Radio Astronomy Experiments at 4 GHz

Ken Tapping

ken.tapping@nrc-cnrc.gc.ca

Introduction

Some years ago, someone found they could receive the signals in the 3.7-4.2 GHz Band (C-Band), which is used by broadcasting companies to transfer programme material. This led to a flowering of back garden 10ft and 12ft dishes, mainly in North America, as companies started to sell domestic satellite TV systems to receive this signals. Of course, this free distribution of broadcasts was not what the broadcasting companies intended, and they started to scramble the transmissions. There then followed an "arms race" between the broadcasters and manufacturers of "descramblers". This ended with the introduction of formal broadcasting from satellites, but at a much higher frequency, where domestic satellite receivers only need antennas about 2ft (60cm) or so in diameter.

The C-Band satellite TV market collapsed, leading to relatively state-of-the art receiving equipment becoming available free, or at most, for junk prices. One of the first people to realize that this equipment could be used for a wide range of radio astronomical experiments was Bill Lonc, of St Mary's University, Halifax, Nova Scotia, Canada. In his book "Radio Astronomy Projects" he describes experiments done with the participation of undergraduate students. These were usually aimed at solar observations, or in a few cases, observations of the Moon. With his assistance, Heather Cameron in Nova Scotia used such systems for single-dish and interferometric observations of the Sun.

For a long time I had no plans to do anything in this frequency range. However, a couple of years ago this changed, thanks to a friend, Tony Zonta, who was (Tony died last year) an avid amateur astronomer. To fund his hobby he ran a pub and small hotel. Tony's pub produces the best pub food in Penticton, and one day, my family and I were enjoying some of this, when Tony joined us. During the conversation he said that he had asked a radio astronomer if one could make a radio telescope out of old C-Band satellite TV equipment, and had been told "No". Did I agree with that? I said no. I knew of many examples of radio telescopes having been made out of old satellite TV equipment, Bill Lonc's experiments for example. His reply was "There's one on the roof. It's yours!"

With a lot of help from Tony, we got the 10ft dish and electronics to our (fortunately) large back garden. Experiments with this led to my getting very interested in the possibilities offered by such cheap but high quality equipment, and led to the series of experiments which are described in this article.

Initial Experiments With Tony's Dish

The receiver used an LNB (a low-noise block down converter), which received the 3.7-4.2 GHz satellite signals, and, using an internal local oscillator, down-converted them to the 950-1450 MHz range. The noise temperature of the LNB was about 35 K. The rms noise fluctuations in a simple, total-power receiver are given by:

$$\Delta T_{\min} = \frac{T_{sys}}{(B\tau)^{1/2}}$$

where T_{sys} is the noise temperature in Kelvins, B the receiver bandwidth in Hz, and τ the time-constant in seconds. If we assume that on the antenna, the receiver noise temperature is about 50 K, $B = 500$ MHz and $\tau = 2$ s, $\Delta T = 2\times10^{-3}$ K. If the aperture efficiency of the 10ft (3-m) dish is about 60%, this gives an effective collecting area of roughly 4 square meters.

The sensitivity limit of a radio telescope, in terms of flux density, corresponding to the level of rms noise fluctuations, is:

$$S_{\min} = 2k\frac{\Delta T_{\min}}{A_{eff}}$$

where A_{eff} is the effective collecting area and k is Boltzmann's constant (1.38×10^{-23} Joules per Kelvin). If we insert $\Delta T_{min} = 2\times10^{-3}$ K, we get $S_{min} \approx 10^{-26}$ W.m^{-2}.Hz^{-1}. This is an amazing sensitivity for a small, backyard radio telescope. However, in the case here, this sensitivity was unattainable. There were two reasons for this: the stability of the gain-bandwidth product in these commercial-grade components, exposed to the outdoor temperatures, was simply inadequate. The other reason was that the band 3.7 – 4.2 GHz is allocated for TV satellite broadcasting. There are satellites every couple of degrees along the geosynchronous belt, transmitting in this frequency band. These transmissions are far stronger than the emissions from cosmic radio sources, and no matter where the dish was pointed, some of these emissions leaked into the antenna through the sidelobes in the beam pattern. The result was that the stability of the receiver output was so bad that only the Sun was easily observable, and that over a day, the output would drift by more than the height of the solar peak. This system was not amenable for use on sources other than the Sun. A Dicke receiver would be hard to make because of the feed and receiver front end being made in one lump. However, an interesting alternative is the correlation (or multiplying) interferometer.

Theory of the Correlation Interferometer

In the correlation interferometer, there are (at least) two antennas, each feeding a separate receiver, one for each antenna. In its simplest form, the signals are received by two antennas, in an east-west line, and separated by a fixed distance. The signals received by the antennas are amplified to a level suitable for processing, and then multiplied. This can be done all at a single frequency, without down-conversion, or after some amplification, the signals can be down-converted to an intermediate frequency, where most of the amplification is done. In this case, the local oscillator must be common to all the receivers, or else the phase information, essential in the operation of an interferometer, will be lost. The multiplication of the signals may be done digitally or using an analogue correlator. In the designs here, the multiplication is done using analogue double-balanced mixers. These are inexpensive, simple to use, and work well.

When a source θ degrees west of the meridian (hour angle) is observed with an interferometer with an east-west baseline of length d, the path difference travelled by the signal to reach the two antennas is $d\sin\theta$, which yields the phase difference ϕ =360 ($d\sin\theta/\lambda$) degrees. The correlator (a double-balanced mixer) performs the calculation:

$$S = (W_E G_E)^{\frac{1}{2}}\cos(\omega t + \phi)\times(W_W G_W)^{\frac{1}{2}}\cos(\omega t)$$

where W is the power from the radio source collected by the antenna and G is the gain of the antenna preamplifiers and cable loss. The subscripts E and W refer respectively to the east and west antennas. If we multiply out the above we get

$$S=(W_E G_E W_W G_W)^{\frac{1}{2}}(\cos\phi - \sin^2\omega t\cos\phi - \sin\omega t\cos\omega t\sin\phi)$$

All the expressions containing ωt are at radio frequencies and are filtered out with the post-demodulation low-pass filter, leaving $S=(W_E G_E W_W G_W)^{\frac{1}{2}}\cos\phi$.

For the 4 GHz experiments discussed here, the advantages are that the uncorrelated noise or signals have a mean value of zero, so the variations in gain-bandwidth product of the receiver act only upon the signals arriving at both antennas. Since any signals reaching both antennas will correlate, producing receiver output, it was made sure the antennas were far enough apart that they are not seeing the same bit of ground. Anything unwanted but producing correlated output will give rise to unwanted output from the receiver, making it less stable and corrupting the data.

In addition, since the geosynchronous satellites, where the most of the 4GHz transmitters are located, are stationary in the sky, their signals might contribute a constant or slowly varying signal to the receiver output, but they won't make fringes. Cosmic radio sources will make fringes at a predictable rate. If there are any non-geosynchronous satellites operating in this band, they will make more rapid fringes. Another source of interference is radio altimeters in aircraft, which use an adjacent band. However, these will either make no fringes or more rapid ones. The hardware was available, and the experiment sounded worth doing.

The Minimum Interferometer

The 3.7-4.2 GHz low noise amplifiers (LNA's) are boxes with a WR229 waveguide input, and a Type N coaxial output. These devices are designed so that the power is transmitted along the centre conductor of the coax. This makes them difficult to use with attenuators and other equipment. If one removes the lid from one of these amplifiers one will see a wiggly, printed inductor on the circuit board, running to the output socket, and a little chip capacitor connected to the output from the amplifier. The inductor passes the power to the amplifier circuits while blocking radio signals. The chip capacitor passes the radio signals from the amplifier to the socket while blocking the DC power.

It was easy to use a sharp-ended screwdriver scrape away the inductor, and to drill a hole in the side of the box for a feed-through capacitor. A wire from the feed-through to the end of inductor going to the amplifier power line completed the modification. The most difficult task was just making sure that all the filings and turnings from the drilling operation were safely removed. The amplifier could then be powered using a separate wire, and the coaxial cable was used for signal transfer only. The power supply modification made it possible to connect amplifiers in series, with attenuators and other components between them.

Experiments showed that the outputs of the LNA's changed when one waved hands near the open mouth of the input waveguide, and showed hum when pointed at a fluorescent light a few meters away. It was not clear how efficient the open end of the waveguide was as an antenna, but it did work. This raised the idea of seeing if it was possible to make a radio interferometer with no antennas others than then open ends of the waveguides. There were too attractions in this: firstly, it was an experiment that could be done with very little work, and secondly, such an interferometer would be the least conspicuous back garden radio telescope ever.

A block diagram is shown below:

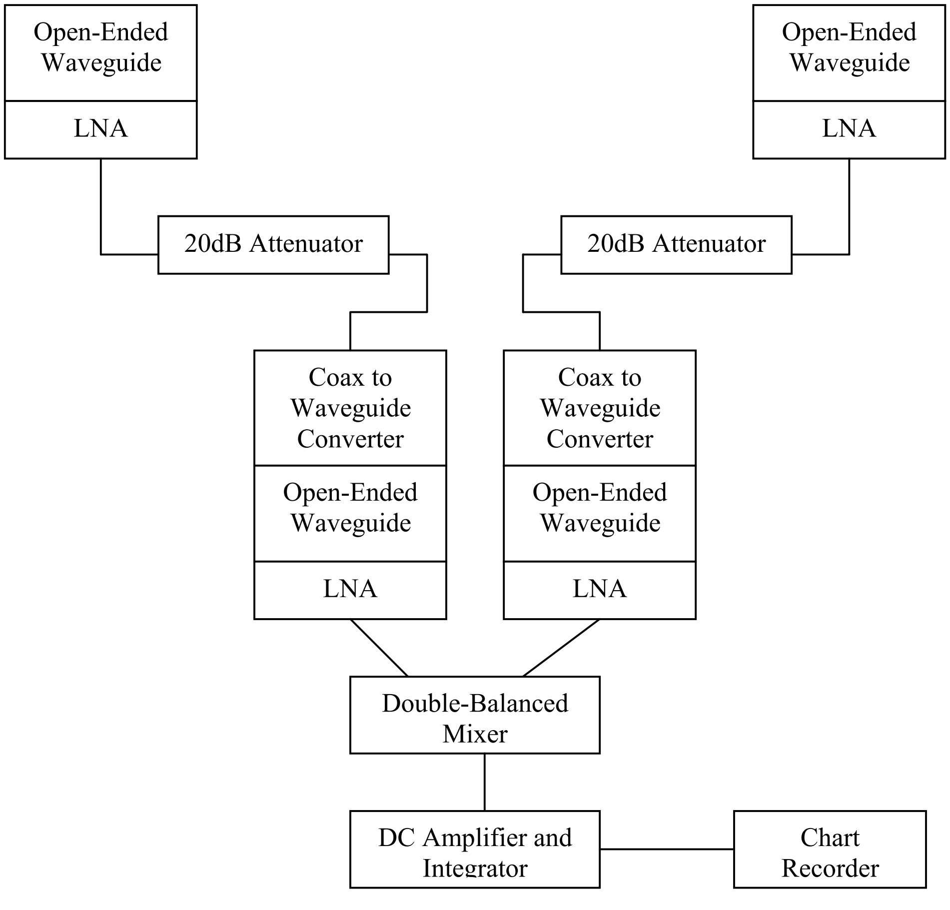


Figure 1: Block Diagram of the "Minimum 4 GHz Interferometer"

It sounded almost too good to be true. However, if we assume that the beam-width of the open-ended waveguide when used as an antenna is around 60°, the average disc temperature of the Sun at 4 GHz is about 25,000 K, and the Sun subtends 0.5 degrees, the Sun will increase the antenna temperature by $\Delta T = \left(\frac{0.5}{60}\right)^2 \times 25{,}000 \approx 2\text{K}$

An antenna temperature of about 2 K does not sound like much. However, the theoretical sensitivity of the receiver is in the milliKelvin region. The experiment sounded worth doing.

The open-ended waveguides acted as antennas, picking up at least some of the radio emissions from the sky. The LNA's amplified them by about 55dB; then the signals were fed through 20dB attenuators, with avoided overloaded the second amplifier, and also greatly removed the effects of any mismatches in the homemade coax to waveguide converters. The coax to waveguide converter launched the signal into the mouth of the waveguide input to the second LNA, where it was amplified by a further 55dB. The outputs from the second amplifiers were fed to the inputs of a 2 – 4 GHz double-balanced mixer. The output was passed to a DC amplifier, with adjustable gain, backing off and time-constant.

The first amplifiers were clamped to sawhorses, pointing up at about 45 degrees. The rest of the electronics was on the table between them. The RF cables between the amplifiers were heliax with N-Type connectors, and the connections between the LNA's and the double-balanced mixer were 3-mm semi-rigid cable with SMA connectors. These precise types are not mandatory, but since the signals are all at 4 GHz, appropriate cables should be used. The coax-to-waveguide converters are very simple, and were adapted from the design in Bill Lonc's book. It's easiest to explain them while building them.

Using the waveguide ends as templates the outline of the flange and the positions of the holes for the mounting screws were traced onto copper-clad board. The copper had to be held hard against the end of the waveguide. A Type N socket was mounted in the middle of the Board, going through it so that the flange was touching the side that would be inside the end of the waveguide. A piece of thick, tinned copper wire was made into a small loop, coming horizontally from the end of the central terminal on the Type N socket and turning 90 degrees at the edge of the flange to go down to the copper-clad board. It was soldered in place. This loop acts as a small antenna, radiating signals into the waveguide. Such a crude design would not be efficient, but with 55dB gain in front of it, it did not have to be. The edges of the board, including the holes, were cleaned of stray, loose bits of copper, and the crude coax-to-waveguide transformer screwed down hard against the waveguide aperture. All the screw holes were used, so that the contact was as snug as possible. It is probably best not to know what the impedances of these crude transformers happened to be. However they were always to be used with an attenuator of at least 10dB between the input to the amplifier fitted with the transformers and the outputs of the amplifiers feeding them. A coaxial detector was put at the output of a pair of amplifiers connected in series, and the amplifiers powered up. A suitable output (about 10mV) was obtained when 20dB attenuation was installed between the amplifiers. The detector was removed. The input amplifiers were clamped to sawhorses, so that they looked into the southern sky at about 45 degrees elevation. The signals were taken to a table located between the sawhorses, where the 20dB attenuators and second amplifiers were located, each fitted with its coax-to-waveguide transformer.

Figure 2: The Minimum Interferometer. The two LNA's are clamped to those vertical pieces of wood nailed to the sawhorses. The signals are carried to the table, where the rest of the electronics is located, by heliax cables. On the table are the additional amplifiers and the rest of the electronics and an old chart recorder. Parts of other experiments lie in the background. If this were a more permanent set up, the electronics would be indoors, and the waveguide openings would be covered with plastic sheet.

The problem with this arrangement was that all the signal cables were carrying 4 GHz signals. Cables should therefore be of good quality, preferably heliax or semi-rigid, copper coax. It is helpful to have them as straight as possible and no longer than they need to be.

This radio telescope design would be useful for making solar observations, and has the great advantage that it can be very inconspicuous. Not much space is needed, so it can be installed in a small back garden or on a balcony, and with the large beam-width of the antennas, the antenna declination would need few adjustments a year. In fact, with appropriate correction curves, and pointing the waveguide at the celestial equator, solar measurements could be done with no adjustments to the antenna at all. To best do this, mount the LNA's not as shown here, but with the largest waveguide dimension horizontal. This will produce a wider beam-width in the declination direction.

This configuration worked first time. The record in Figure 3 shows the chart obtained during that first test run. With the huge antenna beam-width, the solar fringes show almost constant amplitude. The excellent signal to noise ratio is obvious. Credit for this is due to the ability of manufacturers to turn out excellent, consumer-level equipment.

This experiment demonstrated that the principle worked, and that it would be worth going on to a larger instrument.

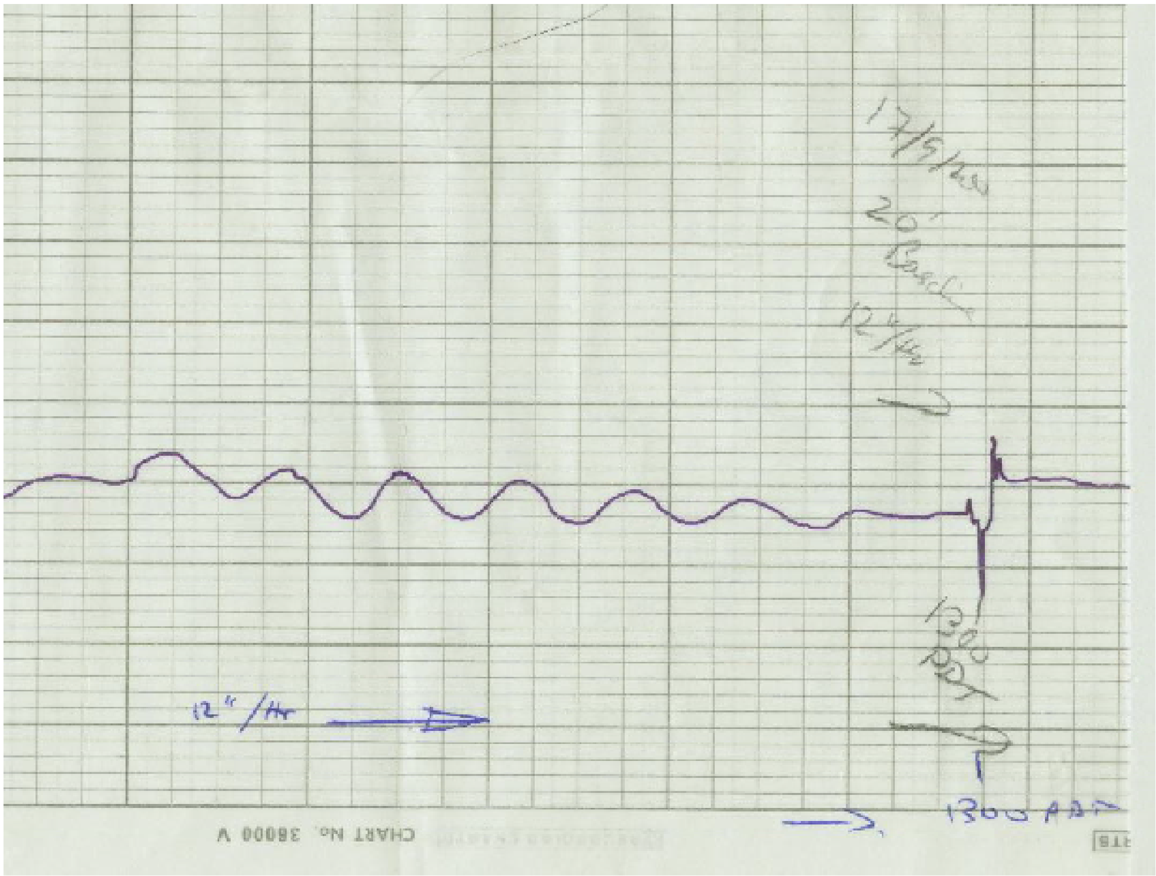


Figure 3: A test observation of the Sun using the simple interferometer. Note the good signal to noise ratio. The observation was made on 17 September, 2000, with a 20 ft baseline. The chart speed was 12"/hr.

The Aluminium Pipe Interferometer

Large antennas are highly desirable in radio astronomy because they do two things: bigger antennas collect more signal, making the radio telescope more sensitive, and they also provide higher angular resolution. However, the higher resolution raises issues that are not important at longer wavelengths.

At lower frequencies, where most amateur radio astronomy is done, the antennas are not large compared with the wavelength, so the beam-width of an individual antenna is quite large. For example, in the 408 MHz interferometer that was described in a previous article, the yagi antennas used have beam-widths of about 45°. If the two yagis making up each antenna unit, or the two antenna units are not pointing in exactly the same direction, the consequences in terms of lost sensitivity and calibration error would be small, and probably negligible. However, at centimeter wavelengths the situation is very different.

A 10 ft (3 m) dish at a frequency of 4 GHz (a wavelength of 7.5 cm) has a half-power beam-width of 1.5°. To make a useful measurement, the antenna has to be pointed within at least a tenth of a beam-width of the source, that is, the maximum permitted pointing error would be about 0.15°. This is not trivial. If such an antenna were to be part of an interferometer, all antennas would have to be pointing in the right direction to within 0.15°! That would also be hard to arrange.

For some years, as we moved from one house to another, we had been carrying with us a piece of aluminium pipe that was too nice to leave behind, even though we had no immediate use for it. It was about 7 m long, about 9 cm in diameter, with walls at least 8 mm thick. It had been used for a number of things, including levering fence posts and tree stumps out of the ground, without bending; it is extremely strong. It occurred to me that this could be used as the baseline of a rigid interferometer. If an antenna were to be attached at each end, it would be possible to ensure they would always be pointing in the same direction. However, 10 ft dishes would be a bit too big, so, after some phoning around I got hold of a couple of smaller ones: a 6 ft mesh dish and a 5 ft solid one with a number of golf-ball dents. The half-power beam-widths of these dishes at 4 GHz are 2.5° and 3° respectively. This is rather more manageable. The photo shows the initial test arrangement.

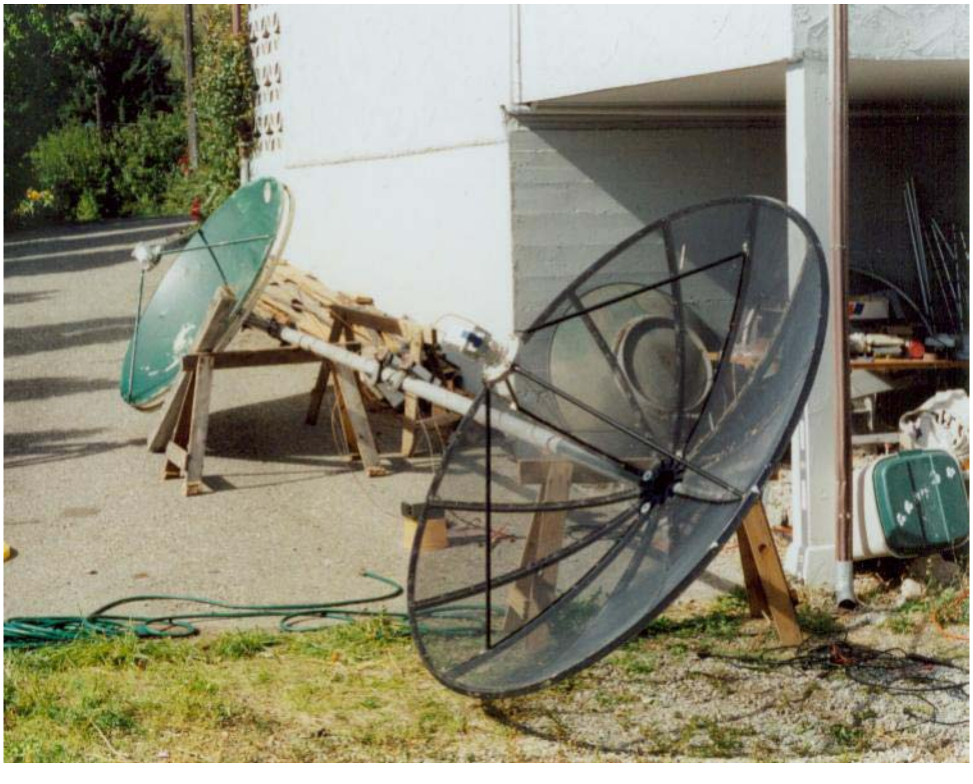


Figure 4: Trial version of the rigid interferometer. The antenna-mounting pipe is resting on the sawhorses used for the initial experiments.

Success was immediate. The solar fringes were enormous. However, to make serious observations the antennas needed to be mounted properly, and in a location with good access to the southern sky through north of the zenith. A wooden structure was made from 4×4″ and 2×4″ treated timber on the southern slope of our property to support the aluminium pipe so that it would rotate in the declination direction but fixed in a (more-or-less) east-west line. The pipe was then levelled using a spirit level. The two dishes were attached to the ends, and set to face the zenith by levelling them with the spirit level across their apertures in the east-west and north-south directions.

The feed horns were adjusted onto the focal lines by dropping a plumb line to the vertex of each dish. The focal lengths of the dishes were measuring the depth of the dish at the centre from the plane of the aperture. The focal length is then given by $f=D^2/16d$ where D is the diameter and d the depth of the dish. The feeds were positioned on the assumption that the phase centres of the feeds were about 2 cm in from the opening.

The feed horns that come with the satellite dishes have adjustable polarization. There is a little antenna at the back end of the feed horn. It is adjustable. The antennas on the two dishes were turned with pliers until they were both in the same direction.

One tremendous advantage of this interferometer design is that the cables carrying the signals from the antenna amplifiers to the rest of the receiver, which is mounted at the centre of the baseline, can be treated as rigid. This is a real advantage when the signals are at 4 GHz. If this cable radiates a little signal, it could be picked up by the antennas and would make the receiver oscillate at worst, or badly degrade the gain stability at best.

Some years ago a friend had given me about 50 ft of 3 mm semi-rigid coaxial cable. Someone had driven a van over the roll as it lay on the ground and it was deemed unsafe to use, so I got it. It had no signs of damage apart from a few abrasions. Two identical lengths were cut and SMA connectors put on each end. The lengths were about 50% longer than the length of the pipe. The excess length was taken up by spiralling the cable loosely around the pipe and securing it at intervals with bands of tape.

The second amplifiers, double-balanced mixer and a DC amplifier, with their power supplies were put in a thick-walled, plywood box attached to the middle of the pipe. Mains power was brought from the garage, and the signal carried back through coaxial cable. An antenna arrangement is shown in Figure 2. Success was immediate. However, the baseline stability was poor. It was interference from the geosynchronous satellites. The solution was simple. High-input impedance operational amplifiers (with field-effect transistor inputs) were used to make a high-pass filter, with a cutoff frequency of a few millihertz. With good-quality resistors and polycarbonate capacitors, such pathological filters are actually quite easy to make. This got rid of DC and slowly varying signals. The receiver output was now a straight line down the middle of the chart, with fringes. However, the fringe patterns indicated that one or both of the dishes was not properly focussed. The focal lengths were re-calculated and the dishes re-set up. One of the feeds had somehow moved by more than an inch, which is a significant distance at 4 GHz.

The collecting area of an interferometer is the geometric mean of the areas of the two antennas. At a guess, including the inherent inefficiencies in the feeds used to collect the signals at the focuses; the collecting area is probably about 2 square meters. Using the formula for the antenna gain:

$$G = 4\pi \frac{A_{eff}}{\lambda^2}$$

We get a gain of about 5000 times, which is 37 dB.

The antenna declination is determined using a big quadrant and plumb line, marked in degrees, and attached to the pipe. It is the white object on the right hand side in the figure.

Figure 5: The rigid interferometer. The green, 5ft dish is on the left and the 6ft mesh dish is on the right. The receiver box is in the middle of the pipe. Also visible is the original 10ft dish and the yagis of the 408 MHz interferometer's west antenna.

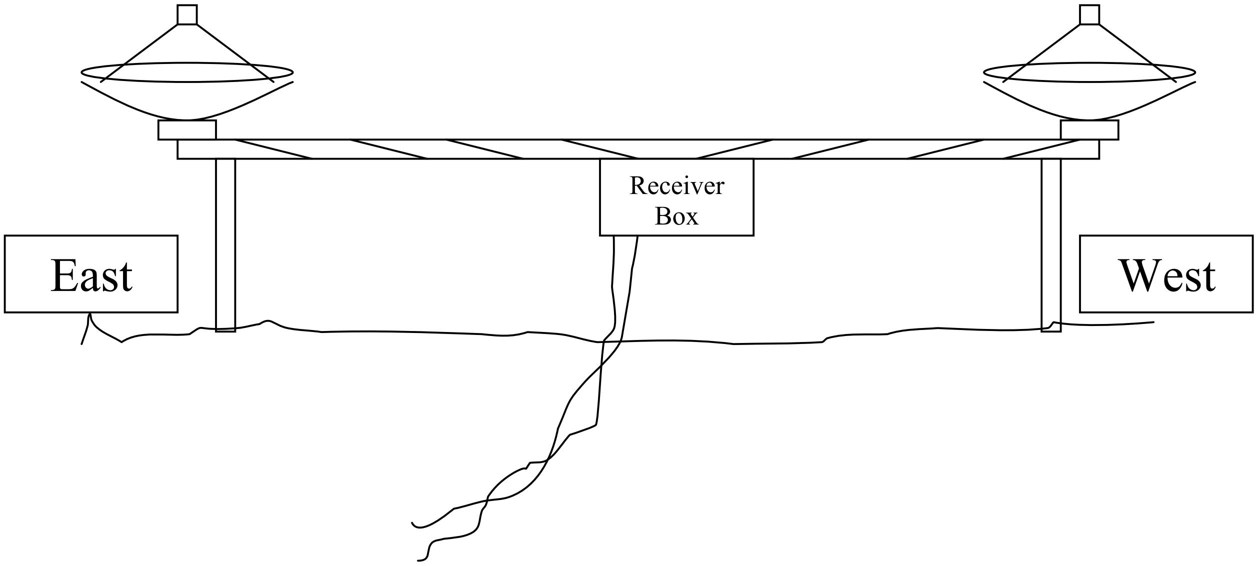
If we have a noise temperature of about 100 K, a bandwidth of 500 MHz and an interferometer with a collecting area of 2 square meters, and a time-constant of a second, the random fluctuations in the output in Kelvins are:

$$< \Delta T >= \sqrt{2}\frac{T_{sys}}{\sqrt{B\tau}} = \sqrt{2}\frac{100}{\sqrt{5\times 10^{8}}} \approx 10mK$$

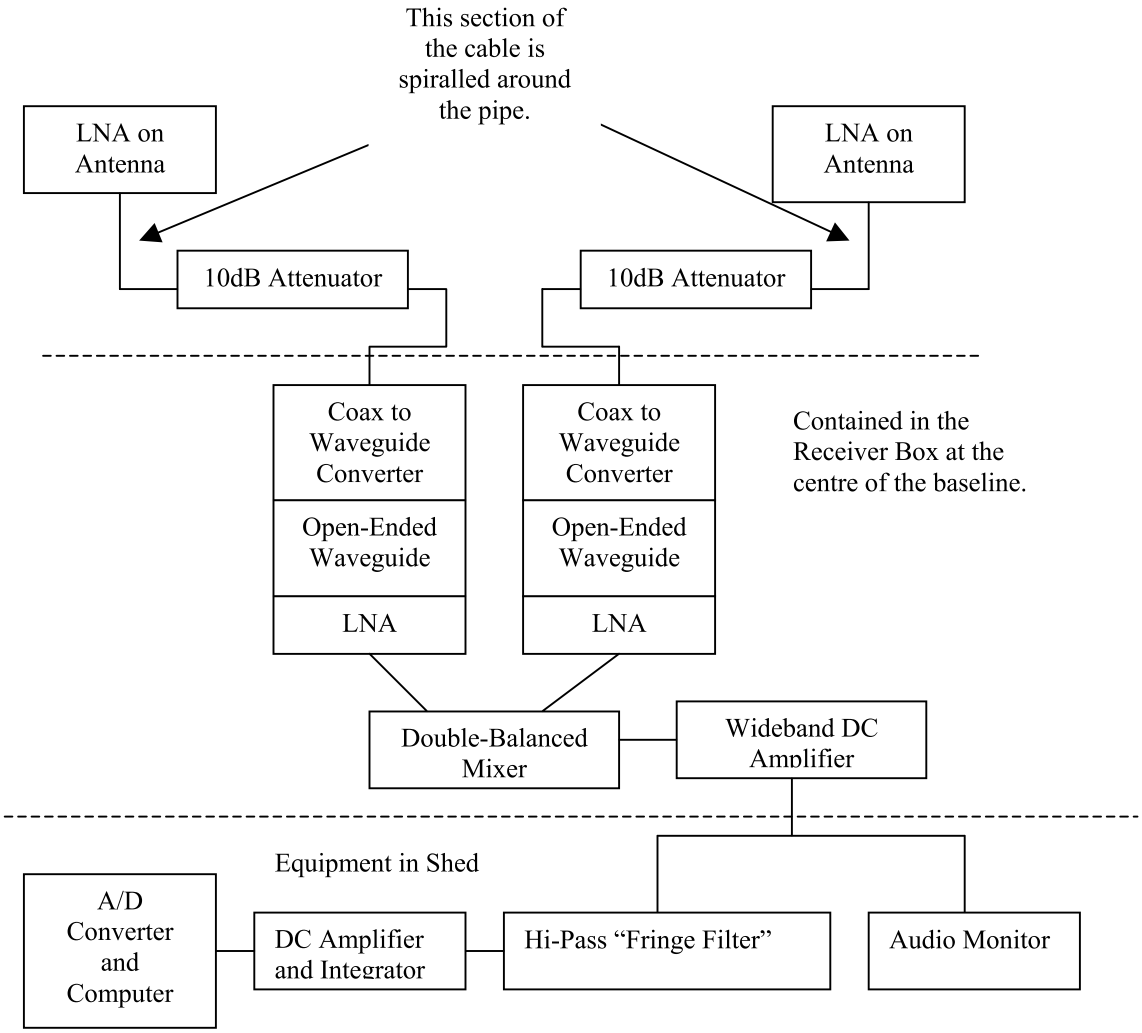
In terms of the attainable minimum flux density:

$$< S_{\min} >= 2k\frac{< \Delta T_{\min} >}{A_{eff}} = 2(1.39\times 10^{-23})\frac{10^{-2}}{2} = 28\times 10^{-26}\, w.m^{-2}Hz^{-1}$$

By amateur standards, this is quite a remarkable sensitivity, if attainable in practice.



The block diagram of the receiver is shown below.



This section of the cable is spiralled around the pipe.

Contained in the Receiver Box at the centre of the baseline.

Equipment in Shed

The hardware arrangement was made as rigid and stable as possible. After amplification in the head amplifiers at the focus of the dishes, the signals are transferred via 3-mm semi-rigid coaxial cable to the Receiver Box, which is rigidly clamped to the centre of the pipe (the centre of the baseline of the rigid interferometer). The receiver box is made of wood, and open to the air on the downhill side, so that it is well ventilated. The coax is loosely sipralled around the pipe. It was found that 10dB attenuators were needed to ensure that the second-stage amplifiers were not overloaded. Inside the Receiver Box the signals were further amplified and then multiplied in a double-balanced mixer. The output of the mixer was amplified in a DC amplifier with a pass band from DC to a few kHz. The output of this amplifier, about a volt, was transferred to the rest of the receiver, which was located in a shed. In the shed there is an audio monitor, which is useful for identifying interference. The addition of the "fringe filter" greatly improved the readability of the receiver output. After the DC signal voltage from the satellites is removed, the signal voltage is passed to a DC amplifier with variable gain, back-off and integration time. The radiometer output is read by a computer, which records time-tagged 5-second averaged values. The filter was a worthwhile addition, but led me up the garden path a couple of times. One night I found I could hear no noise from the audio monitor and the computer was showing a flat line. After checking the obvious things I noticed that the DC amplifier output from the Receiver Box was –12V. The antennas were pointed at a declination of –7°, right at the geosynchronous satellite belt, and was overloading. The large DC was blocked by the high-pass filter, leading to a deceptive zero signal voltage at the data logger. A recording of Cygnus A is shown below.

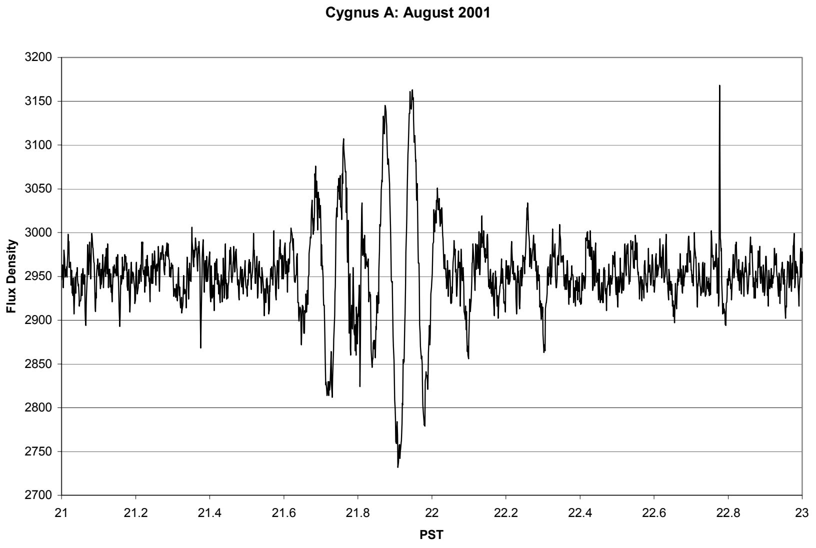
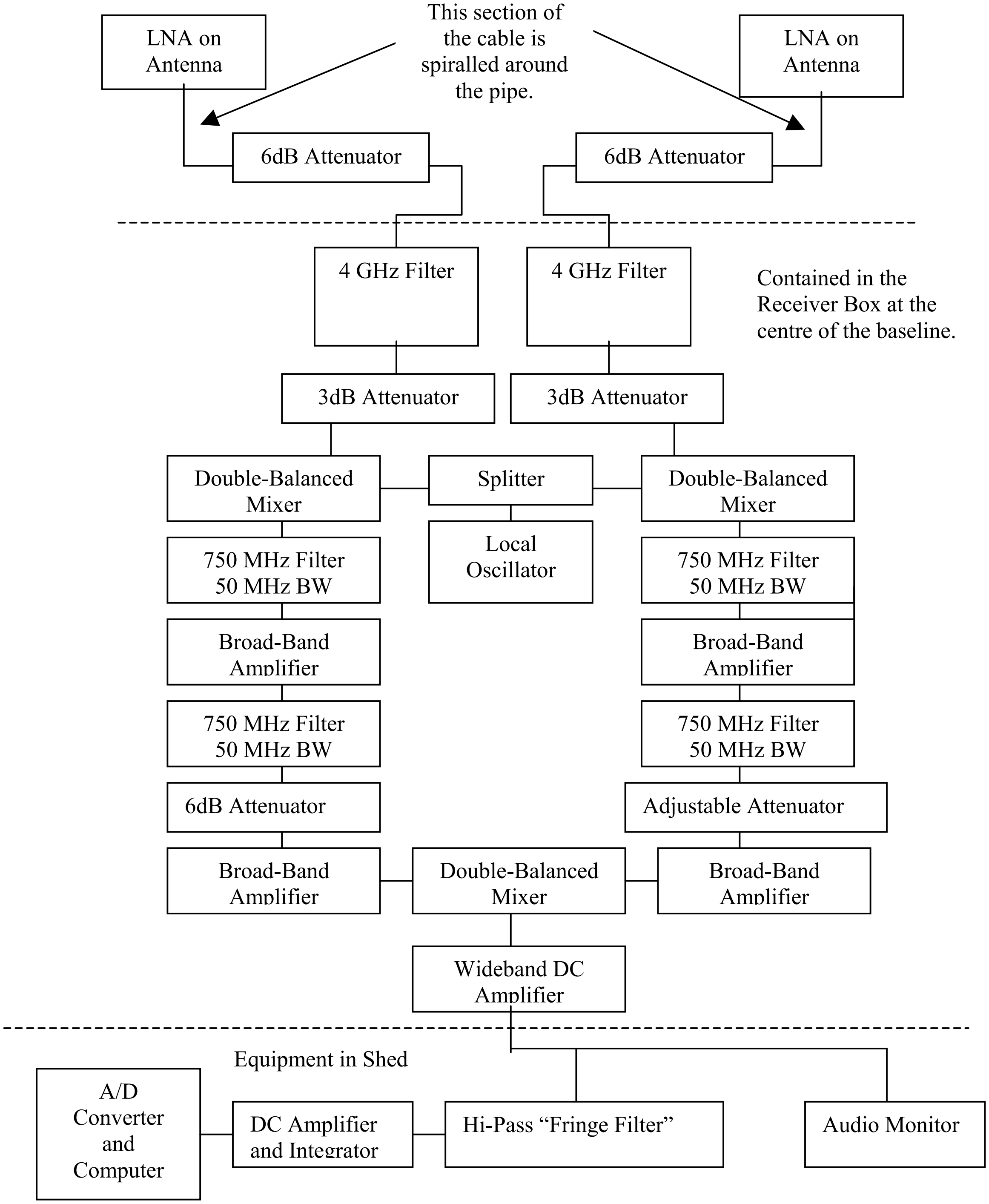


Figure 6: Cygnus A as observed with the first version of the correlation interferometer.

Although it was very gratifying to see Cygnus A at 4 GHz, the random fluctuations were much bigger than theory predicted. A look at the radio frequency signals by means of a borrowed spectrum analyser revealed the cause. The pass band was alive with satellite signals. It was clear that to get rid of at least some of the interference, the bandwidth had to be reduced, and the pass-band of the receiver better defined. This is hard to do at 4

GHz, but easier if the signals are converted to a lower frequency. These days, getting hold of broadband amplifiers is easy and inexpensive, and filters not too difficult to make. The block diagram below shows the revised receiver design.



On the basis of availability of components, an intermediate frequency (IF) of 750 MHz and a bandwidth of about 50 MHz were decided upon. The local oscillator was an old Gunn diode, tunable between 2 and 4 GHz. The antenna layout was unchanged, and the new receiver was installed in the wooden receiver box at the centre of the rigid interferometer baseline. The broadband amplifiers are 500-1000 MHz and have gains of about 35 dB. The mixers are a pair of the double-balanced mixers used in the first version as the analogue correlator/multiplier.

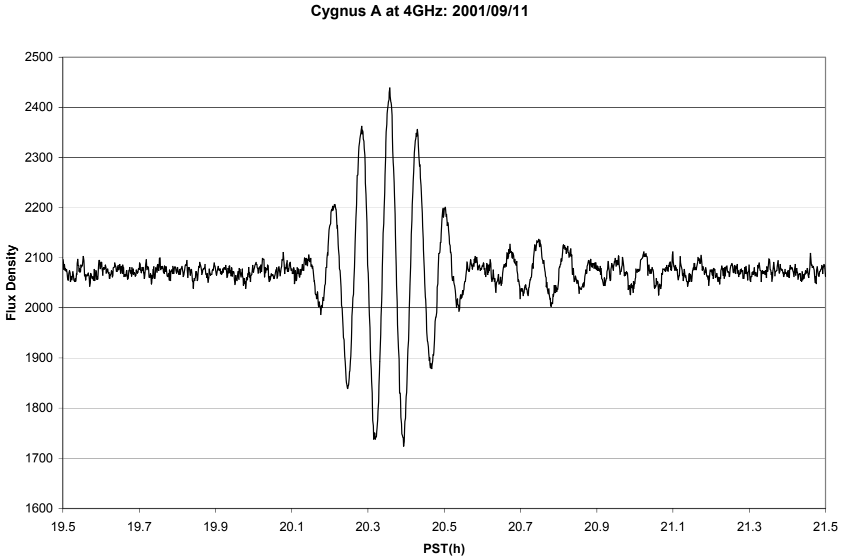


Figure 7: Observation of Cygnus A made using the superhet version of the correlation interferometer. The weaker source to the right of Cygnus A is Cygnus X.

This observation of Cygnus A looked good, so other sources were tried.

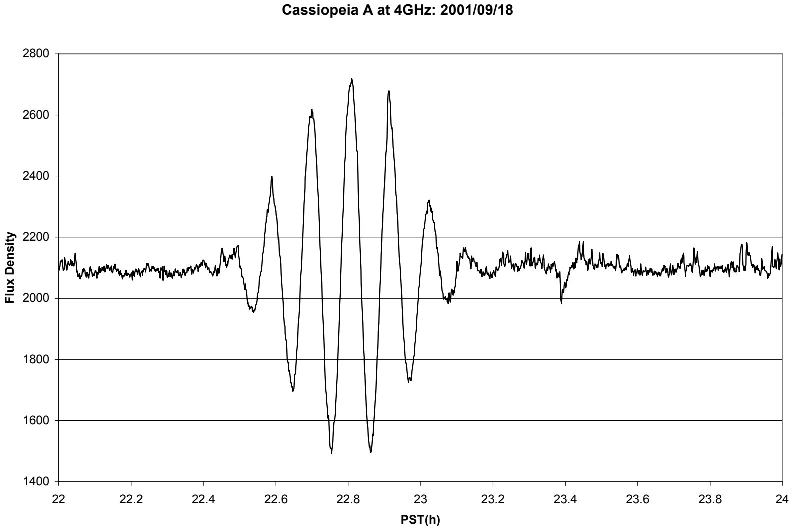


Figure 8: Cassiopeia A using the superhet instrument.

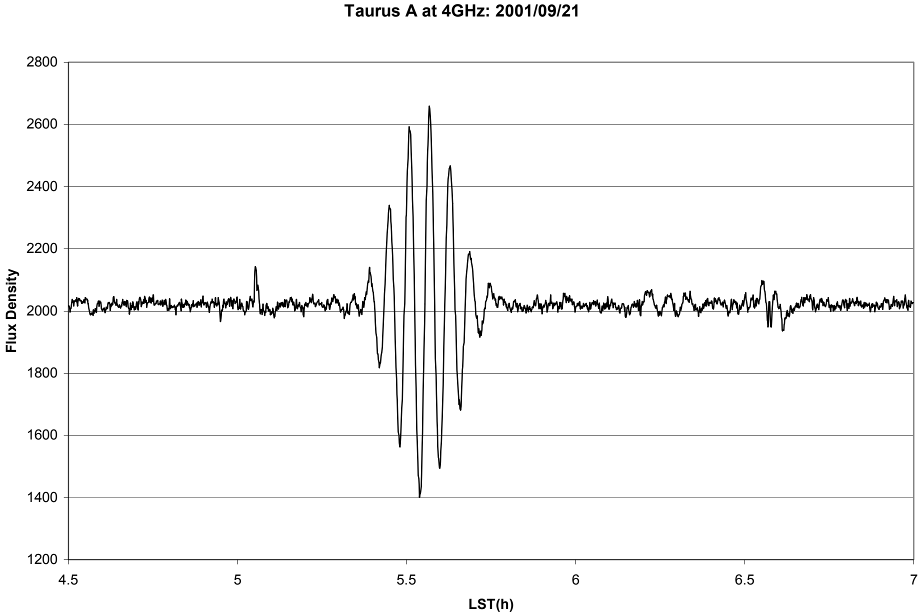


Figure 9: Taurus A at 4 GHz. The source stands out well. The small fringes to the right of the source are due to the much older supernova remnant, IC443.

As the declination got lower, from +60 and +40 degrees for Cassiopeia A and Cygnus A respectively, to Taurus A at declination +22 degrees, the satellite signal level increased. Although the fringe filter got rid of the low-frequency components, what was left over manifested itself as an increased noise level in the data.

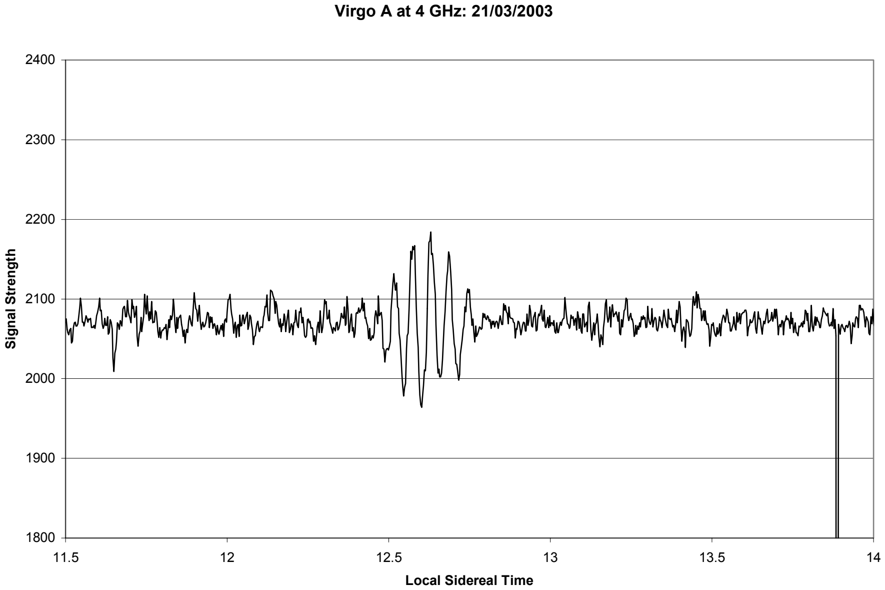


Figure 10: Virgo A at 4 GHz. Note the fainter source and higher noise level.

The sensitivity of the radio telescope suggested having a go at some other radio sources. At 4 GHz HII regions are bright. These sources are clouds of gas that are heated and ionized by nearby stars. At meter wavelengths they are weak, but are much brighter at centimeter wavelengths. The source W3 (IC1795) is a bright HII region, and proved easy to detect, as shown below.

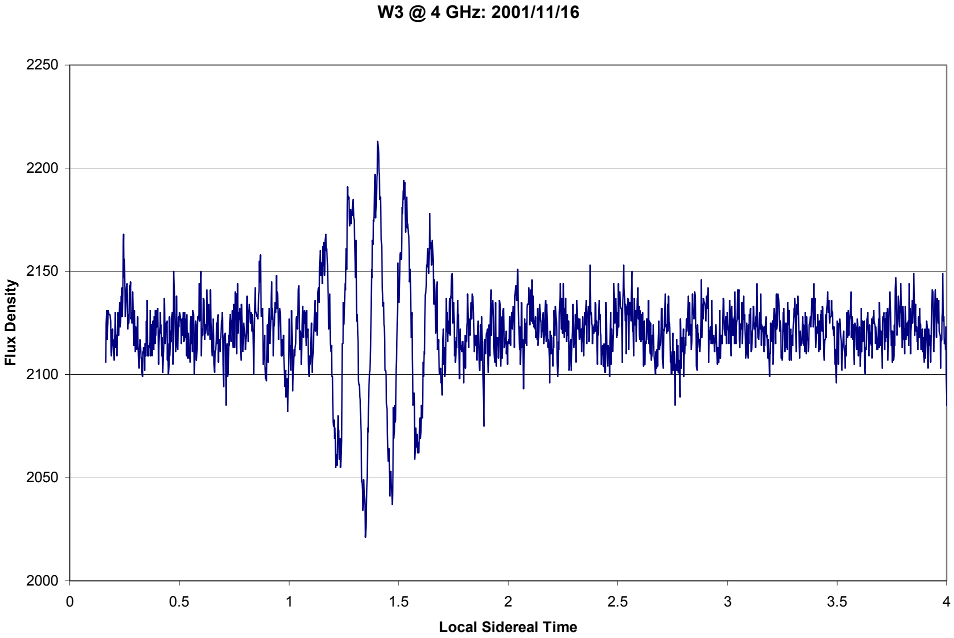


Figure 11: W3, a bright HII region. These sources are weak at the longer wavelengths typically used by amateur radio astronomers, but are bright features at centimeter wavelengths.

It was the observation of this source that suggested looking for other, fainter sources. Anywhere in the declination range +5 to –15 proved hard to observe, due to the geosynchronous satellite belt at –7 degrees (as observed from this latitude). This was really saddening, since the best HI region of the lot is the Orion Nebula, M42, which for latitudes about 50 degrees, lies almost on the geosynchronous satellite belt. Attempts made in hope to observe it failed, with the receiver being overloaded by the satellite signals. One cannot really call them interference, since the 3.7-4.2 GHz band is allocated to them, and it was their presence that made this project possible. It was still possible to look into the southern sky south of declination –15 degrees.

A series of scans were made from declination –30 degrees (due to hills) up to –15 degrees, a degree at a time. At –27 degrees declination, the compact, bright source at the Galactic Centre showed up very strongly. Any surrounding diffuse emission was rejected by the interferometer, leaving only the emission from the compact source.

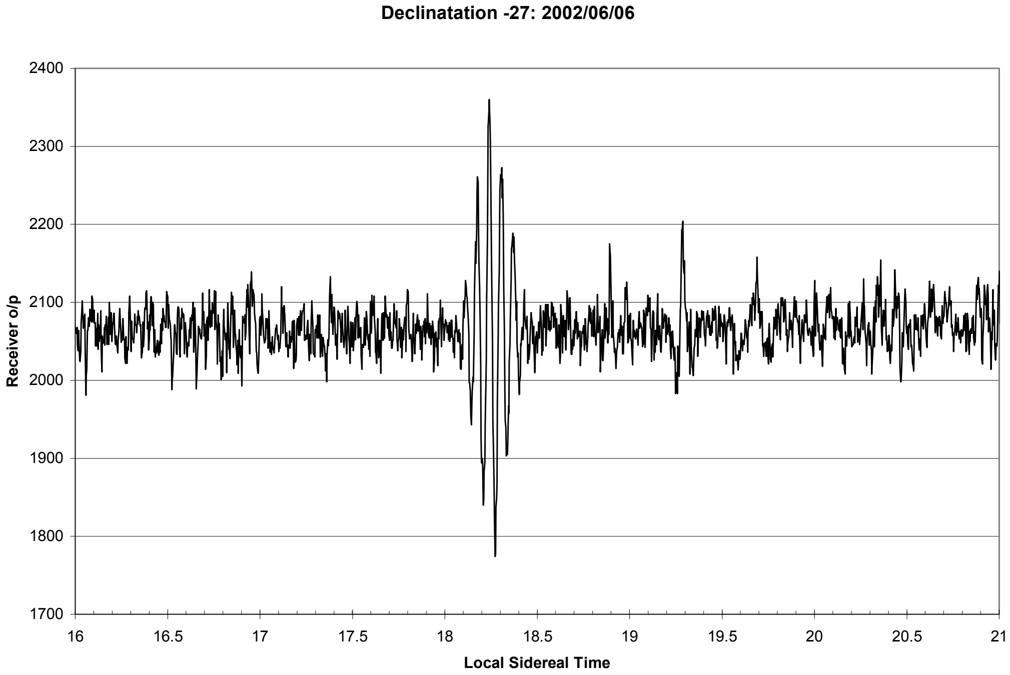


Figure 12: The Galactic Centre at 4 GHz. This source is really strong.

A bit to the north, and declination –16 degrees, close to the satellite interference band, lies another HI region, M17. This also showed up well, although with a high satellite interference level.

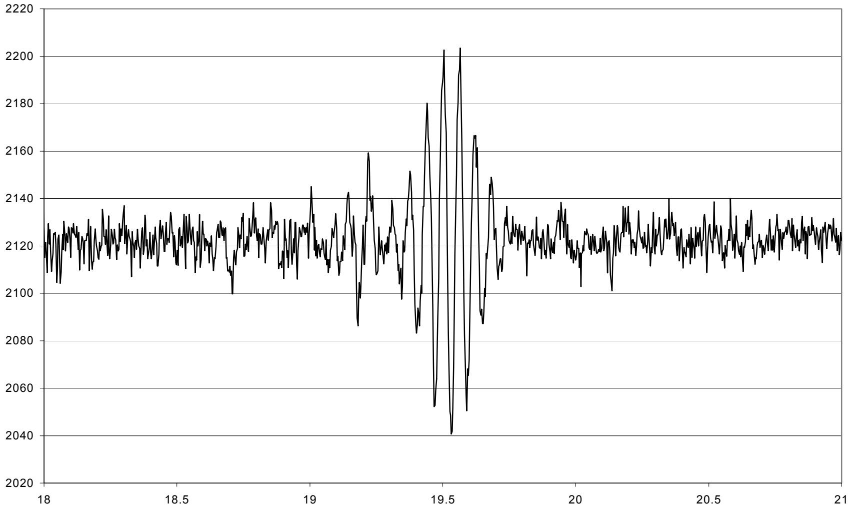


Figure 13: Messier 17, another HII region, at 4 GHz.

The stability of the system suggested the possibility of increasing the sensitivity by averaging a succession of daily observations. This yielded a successful detection of Hercules A, an old supernova remnant that is quite faint at centimeter wavelengths.

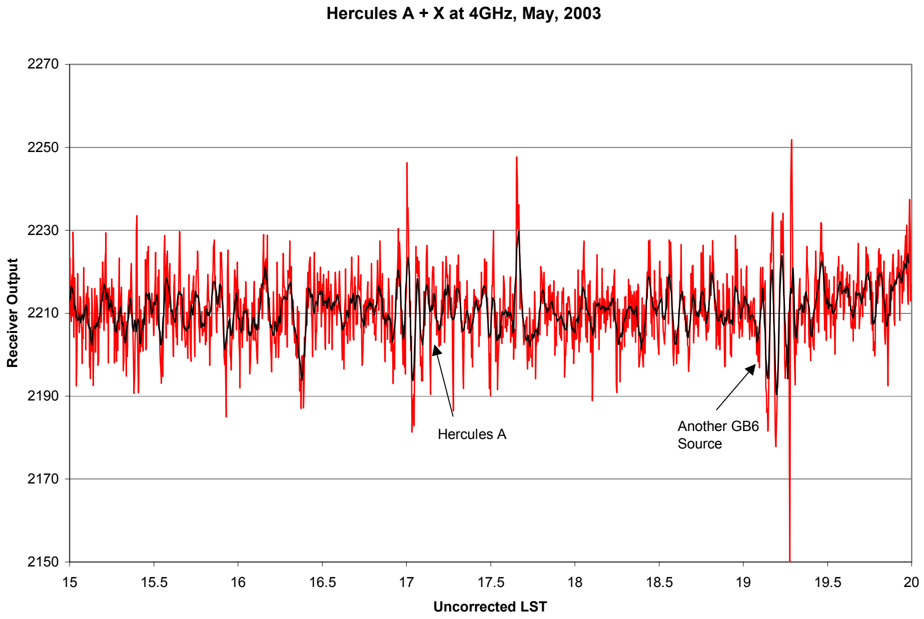


Figure 14: The red trace is the average of four daily transit observations. The black line is a 10-point running average.

A surprise was the presence of another source, to the right. It was one of the un-named sources listed in the Green Bank GB6 Survey, made at 5 GHz using the now-collapsed and replaced 300ft dish. A week's observations, yielded radio galaxy 3C295.

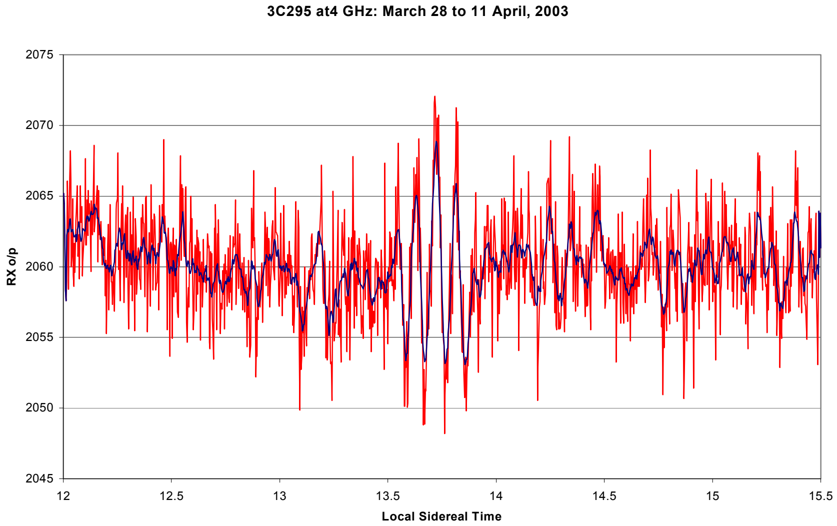


Figure 15: A week's observations of 3C295, averaged. The blue line is a 10-point running mean.

The Green Bank GB6 Survey, made using the old Green Bank 300ft telescope was a comprehensive catalogue of sources between declinations 0 and +75 degrees. The frequency was 4.85 GHz, reasonably close to the 4 GHz observing frequency used in these observations. This catalogue is a thick tome listing over 75,000 sources, almost all of which are only thousandths of a Jansky (Jansky, a Jy = a flux unit = 10^{-26} $w.m^{-2}.Hz^{-1}$). The sources brighter than 10 flux units were taken out of the table, as being suitable for 4 GHz observations consisting of several or more averaged scans). The sources are listed in the table below, with the brightest sources added.

Right Ascension			**Declination**			**Flux Den**	
h	**m**	**s**	**deg.**	**arc-min**	**arc-sec**	**S(J)**	
5	**30**	**30**	**21**	**59**	**0**		**Crab Neb**
12	**28**	**18**	**12**	**40**	**0**		**Virgo A**
19	**21**	**24**	**14**	**24**	**0**		**3C40**
19	**57**	**42**	**40**	**36**	**0**		**Cygnus A**
23	**21**	**12**	**58**	**32**	**0**		**Cass A**
2	1	48.9	64	35	18	15	
2	21	53	61	52	30	39	
2	23	4.7	62	2	13	11	
3	16	28.5	41	19	52	47	
4	33	55.5	29	34	1	16	
12	26	32.8	2	19	20	44	
12	28	16.9	12	40	10	59	
16	48	41.6	5	4	23	12	
18	50	48	1	10	35	13	
18	59	14.7	1	8	40	14	
19	7	53.3	9	1	9	38	
19	20	44.1	14	10	33	10	
19	21	23.9	14	24	28	69	
20	25	34	37	12	48	12	
20	37	15.2	42	9	1	20	
21	34	4.6	0	28	20	11	
22	51	29.8	15	52	54	15	
23	11	28	61	13	57	16	

The sources observed so far, with their measured flux densities, are listed below. Some of them were observable in a single observation, others required averaging up a week of successive observations. The differences between the observed and actual positions indicate errors in the orientation of the interferometer baseline. Since no great effort was made to set it up truly east west, which the available locations would have made very difficult, errors are likely, especially at high declinations.

Source	Observed		Actual		RX o/p	Flux Den
Name	RA (h)	Dec (d)	RA (h)	Dec (d)	Deflection	S(fu)
W3	1.4	63	2.4	62	200	134
3C84	3.7	41	3.33	41	**70**	**47**
Crab	5.6	22	5.6	22	537	361
IC443	6.4	24	6.3	23	30	20
	7.5	32			50	34
Virgo A	12.5	12	12.5	12	255	171
3C295	13.75	52	14.2	52	15	10
Herc A	15.9	5	16.8	5	17	11
Sag A	18.25	-27	17.7	-29	500	336
M17	18.7	-16			450	302
GB6 srce	19.25	5			25	17
Cygnus A	19.75	40	20	40.7	550	369
Cygnus X	20.75	40	20.4	40	100	67
Cass A	22.5	59	23.4	59	1200	806

The sources in the GB6 catalogue stronger than 10 flux units are shown in the plot below, marked in blue. The red sources have been observed with the 4 GHz interferometer. The isolated red point at RA = 13.75, dec = + 52, is 3C295.

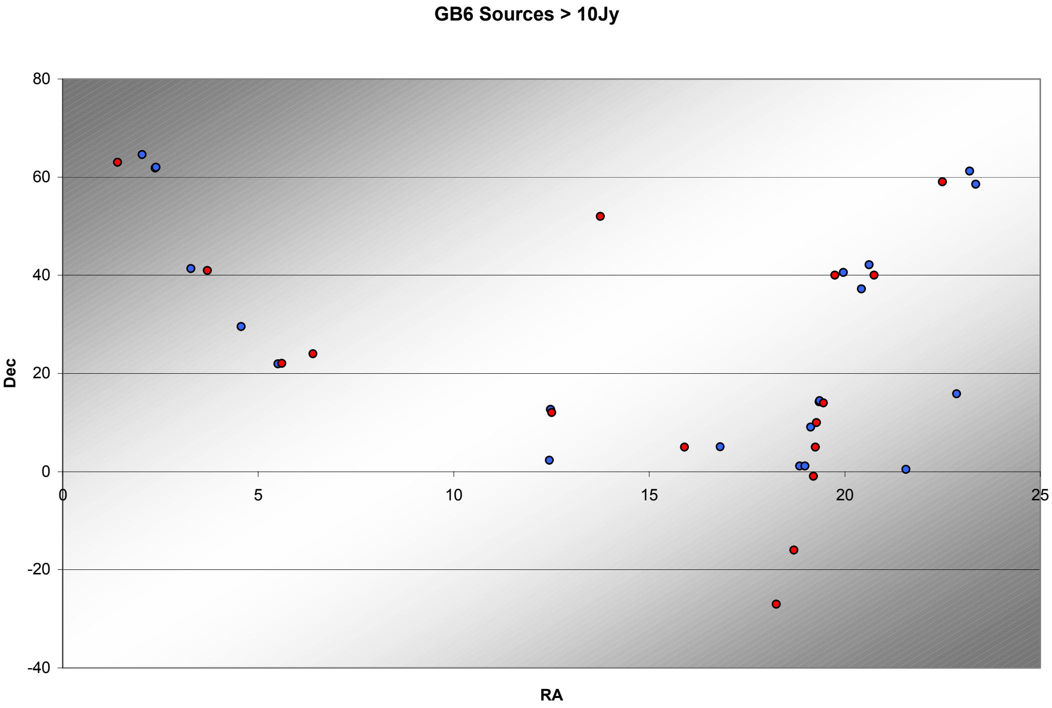


Figure 16: Plots of GB6 sources stronger than 10 fu (blue) and 4 GHz sources observed with the correlation interferometer (red).

The GB6 catalogue includes no sources below the celestial equator.

The 4 GHz interferometer is a usable survey instrument for amateur surveys. However, its position measurement accuracy needs refinement.

The Moon

For most amateur astronomers or operators of small radio telescopes, the Moon is generally discarded as a radio source worth observing. The Moon is actually a strong, thermal radio source, and easily observed at shorter wavelengths. The relationship between temperature and flux density for a source that is larger than a point is:

$$S(\lambda) = 2k\frac{T}{\lambda^2}\Omega$$

where k is Boltzmann's constant, T the temperature of the source, λ the observing wavelength and Ω the solid angle in steradians subtended by the source. The Moon is a black body with an average temperature of about 225 K, and subtends roughly 6.8×10^{-5} steradians. Putting in the values we get: $S(\text{fu}) = 43/\lambda^2$ flux units. At an observing wavelength of one meter, the Moon will have a flux density of 43 flux units, that is 4.3×10^{-25} w.m^{-2}.Hz^{-1}. This is beyond the reach of all but large radio telescopes. Since a meter or more has been the preferred wavelength for amateur radio astronomers, most sources are brighter, and the Sun is a very interesting source, there has been little interest in the Moon. The situation at a wavelength of 7 cm (0.07 m) is very different The lunar flux density is almost 8800 flux units. At 7 cm the Moon is the strongest source in the sky after the Sun! At even shorter wavelengths the Moon is even brighter. At 3 cm wavelength, the Moon produces almost 48,000 flux units.

The emission originates in the Moon's surface layers. At 3 cm and shorter wavelengths, the emission originates close to the surface, so that the temperature changes over the lunar day can be measured. At 7 cm wavelength, there probably is some variation, but for various reasons, I have not yet made any effort to measure it.

The main reason is that the antenna has to be at the right declination. The Moon changes its declination by around 50 degrees over 28 or so days. One has to have the declination correct for the exact time of transit. Secondly,unlike most other sources, the Moon is close enough for there to be significant parallax. On the meridian at a given location, the correction is a constant. In any other direction it is not.

As an experiment, the radio telescope was set to the declination of the Crab Nebula (+22 degrees), and the Moon allowed to go past. Each day the Moon advances about 51 minutes in right ascension, that is about 13 degrees. It is also changing in declination. Figure 16 shows the trajectory of the Moon against the stars.

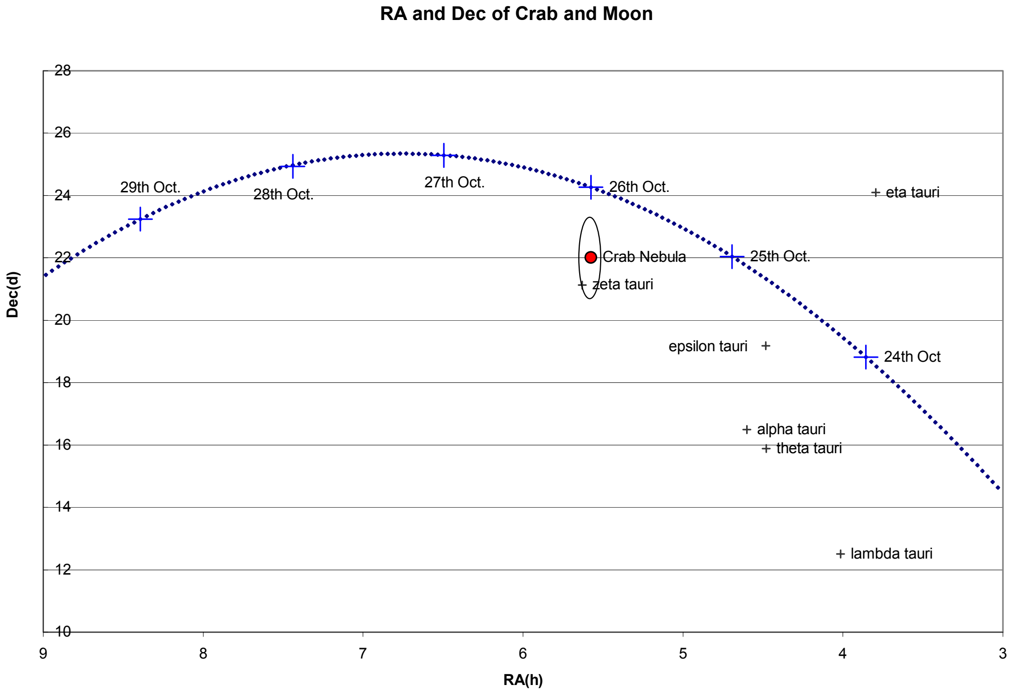


Figure 17: The computed trajectory of the Moon past the Crab Nebula in 2002. The main stars are also shown. The ellipse is the half-power beam of the antennas.

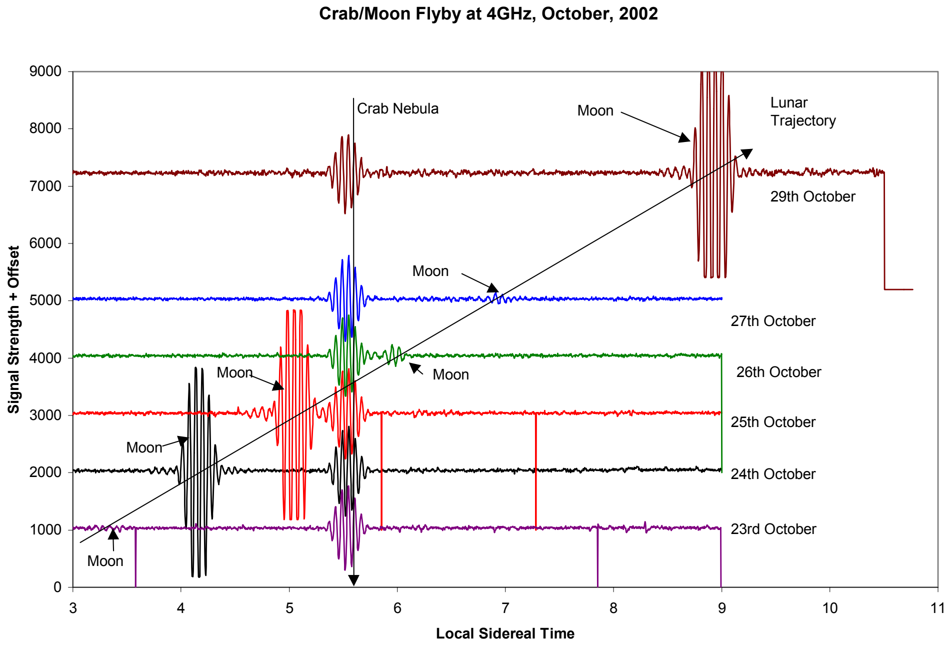


Figure 18: Multiple daily plots of the Moon moving past the Crab Nebula.

Although the closest approach is on the 26th October, 2001, the only day the Moon passes through the half-power beamwidth of the antenna is the 25th. On this day we would expect to see the full strength of the lunar radio emissions. It passes close to the antenna beam on the 29th. On the 25th and 29th, the receiver overloaded on the lunar emission strength. The lunar flux density at 7 cm wavelength had to be at least five times that of the Crab. A record of the changes in the average temperature over a lunation would be an interesting future project.

Final Comments

The credit for what this radio telescope can do must go to the consumer electronics industry. From the days of the early experiments at Goonhilly and Andover, Maine, we have come to TV broadcasting to back yard dishes initially 10-12 ft in diameter, now, at higher frequencies, about 2ft.It is now possible to lay ones hands on very low noise amplifiers to above 12 GHz at low cost. The technical changes that have take place between the early efforts by amateurs in the 1960's and now are almost unbelievable. I remember receiving a letter from John Smith in the late 60's. John was one of the fathers of amateur radio astronomy in the UK, Canada and other countries. This letter mentioned the perfection of a new radio telescope at Cambridge, that could get down to as little as 10 flux units. This small interferometer can get there too. It's amazing what a difference 40 years of technical improvements can do.

The version of this radio telescope using the open ends of the waveguide inputs to the low noise amplifiers as antennas must be a candidate for the smallest and least conspicuous radio telescope. This design could be used for monitoring solar radio emissions, and needs only a small garden or yard. With the large beamwidth, the antenna declination would need ajusting relatively infrequently, perhaps not at all it some correction curves are produced.

Radio telescopes working at centimeter wavelengths are not a replacement for the longer wavelength instruments more typical of amateur projects. At each different wavelength we see a different universe. It is only by making observations at different wavelengths could we get a proper picture of the universe. This is now an attainable ambition for amateurs. Already amateurs are experimenting with aperture synthesis. There is no final word to be made about where we can get with small radio telescopes. If it doesn't seem possible now, give it a year or two – or less.

By the way, that 10ft dish, given me by Tony Zonta, who started my interest in 7 cm wavelength, is not sitting doing nothing, it is becoming part of a new 408 MHz Phase Switched Interferometer, using a second 10ft dish scrounged from a TV repair man.

Acknowledgements

I have to thank Tony Zonta for pushing me onto this slippery slope. John Smith is also due much gratitude. He brought me to the point where I could do projects like this. My wife's Jacqui's enormous tolerance in letting me fill the garden with antennas and the house with electronics made all this possible. Bill Lonc also played a big part in stimulating interest. His antenna farm on the roof of St Mary's University in Halifax, Nova Scotia was something to see! Then of course there are the TV satellite TV installers of southern BC, who passed me discarded equipment rather than carting it to the dump, where most of it ends up.

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“The GB6 Catalog of Radio Sources”: Gregory P.C., Scott W.K., Douglas K., of the University of British Columbia, Canada, and Condon J.J., National Radio Observatory. This catalogue is also available in electronic form.

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