Observation of Cygnus A and Galactic Background with a Callisto Radio Spectrometer

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Abstract

A semester student of our institute was given the exercise to observe a celestial radio source and to determine the sensitivity limits of a small radio telescope at Bleien observatory (Switzerland). The telescope was connected to a low cost Callisto radio spectrometer and in parallel to a modern FFT-spectrometer for comparison. After some rather time consuming pre-tests we decided to observe Cygnus A in transit mode for several days and to integrate all collected data to improve the signal-to-noise ratio (SNR). Several issues were identified and appropriate workarounds were defined to improve the results. Cygnus A was clearly detected and the results showed that the instruments and associated processes can be used for calibration procedures for other observations. We defined and discussed many potential improvements, which will be implemented in early 2014.

Keywords: Callisto, Cygnus A, rfi, LPDA, heterodyne converter, FFT-spectrometer, FITS

Introduction

The main question to be answered by a recent semester student was the sensitivity specification of an old 5 m parabolic dish previously used for solar radio astronomy at Bleien (Aargau) about 50 km south of Zurich (47°20'23.66"N, 8° 6'41.72"E). During preliminary tests we found a lot of interference from all directions at almost all frequencies in the L-band (1 to 2 GHz). Most of the radio-interference (RFI) was from mobile phone transmitters, pager systems, air-traffic control, radar, military applications, and GPS among others. The RFI observed by our spectrometers was many times stronger than the sun, so we expected zero chance to observe any one of the strong celestial radio sources (Cygnus A, Cassiopeia A, Taurus A). Even worse, the dynamic range of the RFI was much larger than the input range of the 8-bit analog-digital converter (ADC) inside the FFT-spectrometer. The FFT-spectrum was totally corrupted not only by the external RFI but also due to cross-modulation in the digitizing circuit. To reduce these effects we would need at least a 12-bit ADC for a digital spectrometer. Here, we can profit from Callisto's design because it contains a logarithmic detector that has up to 90 dB of dynamic input range. The high dynamic range allows us to convert the output of the logarithmic detector with only 8 bits. Although we operated both the Callisto and FFT-Spectrometer in parallel, we discuss only the observation results from Callisto in this paper.

Our first improvement was to replace the logarithmic periodic dipole array (LPDA) with its many sidelobes looking at RFI by a simple cylindrical horn antenna with much lower sidelobes. The low illumination (< 90%) of the dish by the selected horn antenna was such that the sidelobes were lower than −18 dB. As a result, RFI could enter primarily through the main lobe and much less through the weaker side lobes. The disadvantage of the low sidelobes was a much lower effective aperture of the dish, but the improvement was important to improve detection of a weak celestial radio source. To keep local RFI more or less constant we decided to set the telescope at a fixed position and simply to wait for the daily transit of Cygnus A. Our plan was to observe the source for several days and to integrate these observations to a final light curve, taking into account that the source arrives 4 minutes earlier each day. Luckily, RFI as well as temperature changes are not correlated over different days of observation while the radio source is correlated over all the observations. Below we describe the instrument and procedures we used to obtain an acceptable result, a light curve of Cygnus A with an acceptable signal to noise ratio of about 20 (13 dB).

Frontend

The frontend is composed of a 5 m parabolic dish with a ratio of focal length to diameter (F/D) of 0.507, see figure 1. The geometric aperture is about 19.6 m^2 while the effective aperture is in the order of only 11.7 m^2 (about 60% aperture efficiency). At the beginning of the experiment we installed an LPDA from the German company Scharzbeck that covers 1 GHz to 5 GHz in two linear polarizations. One linear polarization is connected via a low loss coax cable to a MITEQ low noise amplifier (gain ~30 dB, noise figure ~0.8 dB) inside of the focal plane unit (FPU) just behind the LPDA. The FPU also contains a lot of surveillance electronics for voltages, temperatures, and humidity,.which can be checked via a website, see **Links** at end. The antenna can be tracked in azimuth and elevation via a standard Windows PC and it can also be controlled remotly via remote desktop (RDP).

Figure 1~ 5 m parabolic dish (left) at Bleien with a linear polarized LPDA in the focal plane. A 7 m parabolic dish for solar observations can be seen in the background at right.

Backend

The backend is composed of a prototype heterodyne down-converter, based on a 1720 MHz local oscillator (LO), mixer and filters, which convert 950 MHz to 1300 MHz (RF) into the UHF-range 770 MHz to 420 MHz (IF), see figure 2. The output of the down-converter is fed into a resistive power splitter which delivers 50% of the energy to the frequency agile radio spectrometer Callisto and the other 50% to a Fast-Fourier-Transform spectrometer (FFT-spectrometer) for comparative data analysis. Both spectrometers are controlled by a standard Windows PC and connected to the internet. Data files (FIT-files) are automatically transferred to an archive at the Technical High School FHNW, see **Links** at end. All related software is dedicated and was written in BORLAND C++ BUILDER 6.

Callisto is configured to produce 15 minute FIT-files with 200 rows x 3600 columns (720 000 pixels). Each file entry, or pixel, contains relative power, frequency and time and is represented with 8 bits in logarithmic scale given by the Callisto's logarithmic detector (AD8307). Each pixel of Callisto output is filtered with 300 KHz bandwidth and 1 ms integration time. At the same time with identical analog input, the FFT-spectrometer produces 16 384 channels every 250 ms with 16-bit resolution in linear scale. Bandwidth of the FFT-spectrometer is around 100 KHz.

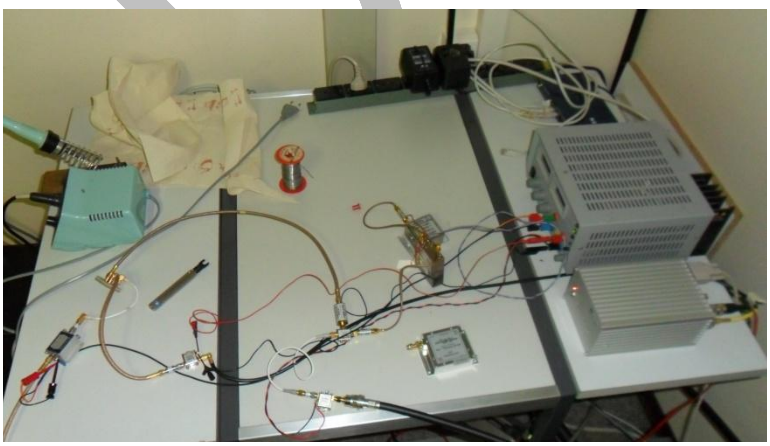

Figure 2~ A prototype heterodyne down-converter (consisting of modular components including 1710 MHz local oscillator with 10 MHz reference oscillator, mixer, band pass filter, low pass filter, three low noise amplifiers, power supply and SMA cables) and Callisto (bottom right).

Observations
We tried many antenna pointing positions but found extreme interference by mobile phone transmitters, air navigation, radar, GPS and military activities. It was very difficult to find a few positions with acceptable level of RFI. However, we found a terrestrial position with relatively low RFI by pointing at 238.49° azimuth and 78.80° elevation. We decided to stay at this position during Christmas 2013 and New Year and to wait every day for the transit of Cygnus A. We collected data 24 hours per day. All PCs involved were synchronized in time via an internet time server while the spectrometers were locked to a local GPS system. We took into account that Cygnus A and the galactic background are 4 minutes earlier in time each day due to sidereal time with respect to civil time (UT).

Data reduction
We reduced the collected data once a day at 16:00 UT after transit of the galactic background. Then we downloaded the 10 corresponding FIT-files from the archive and, using an IDL-program (Interactive Data Language), appended the daily observations. A two-dimensional plot (intensity versus time and frequency) was generated to get an overview for quality control, see figure 3. We then conducted a dedicated data selection with the following criteria:

- Exclude all channels within 950 MHz – 970 MHz due to RFI from mobile phone activity
- Exclude all channels occupied by GPS around 1227 MHz ± 5 MHz
- Exclude all channels with standard deviation (rms) larger than 1 digit due to RFI

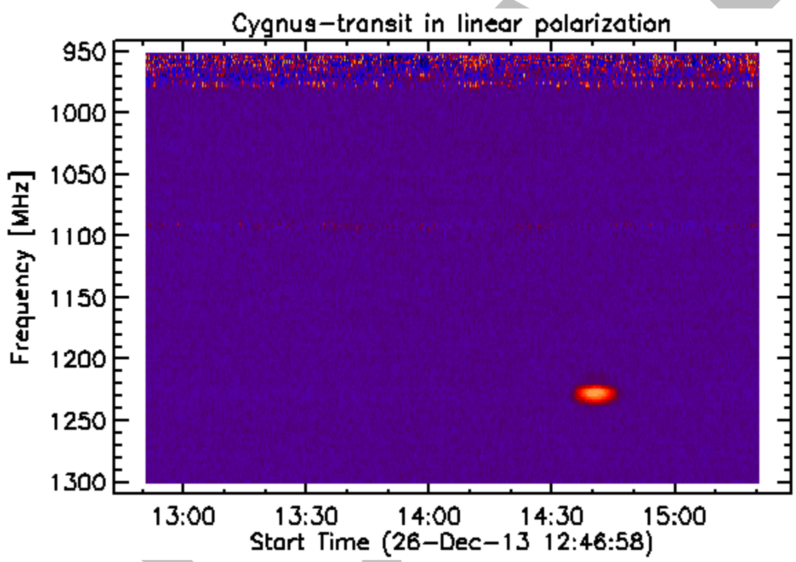

Figure 3~ A 15 minute L-band spectrum during expected Cygnus A transit at 14:30 UT. Neither Cygnus A nor the galactic background can be seen in this plot, but the signature of a GPS satellite around 14:32 at 1227 MHz can be recognized which is many 1000 times stronger than Cygnus A radiation and thus counts as interference (RFI). Between 950 MHz and 980 MHz we can see a lot of interference due to mobile phone activity (GSM).

We integrated the remaining channels (usually around 150 out of 200) in frequency leading to an effective radiometric bandwidth of 150 x 300 KHz = 45 MHz. After that we conducted a coordinate transformation to get right ascension out of longitude, latitude, altitude, azimuth, elevation, date and time (UT). We then generated a light curve plot in IDL, see figure 4. Each day looks completely different with respect to the baseline due to changes in temperature of the receiver and/or changes in RFI. Although the temperature is controlled by an air conditioning system to ± 1 degree, changes in the baseline are larger than any deflection caused by Cygnus A or the galaxies. However, since the temperature changes on different days are not correlated, they do not contribute much to the accumulated plot. The 10 files x 3600 pixels/file = 36 000 pixels in time are too much to plot in EXCEL so the plots are re-binned (decimated??) down to 900 pixels per light curve such that they can be plotted in the spreadsheet program, see figure 5. In addition each light curve is smoothed in time with a boxcar filter of 40 pixels to eliminate RFI-spikes. Data filtering, integrations, re-binning and plotting takes about 30 minutes of work per day of observation.

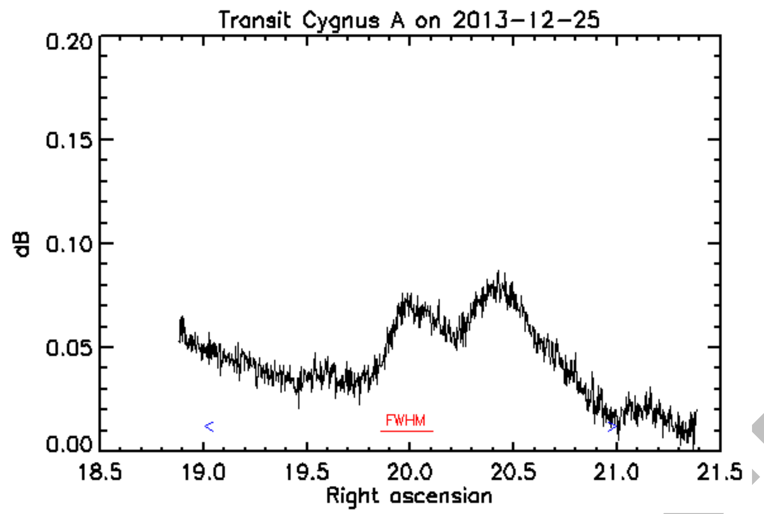

Figure 4~ A single, good looking Cygnus A transit observation from December 25th. Red FWHM marks the expected position in right ascension of Cygnus A. Blue characters (<>) mark the range in right ascension for further integration.

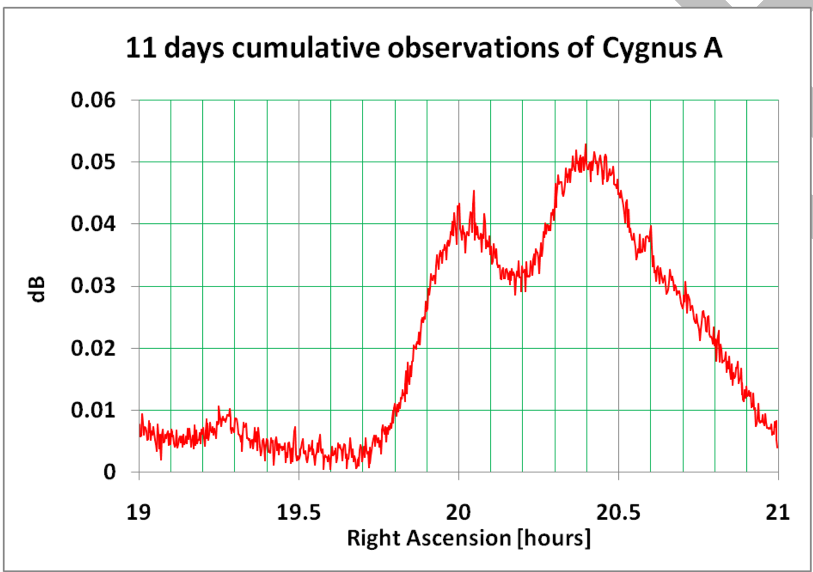

Figure 5~ Cumulative plot of 11 days of observation. Around 20:00 right ascension we see Cygnus A and around 20:24 right ascension we can clearly see galactic background. The vertical axis indicates the signal amplitude above the current baseline expressed in dB.

Conclusion

Changes in temperature of the receiver and a high level of RFI are the big issues while observing celestial radio sources. The only way to observe weak sources is given by the transit mode such that the RFI level is more or less constant. It is also very important to under-illuminate the dish such that the sidelobes do not contribute a lot of RFI from nearby transmitters. If we accept a lot of observation time it is possible to observe weak sources because the source signals are correlated over several days while temperature and RFI usually are not correlated. By integrating oberservations over many days the signal-to-noise ratio is improved constantly but slowly. Even with a low sensitive instrument like Callisto where the source signal is below the 1-bit resolution of the ADC, it is possible to observe weak radio sources by integrating over many observations. Statistically correlated signals increase linearly while uncorrelated signals partly compensate each other, leading to a smaller increase.

Links:
Callisto general information: http://www.e-callisto.org/
Surveillance data 5m dish: http://soleil.i4ds.ch/solarradio/data/status/RSG/status5m.php
Surveillance data 7m dish: http://soleil.i4ds.ch/solarradio/data/status/RSG/status7m.php
Environmental data : http://soleil.i4ds.ch/solarradio/data/status/RSG/environment_rsg.php
Access to the data archive: http://soleil.i4ds.ch/solarradio/callistoQuicklooks/

References and further reading

[Benz (2004)] Arnold O. Benz, Christian Monstein and Hansueli Meyer, CALLISTO, A New Concept for Solar Radio Spectrometers, Kluwer Academic Publishers, The Netherlands, 2004.

Meet the author: Christian Monstein is a native of Switzerland and lives in Freienbach. He obtained Electronics Engineer, B.S. degree at Konstanz University, Germany. Christian is a SARA member since 1987 and is licensed as amateur radio operator, HB9SCT. He has experience designing test systems in the telecommunications industry and is proficient in several programming languages including C and C++. He presently works at ETH-Zürich on the design of digital radio spectrometers (frequency agile and FFT) and is responsible for the hardware and software associated with the e-CALLISTO Project. He also has participated in the European Space Agency space telescope Herschel (HIFI), European Southern Observatory project MUSE for VLT in Chile, and NANTEN2 (delivery of the radio spectrometer for the Submillimeter Observatory at Pampa la Bola, Chile). Currently he is quite involved to prepare the radio telescopes for cosmological test observations. He plays also the role of a coordinator of SetiLeague in Switzerland. Email: monstein@astro.phys.ethz.ch