The "Astropeiler Stockert Story"

Part 2: Continuum observations with the 25m dish

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Introduction

This is the second part of a series of articles to introduce and describe the "Astropeiler Stockert", a radio observatory located on the Stockert Mountain in Germany. This observatory comprises a 25 m dish, a 10 m dish and some other smaller instruments. It is maintained and operated by a group of amateurs and is as of today the world's most capable radio observatory in the hands of amateurs.

In this series of articles I wish to describe the setup, the instrumentation and the observational results achieved.

This third part of the series will deal with the observation of continuum sources.

Celestial continuum sources

"Continuum sources" in radio astronomy are celestial sources which emit radio energy in a wide spectral range. There are several emission mechanisms for such kind of radiation:

- Thermal emission, where the temperature of the celestial object is the cause of the radiation
- Synchrotron emission, where the acceleration of a charged particle by a magnetic field is the cause of the emission
- Bremsstrahlung (aka free-free emission) where a charged particle is accelerated by other charged particles and thus causing emission.

Typical continuum sources are the sun and the moon, HII (star forming) regions, supernova remnants (SNR) and radio galaxies. There are various tutorials which cover these sources, their characteristics and emission mechanisms, so I will not go into detail here. A list of tutorials dealing with this can be found for example at [1].

Observational method

Using transit scans vs. active scans

Generally speaking, observing a continuum source means to measure a small increase in the noise received. Therefore, one needs to compare the total power received when the telescope is pointing at the source to the total power when the

telescope is off target. As it turns out, there can be already a small change just by moving the telescope, even if there is no observable source.
This can be attributed to a small change in the thermal radiation picked up from the ground: There is some "spillover", i.e. the receiver will not only look at the dish but also to some extent beyond its rim. In addition, side lobes of the receiving horn will also look at the surroundings.
As the thermal radiation varies as the telescope is pointing to the surroundings (different ground vegetation for example), there is a change in received power. This impacts sensitive measurements and may even "mimic" a weak source.

We have therefore adopted transit scans as the method of choice to do sensitive continuum observations. When using this method, we position the telescope so that the source of interest passes through the telescope beam due to the rotation of the earth. By this method we get both the on- and off-target power by recording the power over time but still keeping the telescope itself stationary.

Of course, this method becomes very tedious when mapping of a whole region is desired. In a transit scan the scanning speed is determined by the rotation of the earth and therefore scanning larger areas can become very time consuming. If the sources of interest are strong enough, then an active scan can be sufficient.

In this paper examples for the application of both methods are shown.

Observing bandwidth and frequency

Furthermore, there is benefit in using a high bandwidth, as the signal to noise ratio increases with the square root of the bandwidth as determined by the radiometer equation:

$$\sigma_{\mathrm{T}} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}} \qquad (1)$$

where σ_T is the rms fluctuation of the observed signal, T_{sys} the system temperature, $\Delta\upsilon_{RF}$ the observing bandwidth and τ the observation time.
In case of our 25 m dish, we use a bandwidth of 100 MHz. Typically, the centre frequency of the observation is set to 1380 MHz.

Flux Density Calibration

For calibration purposes we use a noise source which can be turned on and off and which injects a broadband signal into the receiving horn.
We compare the signal from the noise source with the signal received from well known calibration sources [2], [3]. By this, we can determine the equivalent flux density of the noise source:

In the following example the procedure is demonstrated with the radio galaxy 3C348 as calibrator. This source is known to have a flux of 44.3 Jansky at our observing frequency around 1400 MHz [2].
A transit scan is performed where the noise source is turned on and off every second. This provides a set of data with both the celestial source alone and the celestial source with the noise source as shown below:

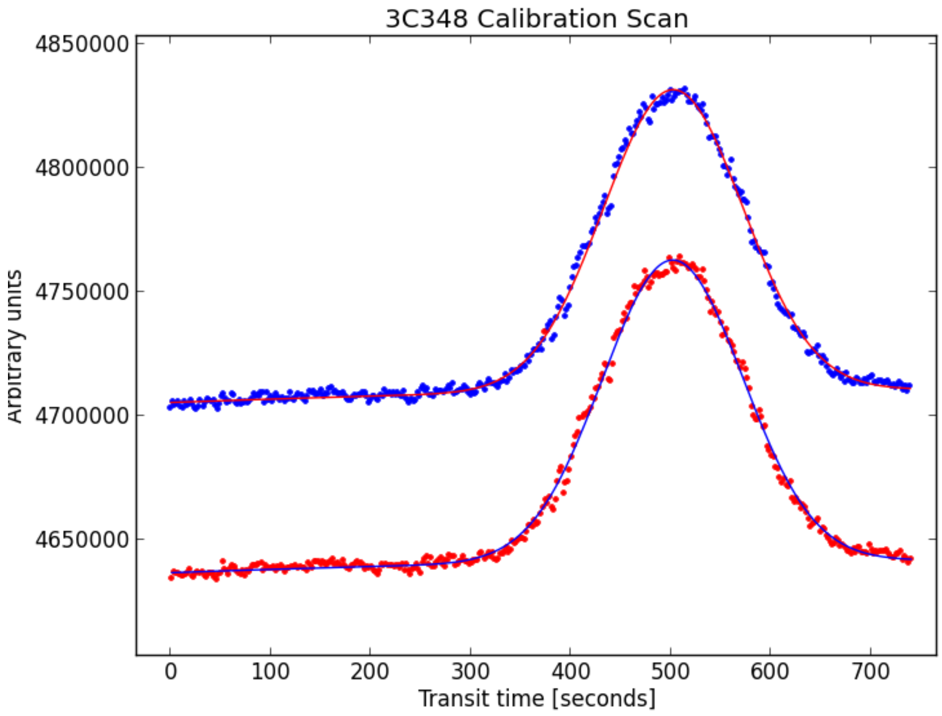

Figure 1: Calibration transit scan of 3C348

The plot of red dots is the measured data with the noise source off, and the plot of blue dots is the measured data with the noise source on. A least squares fit of a Gaussian profile is then performed to establish good values for both the offset between the curves (representing the noise power from the noise source) and the peak of the profile (representing the calibration flux of 44.3 Jansky). The fit is shown as solid lines.

In this particular case, the offset is $6.87 * 10^4$ units.
The peak (above background) is $12.2 * 10^4$ units.

Therefore, the flux density provided by the calibration noise source is 24.9 Jansky. This can be used to calibrate other observations.

Observation Example 1:

Determining the telescope beam width

A transit scan of a source can be used to determine the beam width of the telescope. If the source observed is a point source (such as radio galaxies), the transit time is determined by the rotation of the earth, the declination of the observed source and the beam width. This relationship is depicted below:

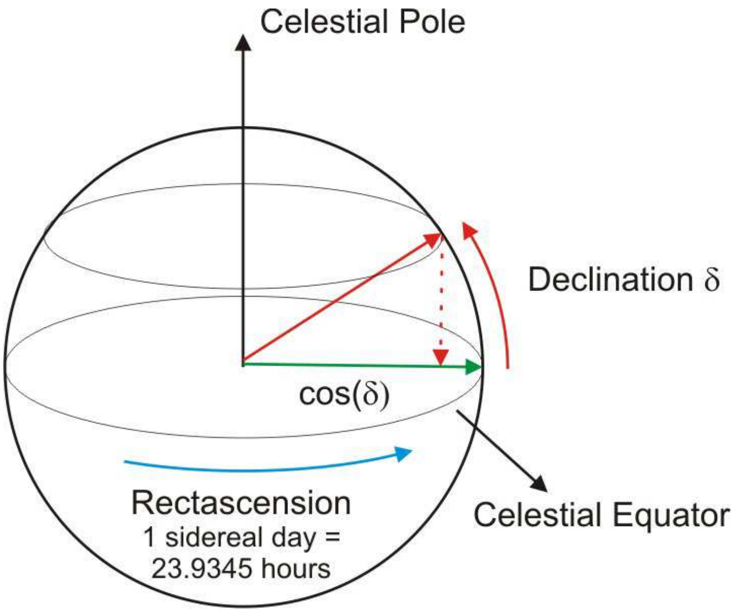

Figure 2: Transit time as a function of declination

If the observed source would be at the celestial equator (Declination 0°), the relation would be straightforward. Since the earth rotates at 15.041° per hour, such a source will pass through a beam of width α in $\alpha/15.041°$ hours. If the source would be at the celestial pole, nothing would happen. The source would stay in the beam indefinitely. For sources at declinations in between, the transit time is determined by the projection of the declination vector onto the plane of the celestial equator.
Then the relationship becomes:

$$\alpha = 15.041 * \cos(\delta) * t / 3600 \qquad (2)$$

where α is the beam width, δ is the declination of the target and t is the transit time in seconds.

Typically one would measure the transit time between the half power points of the profile to get the FWHM of the beam width.

To determine this, one can again use a Gaussian fit to the profile. In the example used for calibration above, the σ (standard deviation) of the profile is 69.8 seconds. The FWHM of a Gaussian profile is approx. 2.355 * σ, hence 164 seconds.
At a declination of 4° 59' of 3C348 this translates into a FWHM beam width α of 0.68° for our telescope.
Theoretically, one would expect a beam width α of approx. arcsin (1.22 * λ/D), where λ is the observing wavelength and D the telescope diameter. In our case, this would be 0.59°.
The wider beam can be explained by several contributing factors: Under-illumination of the dish due to the illumination taper (reducing the spill over), scattering by the feed support and imperfections of the dish surface.

Observation Example 2:

Cygnus A versus Cassiopeia A

The most prominent targets for continuum observations in the northern hemisphere are the two very strong sources, Cygnus A and Cassiopeia A. While both are similarly strong, they are distinct different sources:

Cygnus A is a radio galaxy at a distance of about 750 million light years, quite far away from our own galaxy. The flux from Cygnus originates from the jet emanating from the centre of the Cygnus galaxy. This is a huge structure, and changes in the flux are expected to be on a very long timescale. The flux is reported in the literature is 1581 Jansky [2].

Cassiopeia A is a remnant from a supernova (SNR) which is estimated to have occurred about 300 years ago. Its distance is about 11,000 light years, so it is within our own galaxy. The source of the radiation of Cassiopeia A is within the confined region of the SNR of only 10 light years across. As this SNR region expands, the radiation is expected to decline as described in [2]. According to the prediction as described in equation (1) of [2], we would expect that the flux density had declined to around 1500 Jansky in 2016 and thus would be below the flux density of Cygnus A.

Has this really happened?
Transit scans ob both sources were performed in order to determine the absolute flux density from both sources and their relation.

Below is the transit scan of Cygnus A, calibrated as per procedure described above.

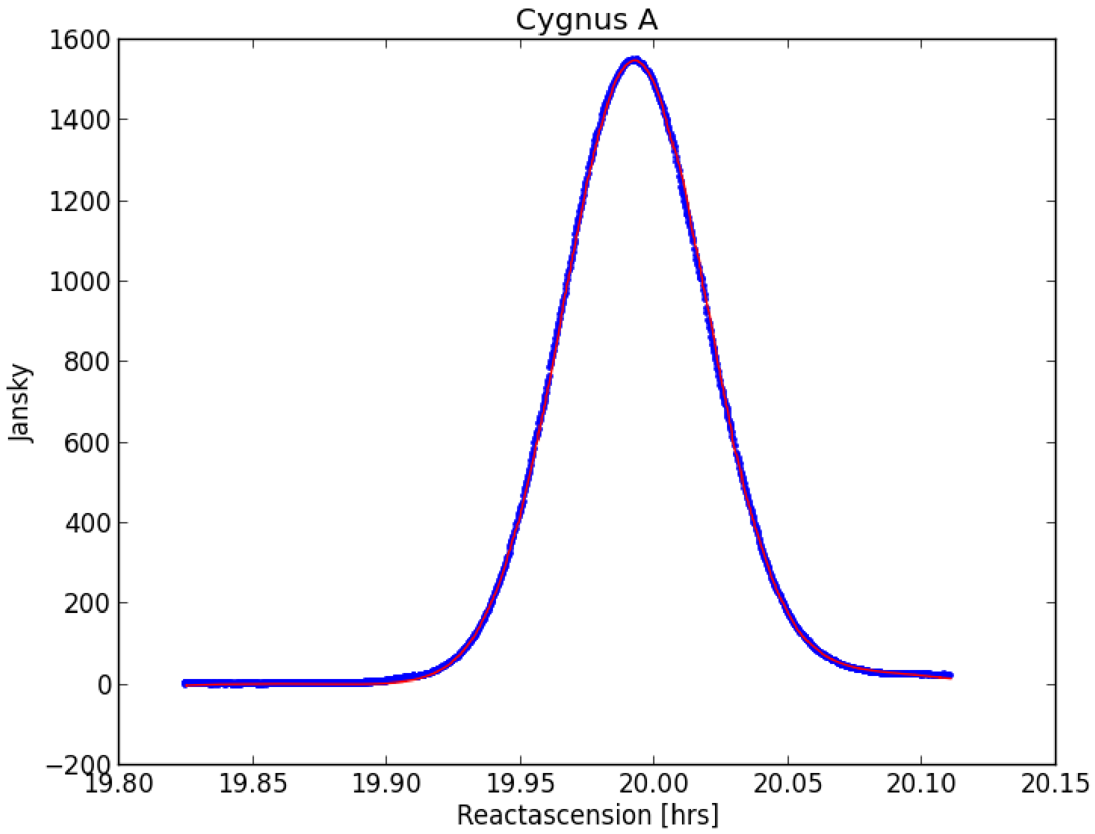

Figure 3: Transit scan of Cygnus A

The blue dots are the observed data and the red line is a least squares fit of a Gaussian profile. Due to the very high SNR of the strong source, it is in perfect alignment.

The measurement of the flux density provides 1550 Jansky. Reference [2] gives 1581 Jansky, so the difference is quite small and well within the measurement and calibration error.

The next figure is a transit scan of Cassiopeia A.

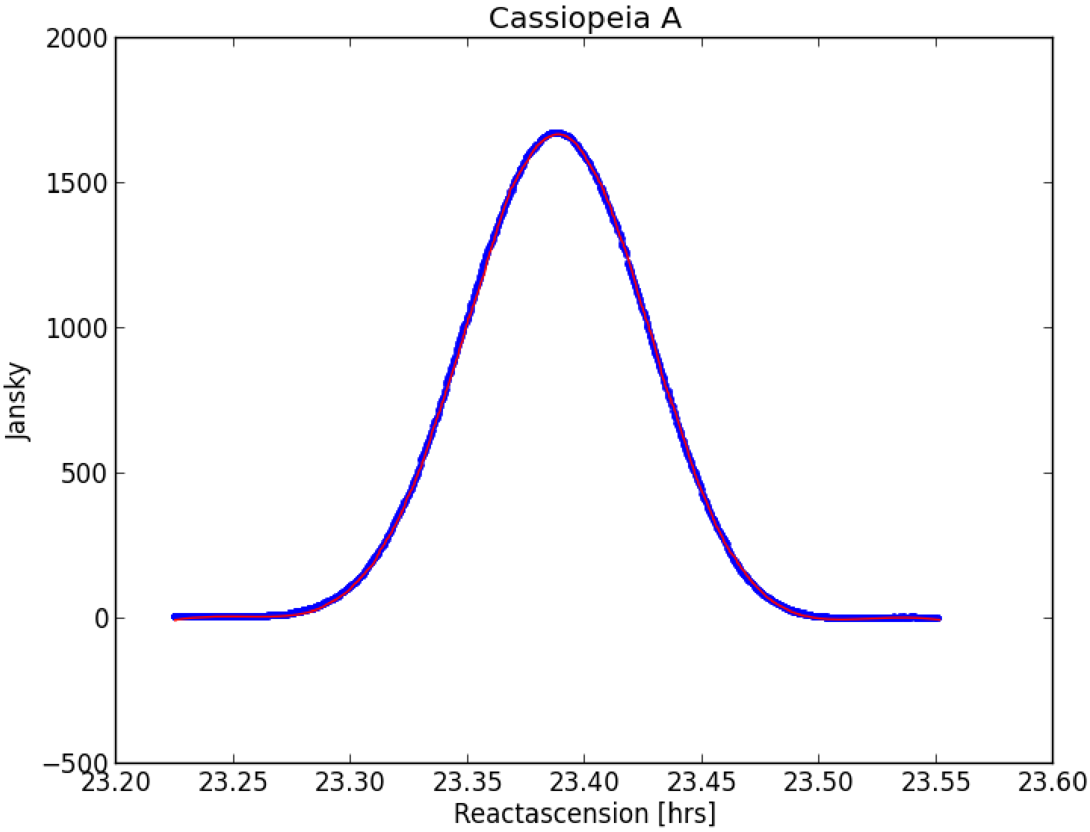

Figure 4: **Transit scan of Cassiopeia A**

Again, the blue dots are is the observed data and the red line is a least squares fit of a Gaussian profile.

From this measurement, the flux density has been determined to be 1671 Jansky.

This is well above the flux of Cygnus A, which is not what would be expected from the prediction of paper [2]. Obviously, the decline in flux density from Cassiopeia A has been slower than originally anticipated.

So this needs to be revisited. A new enhanced prediction, however, will require a multi-frequency observation of the flux of CAS A.

Observation Example 3:

Mapping a region

In this example, an active scan has been performed covering the Cygnus X area. It is a wide area of star formation producing continuum radio emission. Also within the scan area there is Cygnus A which clearly stands out.
This scan has been performed by continuously scanning in RA from 19.5 hrs to 21.25 hrs. Declination was varied in steps of 0.5°.
The telescope control system allows us to perform scans in any of the supported coordinate systems (Celestial, Galactic and Terrestrial).

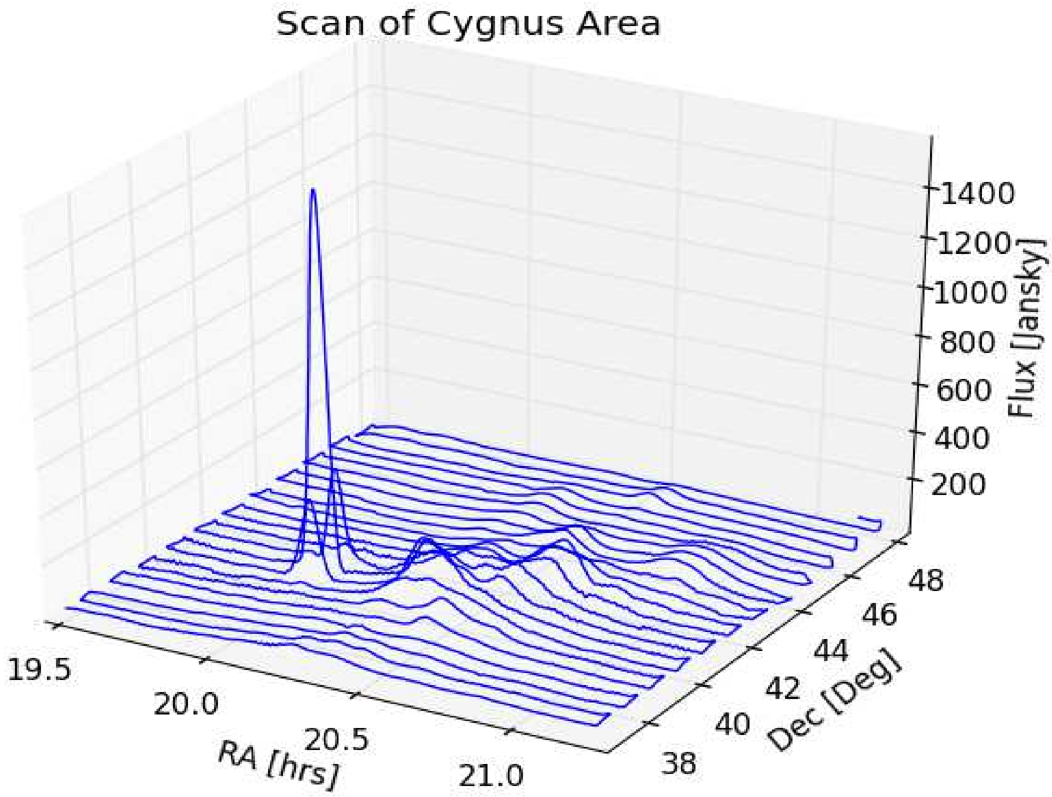

Figure 5: **Scan of the Cygnus X area**

Figure 5 shows the data recorded from the scan. The high intensity source again is Cygnus A, and the extended sources of the Cygnus area can clearly be seen.

Another example is a contour plot generated from the scan data (active scan) of the Omega Nebula region. In this case the data in uncalibrated:

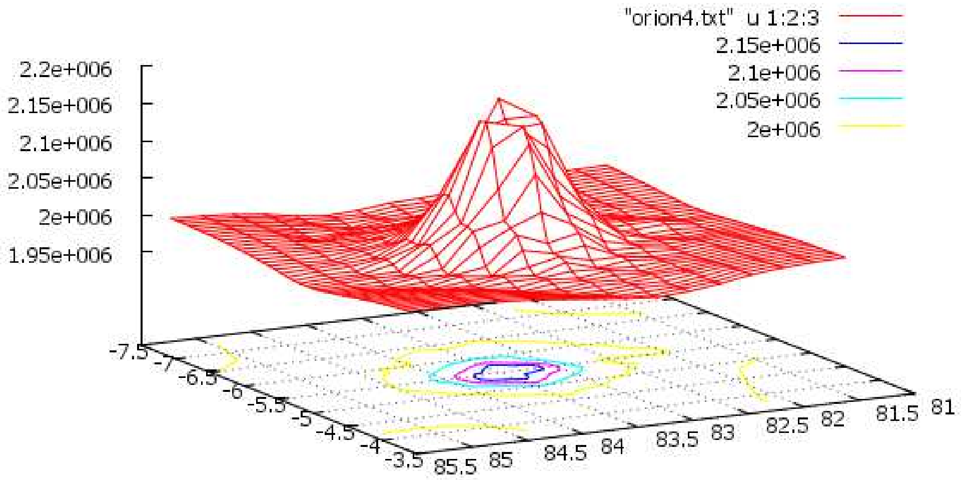

Figure 6: Contour plot of the Omega Nebula region
RA and Dec in degrees, vertical scale uncalibrated

Observation Example 4:

Flat Spectrum Radio Quasars

Galaxies in deep space can be observed in the radio regime when they develop a jet, originating from a super massive black hole. Cygnus A, the source mentioned earlier, is one example of such a source.
Flat spectrum radio quasars (FSRQ) are such galaxies where the orientation of the jet is directed towards the earth. In this case, the electromagnetic emission can be observed in the total electromagnetic spectrum from X-ray to the radio regime. These FSRQ are also designated as "Core dominated Radio Loud Quasars", see graph below.

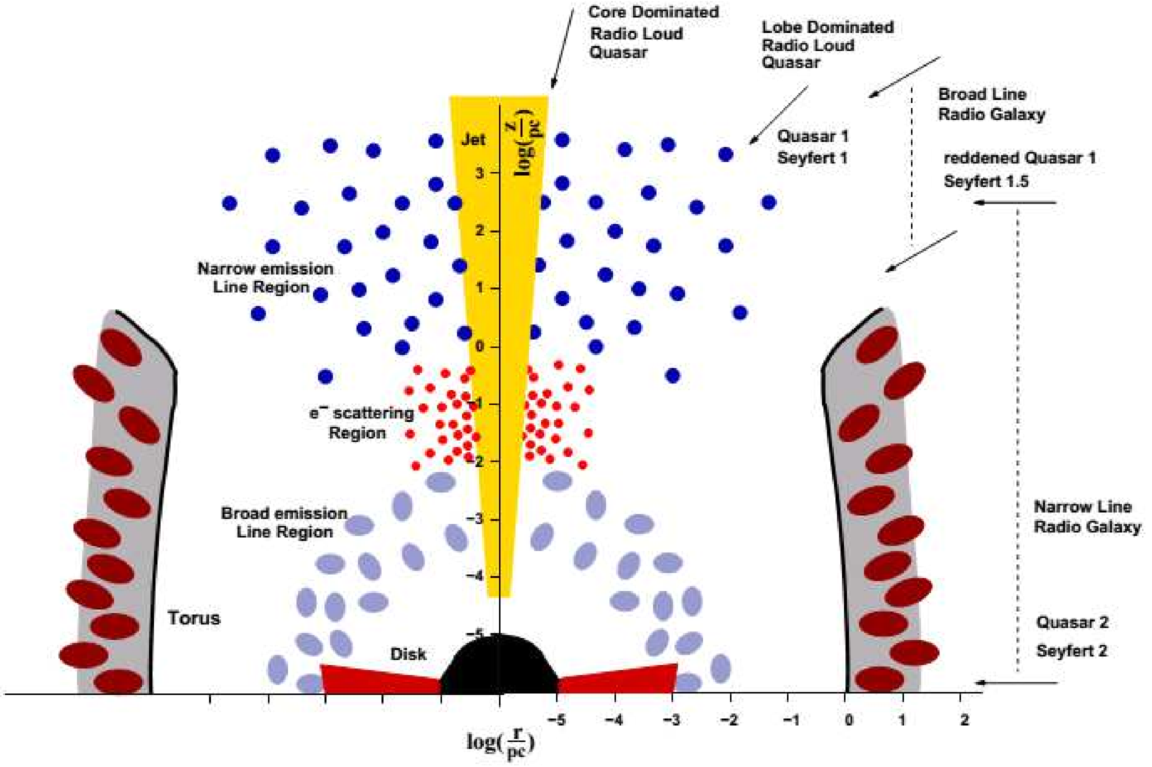

Figure 7: Quasars
Taken from [4]

There is special interest in these FSRQ as the observation of these sources allows testing of various theories about their physical nature.

Due to this interest from the scientific community, an observation program was performed looking at some FSRQs. The aim was to monitor the radio flux density from the FSRQ PKS1510-089 over some time with the Astropeiler Stockert telescope simultaneously with observation programs being conducted at the MAGIC telescope (VHE Gamma ray), the Fermi-LAT telescope (HE Gamma ray), Swift-XRT (X-ray). This program was conducted by Kevin Schmidt as part of his Bachelor Thesis [5] and was complemented by additional observations provided by me.
All observations were performed as transit scans.

During the observation program, an outburst was observed in the Gamma and X-ray regime at around modified Julian day (MJD) 57540. Such outbursts are sometimes followed by an increase in radio intensity a few days later. In this case, however, such an increase was not observed:

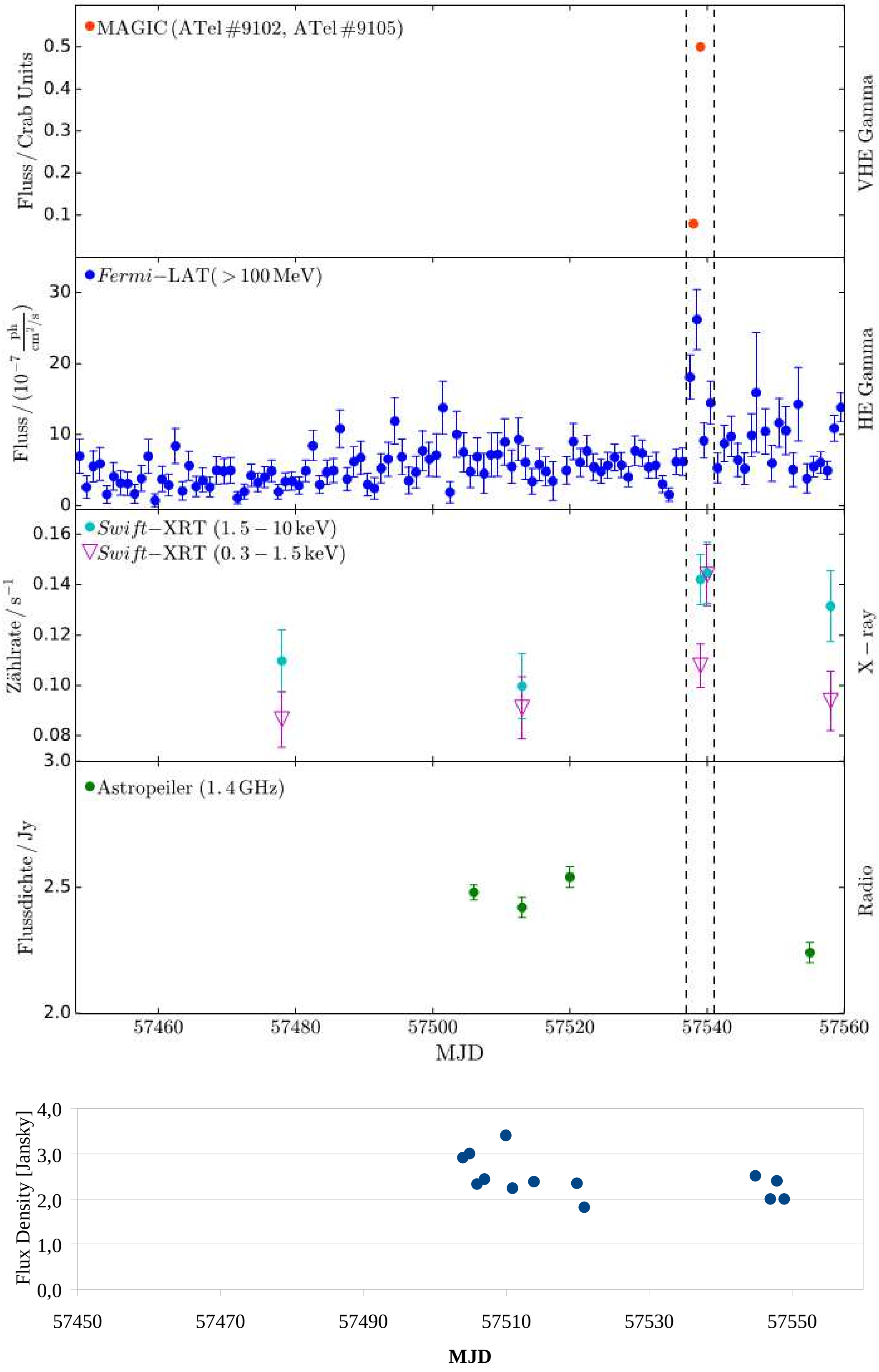

Figure 8: Multi-Wavelength Observation of PKS1510-089
Upper graph from [5], Radio Observations by Kevin Schmidt
Lower graph: Additional observations by Wolfgang Herrmann

Besides PKS 1510-089, a few other sources FSRQs were measured as part of these observations:

Source	**Observed Average Flux Density**	**Published Flux Density [6]**
BZQ J1229+0203	54.2	55.0
PKS 1253-055 (3C279)	11.6	9.7
BZQ J1642+3948	7.1	7.1
PKS 1510-089	2.4	2.7

Table 1: Measured Flux Densities of FSRQ

Calibration was done against 3C123 using reference values from [2].

Observation Example 5:

Distant Radio Galaxy

This is a transit scan of the most distant object observed so far:
3C309.1 is a radio galaxy with a red shift of z=0.9, which corresponds to a co-moving distance of 9.9 billion lightyears (using standard cosmological parameters).
This scan was performed with the calibration noise source turned on and off every second in order to determine the flux density from this galaxy:

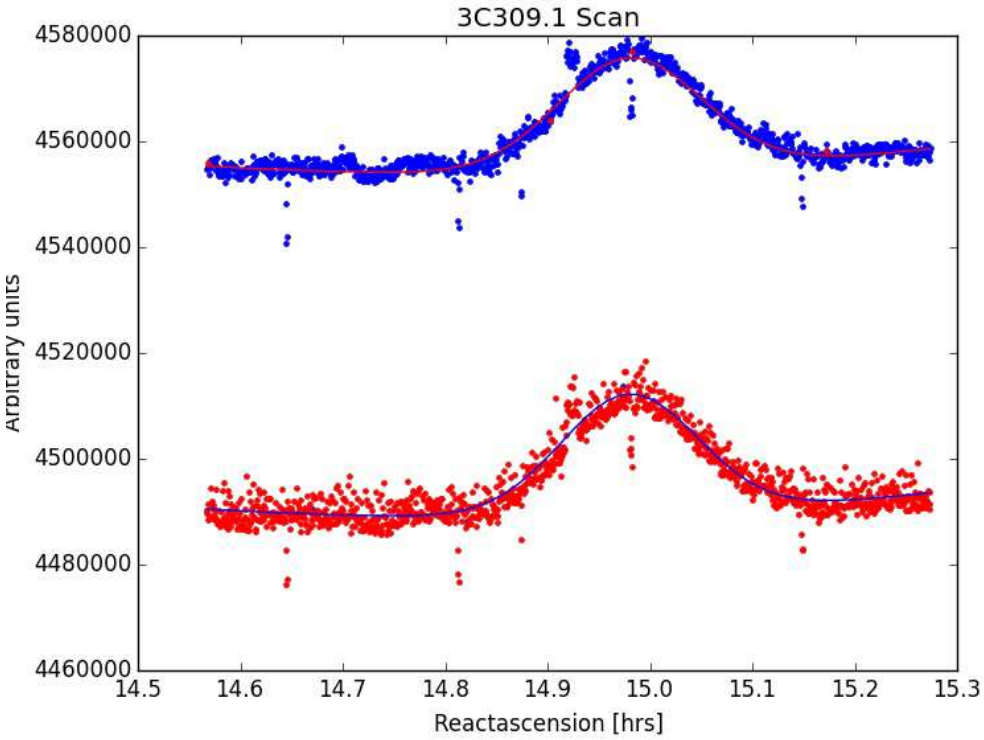

Figure 8: Transit Scan of 3C309.1
Calibration noise source turned on (blue) and off (red)

Both data sets have been fitted with a Gaussian profile to determine the amplitude of the source. The offset between the profiles is due to the known flux of the calibration source (24.9 Jansky, see calibration above). Based on this the flux density of 3C309.1 has been measured to be 8.4 Jansky. Ott et.al [3] reported 7.4 Jansky for this source, so this is in reasonable agreement.

Other sources:

Besides the measurements presented above, a large number of other continuum sources have been observed. Such sources included super nova remnants (SNR), HII regions and radio galaxies.

Conclusions:

We were able to successfully demonstrate the ability of the telescope to perform calibrated continuum measurements. Fluxes measured are in good agreement with published values.

This will enable us to do routine observations of sources of interest. In particular, variable sources like Quasars will be the target of future observations.

References:

[1] http://www.britastro.org/radio/resources.html
[2] J.W.M. Baars et.al, Astron. & Astrophys. 61, 99-106 (1977)
[3] M. Ott et. al, Astron. & Astrophys. 284, 331-339 (1994)
[4] C. Zier and P.L. Biermann, Astron. & Astrophys. 396, 91-108 (2002)
[5] K. Schmidt, Bachelor Thesis, Technical University Dortmund (2016)
[6] E. Massaro et. al., Astron. & Astropys. 495, 691-696 (2009)
see also http://www.asdc.asi.it/bzcat/