in the sky. **Nebulas** are plasma clouds emitting radiation, similar to SNR. **Radio galaxies** are galaxies that have a strong emission at radio wavelengths. **Quasars**, 'quasi stellar objects', are extremely distant galaxies and unusually bright objects at radio frequencies (and/or also at optical frequencies).

Radio Galaxies

Name	RA h:m	Dec °:m	Flux Jy (2)	Comments / (Y at DMK's)(3)
3C123	04:33.9	+29:34	47	
3C218	09:17.5	-11:53	43	D Galaxy
M87	12:28.3	+12:40	198	Virgo A, E Galaxy / (0.05dB)
3C295	14:09.6	+52:26	23	D Galaxy
3C348	16:48.7	+05:05	45	Hercules A, D Galaxy
3C353	17:17.9	-00:56	57	D Galaxy
3C405	19:57.7	+40:36	1495	Cygnus A, D Galaxy

Nebulas

Name	RA h:m	Dec °:m	Flux Jy (2)	Comments / (Y at DMK's)(3)
W3	2:22.7	+61:51	170	IC1795
3C145	5:32.8	-5:27	520	Orion A / (0.03dB)
3C147	5:38.4	-1:54	95	Orion B
W28	17:58.2	-23:22	360	M20
W29	18:01.0	-24.22	260	
W33	18:10.4	-18:00	190	
W37	18:16.3	-13.45	260	M16
W38	18:17.8	-16:09	1060	M17
3C400	19:20.8	+14:08	710	W51 / (0.10dB)

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[2] Total flux values at 1.4GHz. Note that a polarized receive system (linear or circular) will always receive only half of this flux.

[3] Y measurements were done comparing to the source surroundings, not to cold sky. That's why 3C400 has 0.1dB (for a flux of 710) and 3C144 has only 0.08dB (for a flux of 875). These values are only shown for reference.

Quasars

Name	**RA h:m**	**Dec °:m**	**Flux Jy (2)**	**Comments / (Y at DMK's)(3)**
3C48	01:34.8	+32:54	16	
3C147	05:38.7	+49:50	23	
3C196	08:10.0	+48:22	14	
3C273	12:26.6	+02:20	46	1st Ham detection (?!) by: CT1DMK & DK8CI
3C286	13:28.8	+30:46	15	
3C380	18:28.2	+48:43	14	

A total power radiometer

The easiest equipment to perform a sky noise measurement is a total power measuring system, or a total power radiometer. This has an output proportional to the total RF power present at the input. It contains only a band limiting filter, large amplification and power detection. It can be built to easily handle our first transverter IF, usually 144MHz.

The total power radiometer that I used on my experiments, and I present here for reference, operates on 135 to 140MHz, 5MHz bandwidth, and has a total gain of 85dB. The operating band is a segment slightly out of the IF used on EME but still in the range of the transverters and preamplifiers. The main objective behind this selection is to obtain a bandwidth completely free from any local oscillator signals or spurious and still leave the EME set-up unchanged.

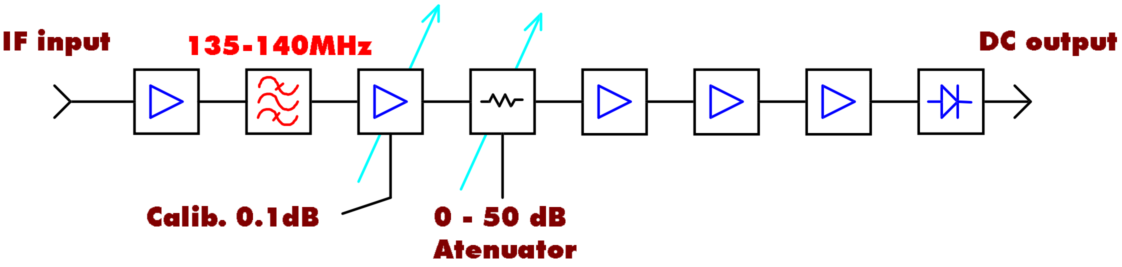

Fig 1 – RF part of the total power radiometer

The IF signal is amplified by a low noise MOSFET before the bandwidth selection filter. The filter is a 4 pole helix filter adjusted to have an absolutely flat pass-band as no ripple is tolerated here (this can be obtained by reducing the coupling between the helix stages, but higher insertion losses will result).

An amplifier isolates the filter output from the variable attenuator that has 1dB steps and 10dB steps to cover 59 dB. This allows me to correctly set the noise power to the optimum level for a diode detector.

An additional 50dB of gain is provided by a 3 stage amplifier before detection.

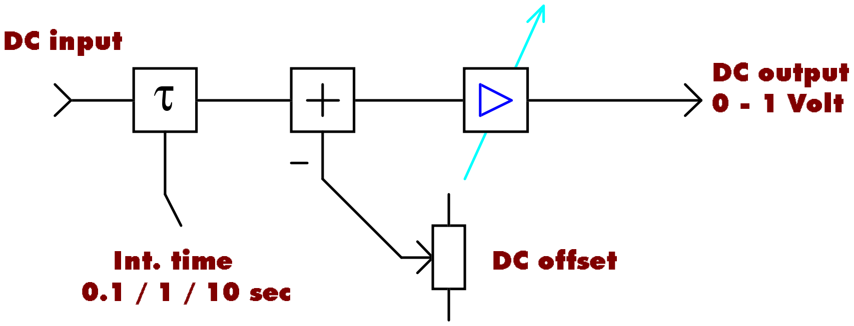

Fig 2 – The DC signal processing of the radiometer.

The DC signal, at the diode output, is integrated over 0.1, 1 or 10 seconds with a RC integrator, and a DC value is subtracted form the signal. This allows additional amplification in order to set the desired range of operation to be within the full range of the ADC. With this technique it is possible to have the full acquisition range corresponding to a 0.1dB of RF signal variation, allowing us to resolve about 0.003 dB (or as far as equation 7 predicts). Further signal processing can be done on the PC such as integration times of 1000s or slope correction to compensate for temperature drifts.

The radiometer output signals are acquired by a PC A/D converter (presently I use a 18bit MAX132 ADC on a i386 computer). Some software was developed to perform the functions of a chart recorder and used on the transit meridian scans. For the 2D sky scans the PC calculates the antenna aiming coordinates, and acquires the signal synchronously with the earth's rotation.

Some Results

The results present here (figures 3 to 8) were obtained during 1997 in a transit meridian configuration. Tests were done essentially at 1290MHz but also some on 10GHz. Due to the high angular resolution at 10GHz (about 0.2deg on my 5.6m dish) I also made some 2D scans with some interesting results, figure 9.

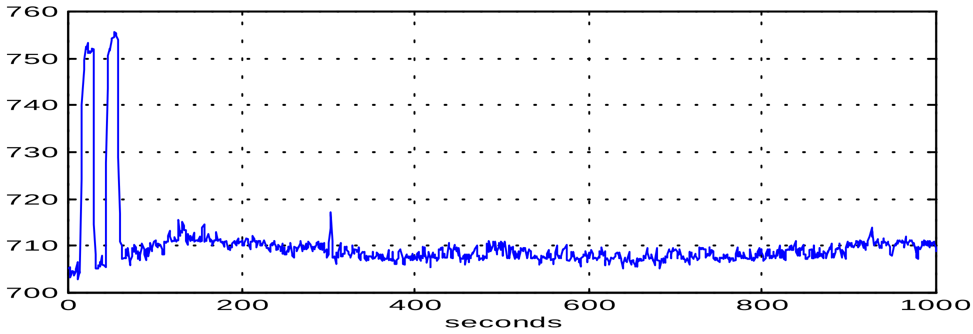

Figure 3 – Amplitude calibration by automatic insertion of 0.1 dB marks at the beginning of each scan.

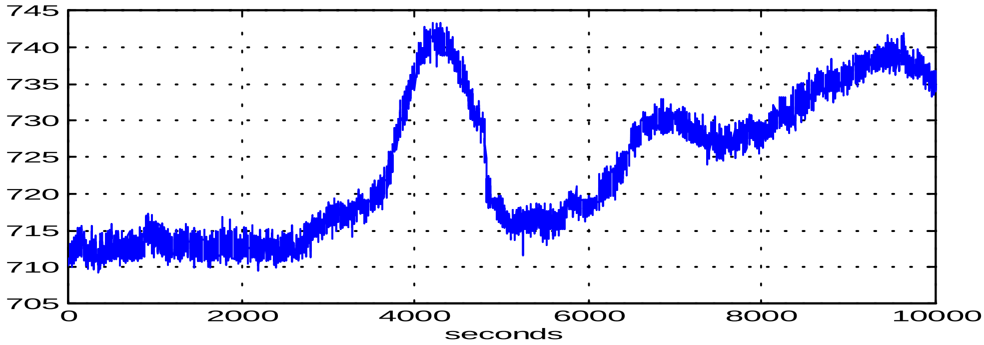

Figure 4 – Raw data of a Taurus A, scan in transit meridian configuration before removing the thermal drift. The amplitude can be quantified using the 0.1 dB marks at the beginning of the scan (figure 3).

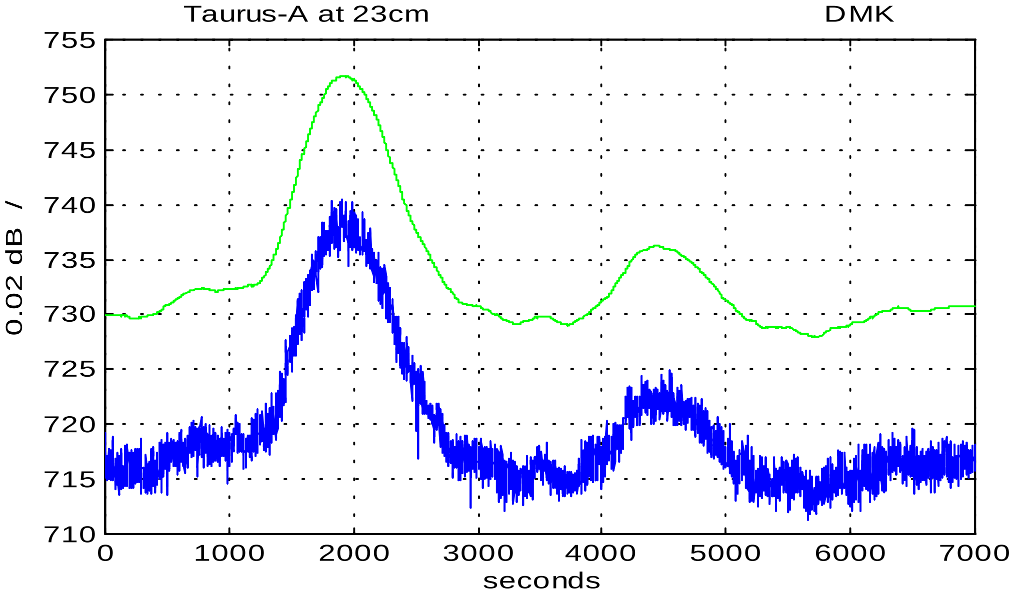

Figure 5 –Taurus A scan in transit meridian configuration. 3C144 is strong at 2000s and also 3C157 visible at 4500s. Lower trace has 1s integration time while upper trace has 250s integration time.

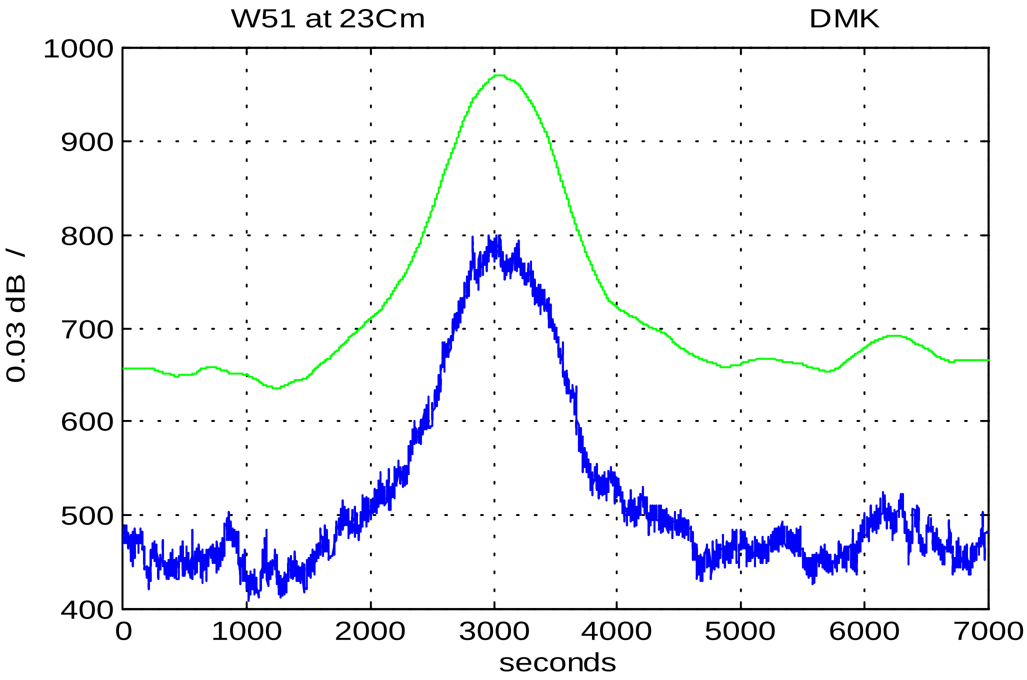

Figure 6 –W51 at 3000 seconds in transit meridian configuration. Lower trace has 1s integration time while upper trace has 500s integration time.

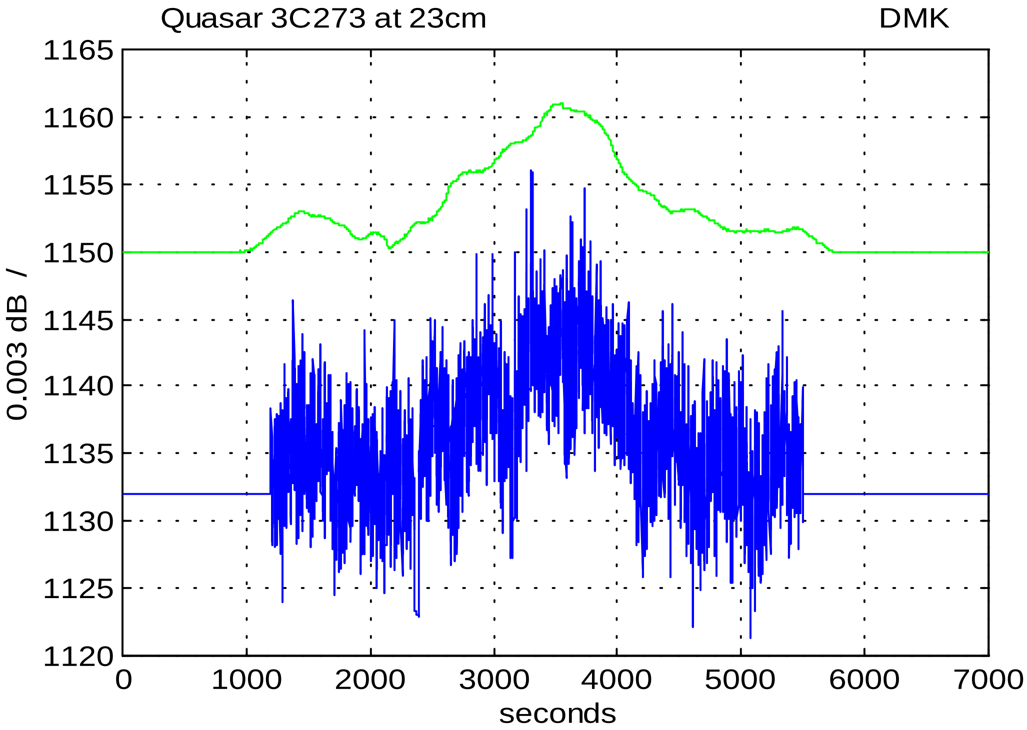

Figure 7 –Quasar 3C273 detected near the instrument sensitivity limit. Lower trace has 1s integration time while upper trace has 500s integration time.

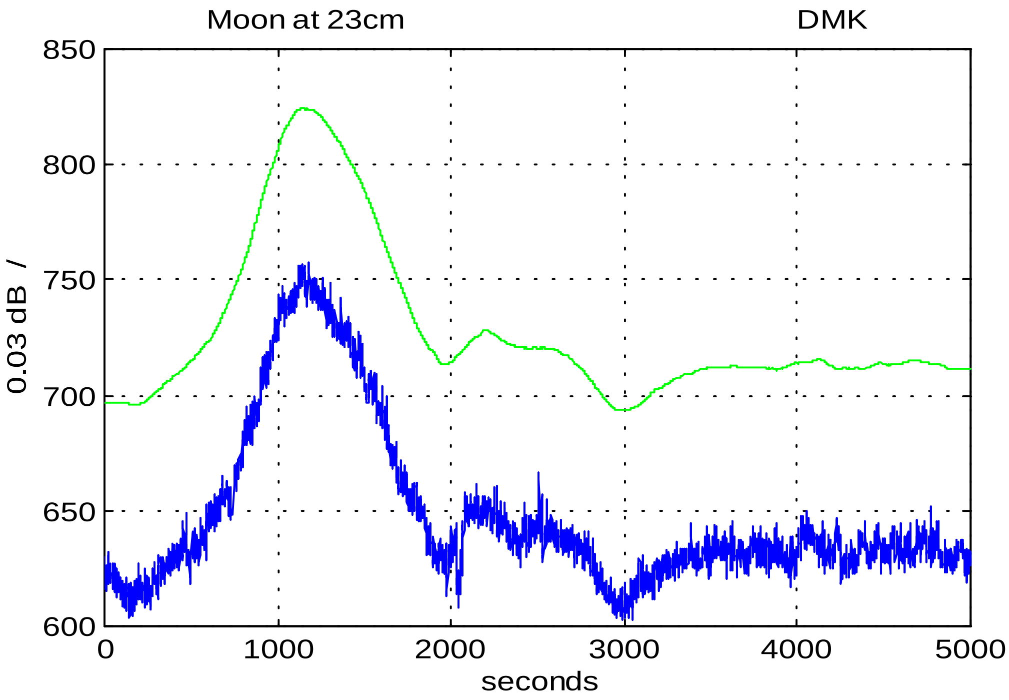

Figure 8 –Moon, transit scan at 23cm. Lower trace has 1s integration time while upper trace has 250s integration time.

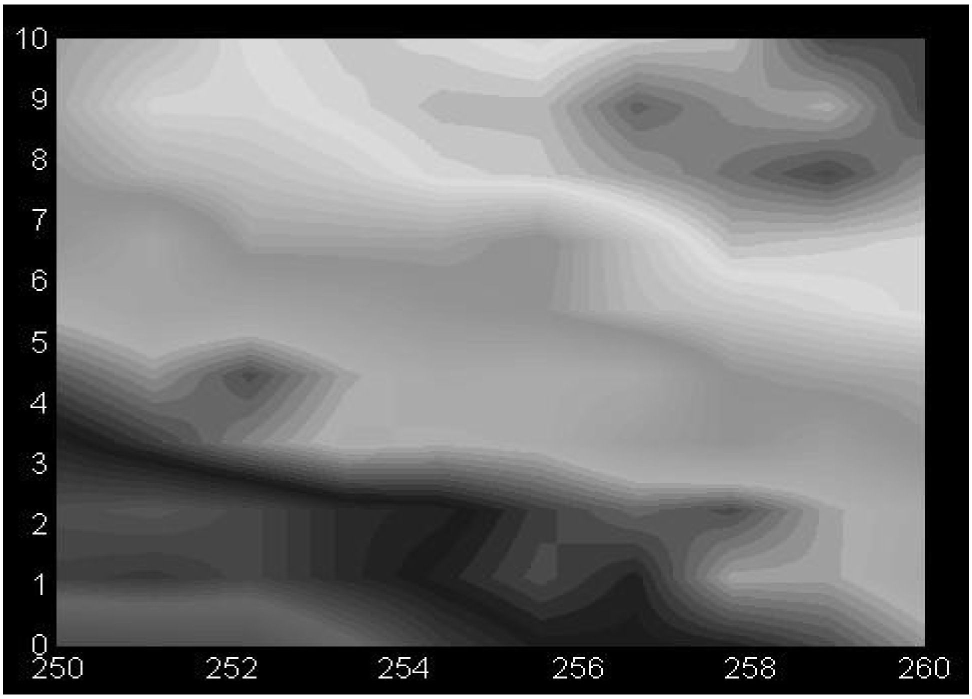

Figure 9 – 2D scan of the Hercules A surroundings at 10GHz. Hercules A is on the upper right corner.