A cheap 1.2 meter radio telescope

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August 26, 2012

This document describes the construction and application of an amateur radio telescope. The telescope is built from easily available, very cheap components; it is a parabolic dish telescope with a diameter of roughly $1.2\,\mathrm{m}$. The telescope can be used for observations at a frequency of about $10\,\mathrm{GHz}$. Observations of the sun, the moon, and the thermal emission of a thermite reaction will be described here.

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1 Idea and origin of the project

The original aim of the project was to use a standard satellite dish and low-noise amplifier (meant for satellite TV reception) to observe the radio sky, in particular radio pulsars. However, it quickly became clear that observing pulsars is not feasible using that kind of technology. The TV satellites use a $10\,\mathrm{GHz}$ carrier frequency, which is unsuitable for pulsar observation. The brightest pulsars visible from earth emit most energy somewhere around the $400\,\mathrm{MHz}$ band, and the flux drops by several orders of magnitude if the frequency becomes as high as $10\,\mathrm{GHz}$. The small dish diameter presents another problem for such observations: because of the large wavelength of $\lambda = 3.0\,\mathrm{cm}$, the main beam will be up to several degrees wide, introducing a large amount of extra noise not coming from the object to be observed.

Large dishes being difficult to handle and mount, and receivers in the $400\,\mathrm{MHz}$ band being expensive, the original idea of observing pulsars was dismissed, and I instead started to build a telescope meant to observe bright thermal sources of radiation such as the sun and the moon.

2 The telescope

2.1 Rough overview of the layout

Figure 1 shows the layout of the experiment, omitting unnecessary detail.

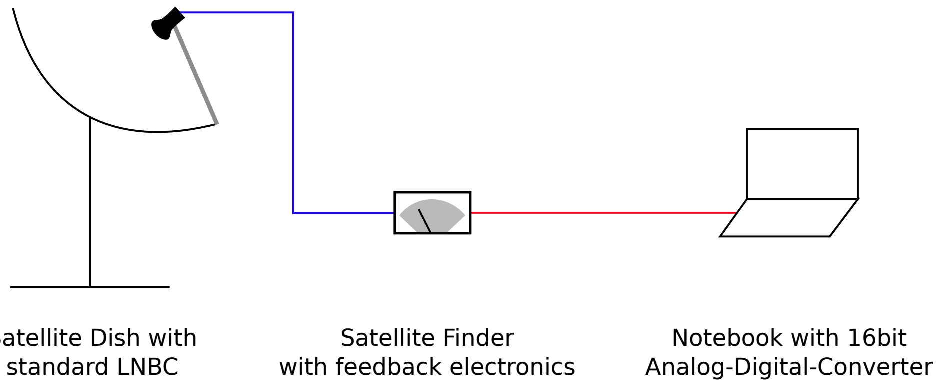

Figure 1: A simplified drawing of the telescope

A standard $10\,\mathrm{GHz}$ Low-Noise block converter (LNB) is attached to a $1.2\,\mathrm{m}$ offset parabolic dish, which is mounted on a HEQ-6 (equatorial) mount, which I luckily had to spare.

The LNB receives and preamplifies the signal, and is connected to a *satellite finder* via coaxial cable (blue). A satellite finder is a little device which you can put in between your TV receiver and antenna; it will then display the strength of the incoming signal. It is normally used to align the antenna with the TV satellite. In this experiment, it serves as amplifier and detector.

The signal detected by the satellite finder, which is now just a low-frequency voltage pattern describing the flux received by the antenna over the last few milliseconds, is then fed into a 16-bit Analog-Digital-Converter (ADC). The digitalized data is recorded and displayed by a small Python program, which I wrote for this purpose.

The following sections will describe the components of the telescope in greater detail.

2.2 Dish and Mount

The satellite dish used for this telescope was bought as a standard TV satellite dish on the internet. The price was about €50, plus shipping. The dish is a $1.2\,\mathrm{m}$ diameter *offset dish*, which means that the antenna feed is not at the center of the dish, but moved aside along the principal axis. This has the advantage of a better antenna gain, as the feed is not inside the main beam and does thus not cause interference. Consequently, the dish is not built symmetrically with respect to its small axis; the long axis of the dish points along the right ascension axis of the mount. This has implications for the data received; those will be discussed later.

Receiver/Preamplifier The LNB used for the project is just the first one I found; the price for those is around €5. It would be interesting to test different LNBs, especially the ones used in America, which work in the $5\,\mathrm{GHz}$ frequency band, but I didn't do that yet.

Mounting the dish The most difficult thing about fixing the dish on the mount is doing it in a way that you have enough counter-weights to balance it.

In my case, I used the mount shipped with the dish, and drilled two holes into it; one of them is then screwed to the mount's camera/telescope slot (the one *meant* to mount things) using a piece of wood (the right one in the image above). The other one is screwed to another piece of wood which has been plugged onto the bar which was originally meant for the counterweights (the left one in the image). If the counterweights are adjusted correctly, this is pretty stable*, and can easily be operated (and set up!) by a single person. Figure 2 shows the finished telescope.

2.3 Satellite finder / detector

The incoming flux is preamplified by the LNB, and mixed down to a lower frequency of about $2\,\mathrm{GHz}$ (the latter is not relevant for this project). The coaxial cable of the LNB

*Remember that this is not optical astronomy, and that the telescope has exactly one pixel which has a $3° \times 3°$ area of the sky blurred into it. Thus, the requirements regarding pointing accuracy and simlar are not as high.

Figure 2: *Left image*: The complete telescope, with mount, LNB and electronics (and me). *Right image*: Detail photo of how the dish is fixed on the mount.

is connected to the satellite finder (those cost about €7). Both devices need a stable 14 V power supply, which is usually provided by the TV receiver†. In this project, the power is instead provided by a laboratory power supply. Due to the nature of the circuits used here, this voltage has to be as stable as possible; jitter or drift in this power supply will cause the same jitter or drift in the measured data values.

The dynamic range of the satellite finder used here is quite large, but only when using the device's turning knob to manually adjust its sensitivity. As this is not practical for real measurements, a small circuit was designed to control the sensitivity automatically. Instead of measuring the actual intensity displayed by the device, the sensitivity is adjusted for the intensity to be some fixed value, and then that sensitivity is measured instead. The feedback control is implemented by feeding back the output value into the sensitivity potentiometer. The circuit used for this will likely vary depending on the exact model of the satellite finder, and will thus not be discussed here. ‡

2.4 Data digitalization and software

The output provided by the feedback circuit attached to the satellite receiver is a voltage between 0 V and 1.35 V, higher voltage meaning a higher sensitivity required to produce the fixed measurement value mentioned earlier. Thus, higher voltages mean lower signal intensity here. For convenient analysis of the data, it is digitalized by a 16-bit, 15 samples per second analog-digital converter, and stored in plain text format on a computer. As buying ADCs which can be attached to a computer via USB or similar are

†The stability of the power supply it not as important for TV applications, as the receivers are not interested in the overall amplitude of the signal.

‡In case you're interested in building a similar thing yourself, I'll be happy to describe the circuit in detail if you contact me by email via `svenbrauch@gmail.com`. Be aware tough that the solution I used is far from optimal for a number of reasons, and that it's probably easy to come up with something better.

ridiculously expensive, I built an USB board using an attiny45 micro controller to talk to I2C-compatible devices, following an excellent guide by Till Harbaum, which can be found here: `http://www.harbaum.org/till/i2c_tiny_usb/index.shtml` The overall price of the board is around €10, and I2C-compatible 16-bit AD-converters are plenty and cheap (around €2). The driver for talking to the board is included in the mainline Linux kernel, thus reading data from the ADC can be done entirely in a language like Python, and only needs about five lines of code. Combined with a little bit of Qt, this gives a very useful plotting tool, visualizing the data received from the ADC in real-time.

A screenshot of the program displaying idle data from the ADC can be seen in Figure 3. In addition to the ADC, a temperature sensor is also attached to the board to check for correlation between signal strength and environment temperature; however, no significant analysis has been done yet.

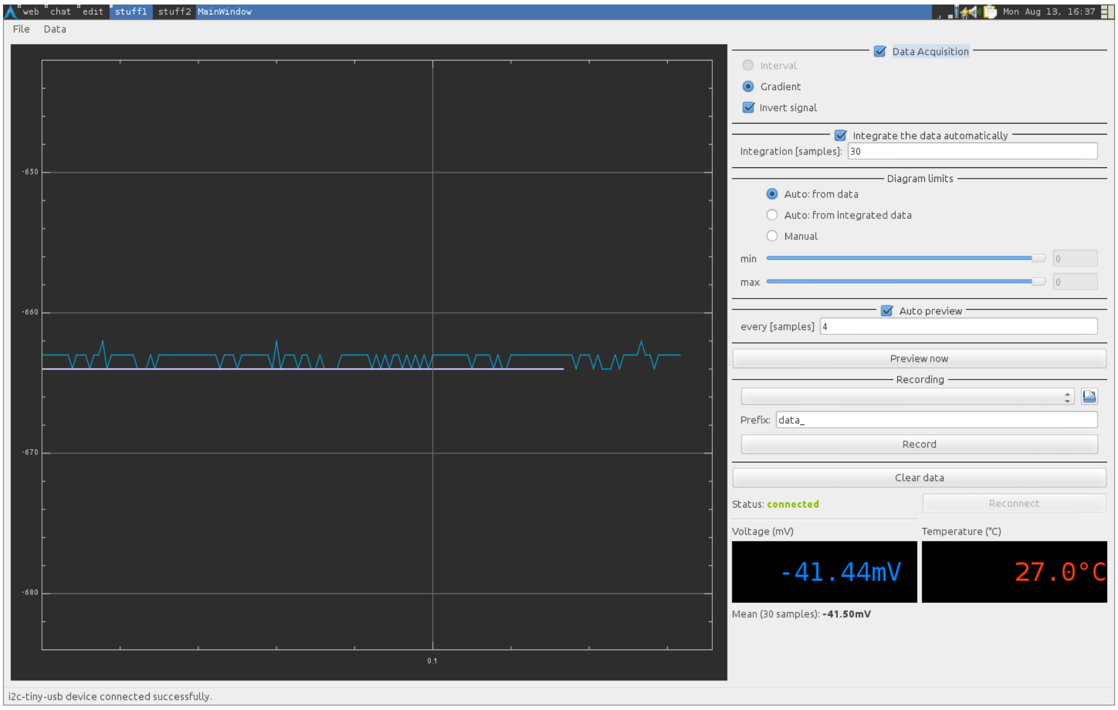

Figure 3: The program used for recording the data received from the telescope

2.5 Calibration

The whole dish / amplifier chain is not calibrated at all, because I don't have access to the equipment necessary for this. Thus, interpreting the data provided by the ADC as "Intensity" is an assumption, as it is not at all guaranteed that it is proportional to the intensity received. Looking at the the curves taken from various objects however suggests that this assumption is at least not entirely wrong.

3 Receiving pattern of a parabolic dish

By means of fourier transformation, a rough estimate of the expected antenna diagram of a parabolic dish with a diameter of $1.2\,\mathrm{m}$ can be made, shown in Figure 4.

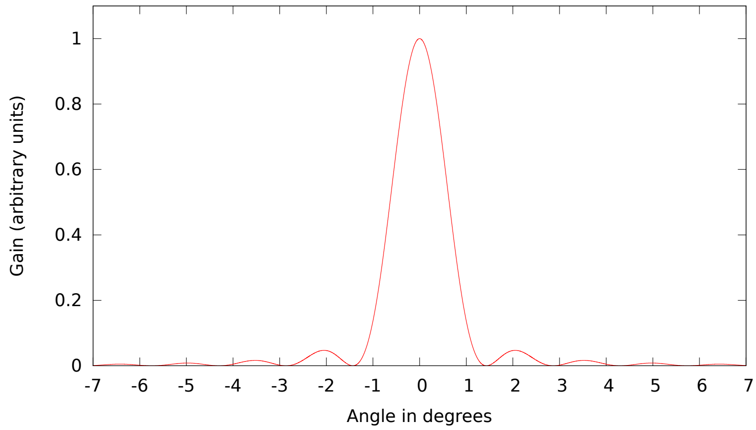

Figure 4: The theoretical antenna diagram of a $1.2\,\mathrm{m}$ parabolic dish (along any axis)

Note that this diagram uses linear scale; as for most larger antennas, the so-called *side-lobes*, meaning the little peaks aside the main peak, are too small to see in linear scale, often a logarithmic scale is applied. Plotting the same function with logarithmic y axis gives the picture displayed in Figure 5, which is more similar to what one tends to find in articles written by professionals. This kind of scale is also directly related to the decibel (dB) units often used for this purpose.

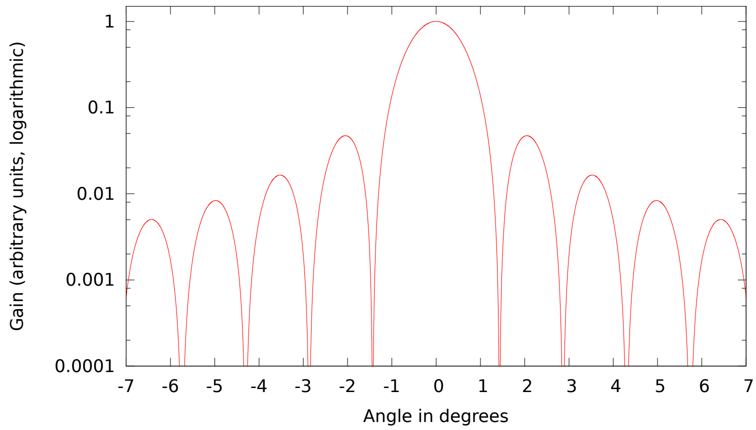

Figure 5: The same diagram as above, but with logarithmic y axis

Both diagrams clearly show that the main beam has a width of about 3 degrees, which is about 6 times the sun's apparent size.

The real antenna diagram will differ from the expected values, mainly because of the asymmetry of the dish, but also because the mirror is uneven, because the receiver is not exactly at the correct location, and several other reasons with smaller impact.

The intensity received over time in case of a telesope pointing into a fixed direction (φ_0, θ_0) is determined by the convolution of the antenna diagram with the sky brightness distribution. For example, assume a point source with dirac-delta brightness distribution $\Phi(\varphi, \theta) = \delta(\varphi, \theta)$, which moves across the sky because of the earth's rotation. The intensity curve one would receive over time with a fixed telescope would then exactly look like the above antenna function (convolving any function $f(x)$ with $\delta(x)$ gives $f(x)$ again). For non-point sources like the sun, the antenna diagram would be blurred a bit, the strength of the blur depending on the object's apparent size.

4 Observation of celestial objects

4.1 Sun

The easiest object to observe is the sun, which emits a comparably large amount of radiation in all wavelengths because of its high surface temperature of about $5778\,\mathrm{K}$. Figure 6 shows the pattern received over time if the telescope is pointed towards a fixed location in the sky, waiting for the sun to pass through the main beam.

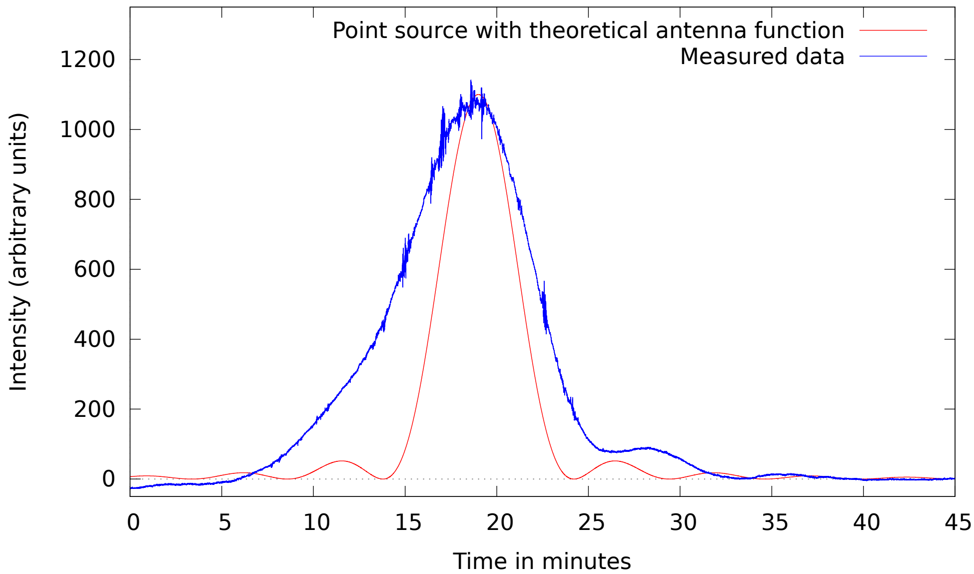

Figure 6: Intensity received by the radio telescope over time when the sun passes through the main beam

The signal-to-noise ratio is very good for this source. The curve is clearly asymmetrical (the left side is much more widespread), which is to be expected as the antenna is not symmetrical either. On the right side, the first and second sidelobe, which originate from the interference pattern explained above, can be seen very clearly (at about 28 and 35 minutes). They are also present on the left side, but are absorbed into the widespread main beam. The brightest sidelobe at around 12 minutes causes a visible uplift in the curve, though.

It is clearly visible that the real "picture" of the sun is much worse in terms of spatial resolution than what would be expected from a point source with an ideal dish (red curve). Part of this comes from the blur caused by the sun not being a point source, but this cannot be the only reason for the difference, as such a blur would not move the locations of the peaks caused by the sidelobes. The real reason for the difference could not be determined with certainty; a possible reason is that the LNB does not receive radiation from all points of the dish (*under-illumination*), effectively making it smaller.

4.2 Moon

Taking curves of the moon turned out to be more difficult; observing from my home town (270 000 inhabitants), there often were unexplainable "cracks" in the curves, as can be seen in Figure 7.

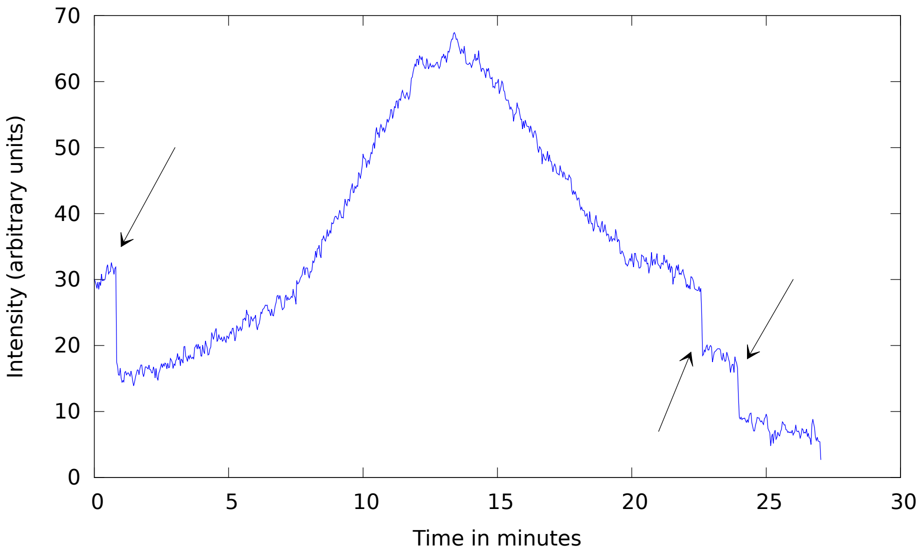

Figure 7: Intensity curve of the moon recorded in my home town, featuring weird "cracks". Like for all curves of the moon displayed here, 30 adjacent data points were binned together to reduce noise.

I do not have an explanation for those cracks, but they were pretty reproducable. The two most likely reasons seem to be crappy electronics (my amplifier / ADC circuits), and devices causing interference (microwaves, cars, ...) being turned on and off. The cracks also occured in absence of the moon.

In a much less populated area of Germany, I was able to take a much more error-free curve, which is displayed in Figure 8.

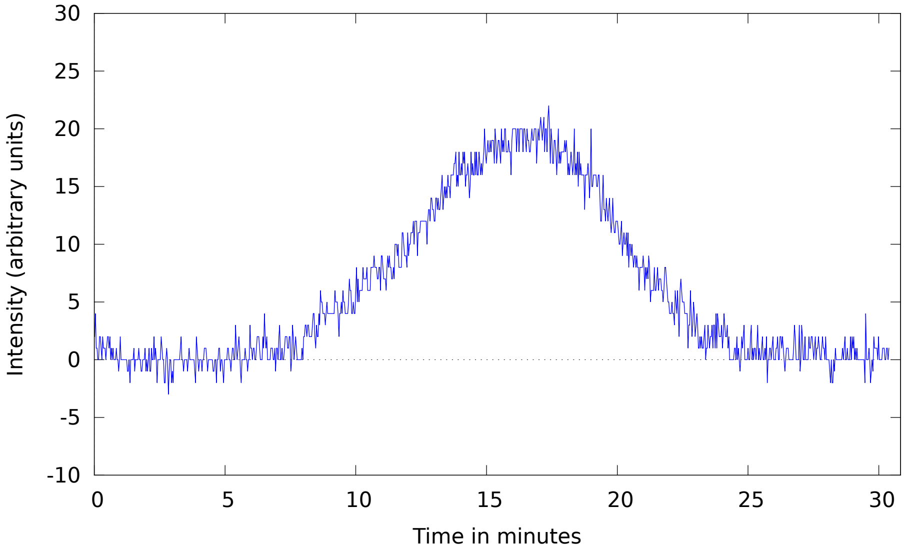

Figure 8: Intensity curve of the moon.

The signal-to-noise ratio in Figure 8 is much worse than in Figure 7, probably because in the former, the moon partially missed the main beam due to poor adjustment of the telescope. Neverthereless, the signal-to-noise is by far good enough to be sure that the object causing the curve is really the moon.

Figure 7 was recorded at a bit more than half moon, Figure 8 at full moon.

Reason for the radiation The radiation received is, unlike in the visible spectrum, not reflected radiation from the sun. Looking at the sun curve and comparing it to Figure 7, one can see that there's about 20 times less radiation coming from the moon than from the sun[§]. Let's assume that the moon is a perfect mirror for radio waves (which it is not); then from a purely geometric estimate it follows that the moon should be roughly 170 000 times darker than the sun. This is different enough from 20 to exclude the theory that the measured radiation is reflected from the sun.

[§]Using a better curve would be desirable, but as I am pretty sure the moon partially missed the beam in Figure 8, it is not usable for this purpose. This happened because I didn't exactly align the equatorial mount into the north direction, thus putting the moon in the center of the beam, then moving the telescope away along the equatorial axis, waiting for it to wander back in made the moon miss the beam.

Instead, if we assume that the radiation from the moon is thermal radiation, and that the moon is a perfect black body (which it is not), then from the linearity of the Rayleigh-Jeans law of radiation in T it follows that the temperature of the moon would be about

$$T_{\text{moon}} \approx \frac{T_{\text{sun}}}{20} = 289\,\text{K} \tag{1}$$

This calculation also uses the fact that the sun and the moon have very similar apparent sizes. When Figure 7 was recorded, the moon was about $^{15}/_{27}$ full. Thus, an estimate for the moon's real average temperature[¶] is

$$T_{\text{moon}} \approx {}^{15}/_{27} \cdot 390\,\text{K} + {}^{12}/_{27} \cdot 100\,\text{K} = 261\,\text{K} \tag{2}$$

the two temperatures $100\,\text{K}$ and $390\,\text{K}$ being the night and day temperatures of the moon, respectively.

As mentioned, this whole analysis is only an estimate for several reasons; in addition to the approximations used in the calculation above, it assumes that the receiver is linear over large scales and under different circumstances (temperature, humidity, ...), which has not been tested, and is probably not the case. Considering this, the result is pretty acceptable.

4.3 Other objects

Other objects, like the Crab Nebula, could not be detected so far. I think some more bright sources should be visible under good conditions, but they are difficult to hit with the telescope without a well-configured finder.

5 Observation of a thermite reaction as an example of a local source of thermal radiation

Every object with a temperature above $0\,\text{K}$ emits radio waves, with an intensity roughly proportional to the object's temperature. Thus, putting hot objects in front of the receiver will potentially yield interesting results. For such an experiment, it is also important that the hot object fills an as-large-as-possible part of the solid angle seen by the receiver[‖]. Because of this, a light bulb is somewhat unsuitable for such experiments, as it is hot, but the hot area is extremely small. In this case, thermite, a mix of rust and aluminium, is used; the mixture reacts to aluminium oxide and iron, and gets extremely hot in the process (up to $2700\,\text{K}$ according to Wikipedia).

For this experiment, a small amount of thermite was placed in mid of a pile of sand; then the receiver was pointed at it, and the reaction was triggered with a sparkler.

[¶] Averaging the temperature this way is allowed because the Rayleigh-Jeans law is linear in T.
[‖] In fact, the sun only fills about $^{1}/_{40}$ of this telescope's main beam.

Figure 9: The first try to detect a thermite reaction ($50\,\mathrm{g}$ of substrate) with the radio telescope, the receiver being outside of the imaged area in this case. In a second try, after the flame went out, the receiver was put directly above the remaining hot iron to make it fill a larger part of the solid angle observed by the receiver. The reflector dish was not used for this experiment.

After a first failed try, where nothing was detected because the receiver was too far away from the reaction, a second attempt was made with $200\,\mathrm{g}$ of thermite, and by placing the receiver directly over the hot mass after the flame went out. This gave a very nice curve, which can be seen in Figure 10 below.

If the following assumptions are made:

- The receiver is linear.
- The lowest point in the curve is roughly $40\,\mathrm{K}$ above the environment temperature $T_0 = 285\,\mathrm{K}$.[**]

then the measured data can be compared to a simulation. The differential equation for the temperature T of an object which loses energy by radiation and heat transfer is

$$k_1(T^4 - T_0^4) + k_2(T - T_0) = \dot{T} \tag{3}$$

Together with the starting temperature, T_{start}, there's three free parameters for fitting. The system is degenerate, as both k_1 and k_2 consist of multiple parameters describing the system.

[**] The $40\,\mathrm{K}$ are a guess, as that temperature sadly was not measured exactly. It is however not too far from the real value, and doesn't change the result significantly anyways.

Using the least square fit algorithm provided by `scipy.optimize` and euler integration with a step width of $\Delta t = {}^{1}/_{15}\,\mathrm{s}$, the differential equation 3 can now be fitted to the recorded curve. The result can be seen in Figure 10.

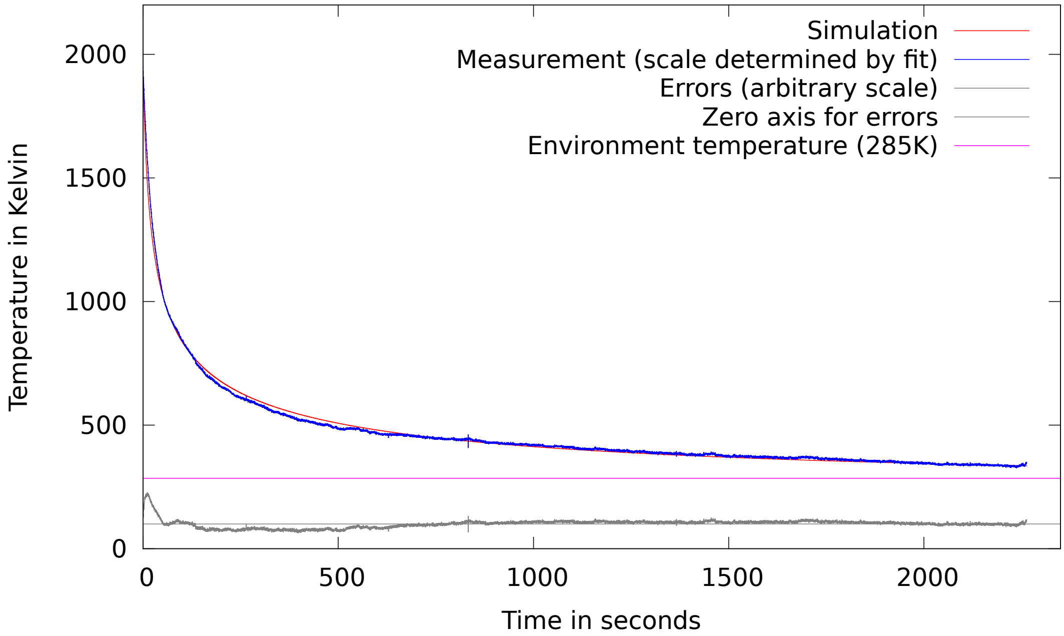

Figure 10: Measurement and simulation for the thermite experiment. With parameters determined by a least-square fit algorithm, the simulation is surprisingly accurate.

The parameters determined by the fit indicate that the contribution of thermal conduction is almost zero ($k_2 T$ is extremely small compared to $k_1 T^4$). This seems strange, but might be explained as follows: In the model presented above, the sand wall is assumed to be heated only by conduction. This is not correct; the sand absorbs large amounts of the thermal radiation emitted by the thermite. Because of this, the temperature of the sand near the thermite will soon be similar to the thermite's temperature, which greatly reduces heat transfer by conduction from the thermite into the sand wall. (Of course, conduction still happens inside the sand wall itself, but as long as the temperature of the sand close to the thermite is similar to the thermite's temperature, this does not matter.)

The k_2-term being almost zero, it doesn't make sense to use it in calculations; it is obvious that the model is not correct here. The fit effectively reduces the model to a new differential equation of the form

$$k_1(T^4 - T_0^4) = \dot{T} \tag{4}$$

The parameter k_1 can be split into several quantities with the help of the Stefan-Boltzmann law of total radiation power:

$$k_1 = \sigma A \frac{\varepsilon}{C} \tag{5}$$

with the following quantities:

Quantity	Description	Source	Value
σ	Stefan-Boltzmann-constant	constant	$5.67 \times 10^{-8}\,\mathrm{W/m^2\,K^4}$
C	Heat capacity of hot object	literature††	$570\,\mathrm{J/K}$
ε	Emissivity of thermite	literature	0.8
A	Surface of the hot object	Fit	*(to be determined)*
T_{start}	Starting temperature	Fit	*(to be determined)*

Table 1: Values used in the simulation

The parameter A was chosen to be determined by fit over the emissivity and the heat capacity, as it is the most difficult to make a good estimate for.

Using Equation 4, the following free parameters can be used together with those listed above in order to produce the simulation curve from the diagram:

Quantity	Description	Value
A	Surface of the hot object	$131\,\mathrm{cm}^2$
T_{start}	Starting temperature	$1951\,\mathrm{K}$

Table 2: Values determined by the simulation

Those parameters seem to be quite realistic. However, they can be varied slightly by picking different values for parameters which are not known exactly, for example the emissivity ε. Note that the starting temperature is not the temperature when the reaction happened, but the temperature the system had when the measurement started, which is about ten seconds later. Thus, the temperature of the reacting thermite probably was a few hundred degrees higher.

6 Pointing direction and background intensity

Pointing the telescope into different directions at an empty sky yields very different levels of background brightness. The fluctuation is very strong when the altitude is changed, and is somewhere around $45°$; changes in azimuth or at different altitudes are

††The mix ratio is 1:3 iron oxide to aluminium.

also noticeable, but less significant. Figure 11 shows the intensity received when the telescope is pointed at different altitudes, 90° being the zenith (blue points).

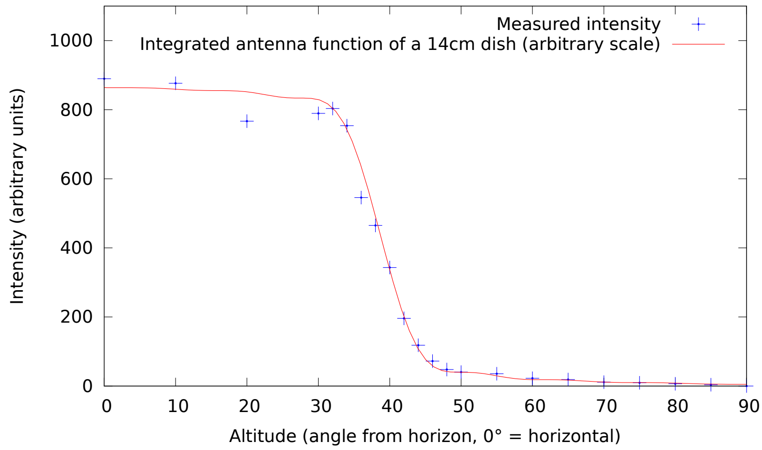

Figure 11: Background intensity as a function of altitude, measured in my garden

I'm unsure about the reason for this effect. The first explanation that comes to mind is an airmass-related effect[‡‡]; however, the airmass curve looks totally different from the pattern observed here. Also, there's no emission to be expected at 10 GHz from air or water vapour. I thus think it's unlikely that the observed effect is related to airmass.

A more useful explanation is radiation from the environment falling into the telescope. The ground, or other objects nearby, such as trees and houses, have a temperature of about 300 K, which makes them emit way more radio waves than the empty sky (which has a brightness temperature of about 3 K). If the telescope is pointed further away from the zenith, an increasing amount of sidelobes is filled with this 300 K background, which increases the measured intensity. Fitting the expected intensity from this effect to the data measured yields the red curve in Figure 11, which looks quite good; however, the parameters required to produce a curve like this don't seem right: the red curve was generated assuming a 14 cm diameter dish, and a (hot) obstracle at 39° elevation and below. The unrealistic dish size of 14 cm is needed to explain the slow rising of the curve between about 32° to 44°: this is the area where the main beam gradually covers the obstracle. To explain such a large interval with monotoneously rising intensity, a very large main beam is needed, which leads to the small dish size. The predicted obstracle at 39° is quite possible, there's a lot of houses and trees around, altough measuring their exact angular size is difficult without proper equipment.

A "fuzzy" obstracle, with a temperature gradient or gaps (such as a tree) would produce an effect similar to a smaller dish diameter, probably allowing to produce a matching curve while using the correct dish size. However, no further analysis has been done

[‡‡] "*Airmass*" in this context means the fact that depending on the elevation angle an observers looks at, there's a different amount of air between the observer and space.

yet here; it would be much easier to repeat the measurement in a free area with no obstracles, and then try to fit the curve again.

In total, I'm almost sure that the explanation presented above is correct, but I don't have a suitable measurement yet to demonstrate this.

Independent of the correct explanation for the phenomen, these observations have an important implication for observations with this telescope: Measurements must be done while the telescope points into a fixed direction. As long as the direction is fixed, the background just adds a constant offset to the measurement, which can easily be subtracted later. Tracking objects with the telescope would require a background brightness map of the environment to be made first, which would then need to be subtracted from the measured intensity to obtain the real source brightness. If the suggested explanation for the effect is correct, then its severity could be reduced by building a larger telescope with smaller sidelobes, by observing at a location with less obstracles (a large field instead of a garden surrounded by houses and trees), or by adding wire or similar to surround the dish in order to reduce the sidelobes in the antenna gain pattern.

7 Conclusion

Given you already have a mount, for little more than €100 it is possible to build a somewhat functional radio telescope. Observing interesting non-thermal sources, such as pulsars, probably requires more money to be spent, and more work.