# A Correlation Interferometer for 408 MHz

**Ken Tapping, 29th November, 2001**

*e-mail address:* ken.tapping@nrc.ca

## Some Background

One day in the 1980's I was helping a visiting scientist get his experiment set up at a remote site to the west of Ottawa. This site contained the decaying remains of decades of radio experiments. Among some trees I found an old shed, crammed to the roof with yagi antennas, combiners, hybrids and many matched lengths of heliax coaxial cable. Many were broken, but mixed in with the debris were some that were intact or not too damaged. They had 14 elements, but were broadband, with a coupled array of dipoles of varying lengths. They were equipped with bazooka baluns that bore a label announcing they were designed to work between 400 and 430 MHz. Everything was equipped with Type N connectors. I managed to get eight yagis into my little Toyota Corolla, along with some lengths of cable and an assortment of combiners. This led to my plan to make a 408 MHz radio telescope. The opportunity came several years later, after we had relocated my research programme, and me, to Penticton, British Columbia.

## The Design Choice

The big question as to what type to make. The objective was to get somewhere near the sensitivity limit; I wanted to detect sources other than the Sun. Since the band 406.1-410 MHz is allocated by international treaty to radio astronomy, I assumed that here, in a relatively rural location, interference would not be too serious, and would be able to use a reasonable bandwidth.

Technology is improving rapidly; even relatively old components provide impressive performances. It is now easy to buy or build amplifiers with noise temperatures better than 45 K (a noise figure of 0.6 dB). Even if we take a worse case of a noise temperature of 75 K, plus (say) 50 K from the sky and ground, and have a receiver bandwidth of 1 MHz and a time constant of 1 second, the attainable sensitivity is very encouraging. The faintest identifiable source would produce an increase in receiver output comparable with the rms fluctuations in the receiver output, which are given by:

$$\Delta T = \frac{T_{sys}}{\sqrt{B\tau}}$$

where $T_{sys}$ is the system noise temperature in Kelvins, $B$ the bandwidth in Hz, and $\tau$ the time constant in seconds. We get a value of the rms fluctuation value, $\Delta T \approx 0.1$ K. If each yagi has a gain of 10dB[1], we can estimate the minimum flux density we would be able to receive with a single yagi:

$$S_{\min} \approx 8\pi \frac{\Delta T}{G\lambda^2}$$

where $k$= Boltzmann's constant = 1.39 x $10^{-23}$ joules per Kelvin, $G$ is the gain of the antenna (10) and $\lambda$ the observing wavelength (0.74m). These values indicate a sensitivity limit of about $8 \times 10^{-24}$ $w.m^{-2}.Hz^{-1}$ (800 flux units[2]), suggesting that even with a single yagi, a good sensitivity is possible – *in theory*. However, in practice, the theoretical limit is rarely achievable. Instabilities in the receiver system, observational requirements and the inevitable presence of various kinds of interference require some kind of signal processing. Whenever anything other than a simple linear process is applied to a flow of information in the presence of noise, some of that information is lost. This applies to radio telescopes too. These degradation factors range from $\sqrt{2}$ to 2 or even more, depending on the type. In addition, little bits of mismatch, nonlinearities, contact potentials, hum and such things will conspire to lose a little more.

In practice, radiometers built by amateurs and used in environments that are not interference-free are unlikely to achieve an overall degradation factor less than 2 or 3. This brings our limiting sensitivity to something like 1600 flux units, with a 1MHz bandwidth and a 1-second time constant. By using more than two yagis we can increase the net antenna gain by about 3dB every time we double the number, which would increase the sensitivity by the same factor.

For amateur radio astronomers and other who cannot locate their radio telescopes at optimum sites, interference will be a fact of life. This can range from weak, broad-band interference that is there all the time, to intermittent, narrow-band interference, with of course some broad-band, short, intense pulses from switches and other devices. In some cases reducing the bandwidth will avoid interference; however, this may increase susceptibility to intermittent, narrow-band interference. Using a longer time constant to recover lost sensitivity might not work. Many kinds of interference are not random phenomena, and won't integrate down with increasing integration time.

These rough estimates suggested that a sensitive radio telescope using these relatively small antennas would be achievable. The question is what type? One option would be to make all the yagis into a single, east-west, 8-yagi array, mounted along a pole. Suitable receivers for such a configuration would be the total power, Dicke, or Ryle Vonberg radiometer. Simple, total power receivers are easy to build but very difficult to make work. They are susceptible to the effects of gain variations, ground radiation and the problems in separating interference from the desired signals. The Dicke radiometer, by rapidly switching the receiver between the antenna and a matched termination, is good

---

[1] A 14-element yagi antenna at 408 MHz would be expected to have a gain of 13-14 dB. However, yagi antennas inherently have narrow bandwidths. Broad-band types can be made by using clever arrangements of the elements, but this is achieved at the expense of gain. Since their properties are more independent of frequency, the broad-band yagis are much more tractable.

[2] A flux unit, also referred to as a "Jansky", is $10^{-26}$ $W.m^{-2}.Hz^{-1}$.

$$S = \sqrt{W_E G_E}\cos(2\pi ft + \phi) \times \sqrt{W_W G_W}\cos(2\pi ft)$$

for reducing the effects of gain variations - if the termination is at (almost) the same effective temperature as the antenna. With the antenna temperature being a few Kelvins and the termination at (say) 273 K, in an ice bath, the imbalance in temperature would be worse than if we used just a total power radiometer. It is possible to balance a Dicke radiometer by horrendously mismatching the reference side. For example, I managed to balance the system by using a 10-ohm resistor as a reference load. This technique came in useful in the 327 MHz Ryle Vonberg radiometer I once made. This is one of the most fascinating types of radiometer. It is a Dicke radiometer that switches against a noise diode which is adjustable by changing the drive current. The output from the synchronous detector is fed through a DC amplifier and used to drive the noise diode. The receiver acts as a null detector. The astronomical data are obtained by recording the drive current to the noise diode. Using this "reference mismatch" technique it was possible to make the reference side appear colder than the sky, so that the noise source could add noise to balance the system. The stability of this radiometer was really good. However, a desirable feature of the design to be used in this project would be to make interference and sources clearly distinguishable; this led to the choice being to make an interferometer.

The so-called drift or adding interferometer, which uses two antennas connected in parallel to the same receiver, does indeed make sources easy to distinguish, because they make fringes at a calculable rate. However, they still suffer from all the gain instability of the total power radiometer. Moreover, if one antenna input is higher than the other, as is almost unavoidably the case, the fringes ride on top of the hump of additional signal from the higher gain input. They are nice examples when discussing interferometers, but hardly anybody uses them for serious observations. This leads one to the classical amateur favourite, the multiplying interferometer. There are two kinds: the phase switched interferometer and the correlation interferometer. I'd already experimented with phase switched interferometers so I decided to try the correlation design. One additional attractive factor is that in this type of radio telescope, the sound from the monitor speaker is not modulated by a switching tone. Solar bursts sound like solar bursts, and more importantly, different types of interference are easy to identify.

## Basic Theory of a Correlation Interferometer

In the correlation interferometer, there are essentially two separate receivers, one for each antenna, but <u>necessarily</u> sharing the same local oscillator (otherwise the relative phase information is lost). Instead of detecting the outputs from the IF amplifiers, the two IF signals, one from the east and the other from the west antenna are multiplied together. This can be accomplished digitally (which is the method used at most observatories), but it is simpler and almost as effective to use a double-balanced mixer as the multiplier.

When a source $\theta$ degrees west of the meridian ( *i.e.*, $\theta \equiv$ 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 $d\sin\theta$, from which we obtain the phase difference between the signals coming from the two antennas: $\phi = 360\,(d\sin\theta/\lambda)$ degrees. The correlator (a cheap, double-balanced mixer) performs the calculation:

Where S is the receiver output (assumed proportional to flux density), *W* is the power from the radio source collected by the antenna, *G* is the gain of the antenna preamplifiers and cable loss, and *f* is the observing frequency. The subscripts *E* and *W* refer respectively to the east and west antennas. If we multiply out the above we get

$$S = \sqrt{W_E G_E W_W G_W}\,(\cos\phi - \sin^2 2\pi ft \cdot \cos\phi - \frac{1}{2}\sin 4\pi ft \cdot \sin\phi)$$

All the expressions containing *ft* are at radio frequencies and cancel out in the mixer and the low-pass filter following it, leaving

$$S = \sqrt{W_E G_E W_W G_W}\,\cos\phi$$

This is the equation of the fringe pattern. The $\cos\phi$ term describes the fringes and the variation in antenna gain (*G*) with hour angle defines the envelope of the fringe pattern. In instruments such as this radio telescope, where the total amplification at radio frequencies is high, it is important to prevent radiation from cables carrying output from amplifiers, or from the correlator. If any of this power is picked up elsewhere in the circuit, at best the gain stability will be degraded; at worst the amplifier(s) will oscillate.

**The Design**

One objective was to see what could be achieved with a small antenna system using single or paired yagis: the sort of antenna possible within even small backyards. In addition, even though a baseline of several hundred feet is available, a short baseline of about 50 feet was chosen. Another reason for the short baseline is that the telescope would be used to observe the Sun. The fringe width is given by $\psi \approx 60\lambda/d$. To ensure we collect all the signal from the solar disc, it is necessary for the fringes to be broad enough to see all the solar disc with equal sensitivity. The Sun is about 0.5° across. To meet this need the fringes on the meridian should be around 3° wide. We can rearrange the fringe formula to calculate the antenna spacing corresponding to fringes of this size at an observing wavelength ($\lambda$) of 0.74 m. The formula becomes $d \le 60\lambda/\psi$. For $\psi = 3°$ between the antennas has to be less than about 15 meters - roughly 50 feet.

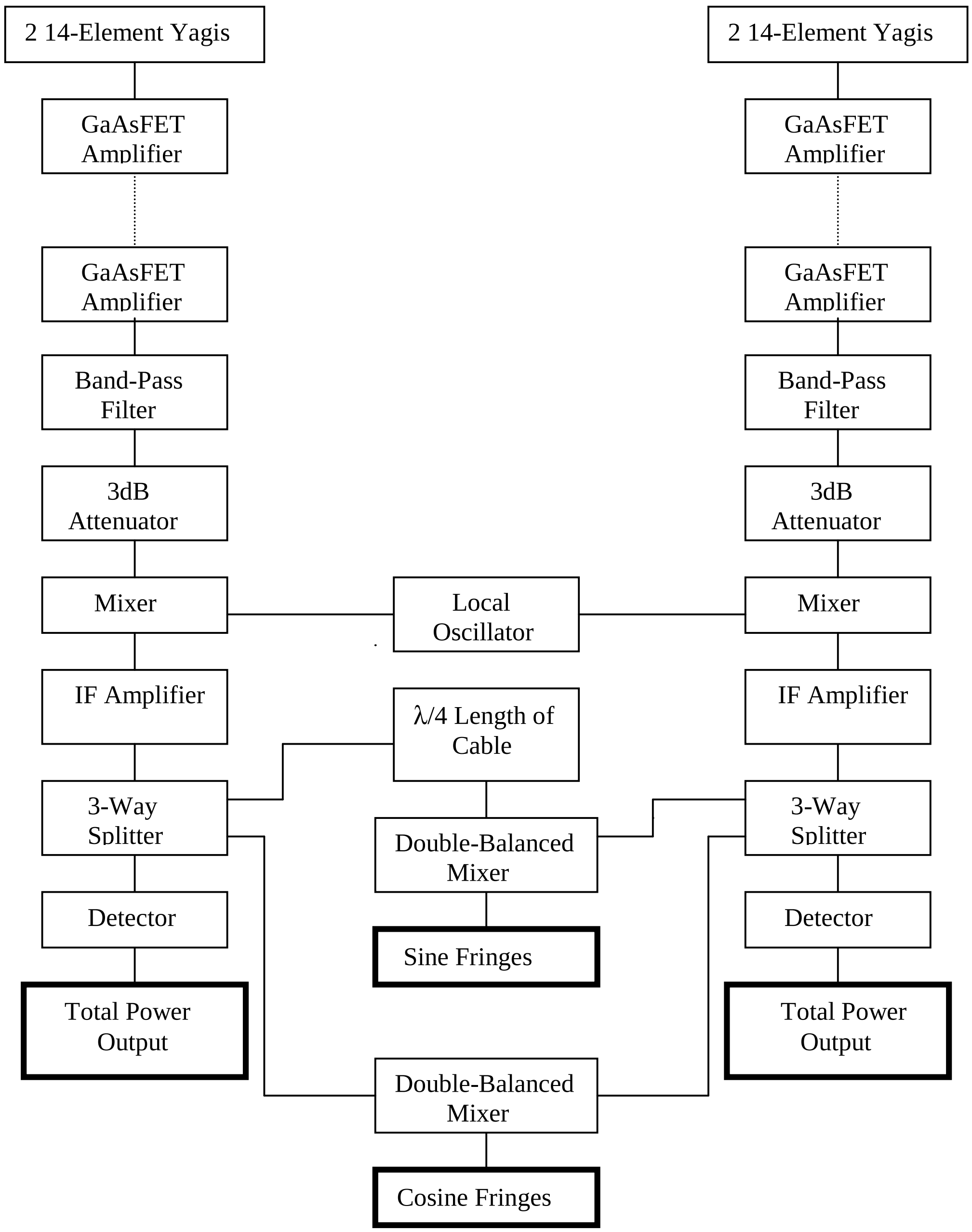
Two versions of the receiver were tried. The first, a more conventional design, was potentially more sensitive, but proved unusable at a location in line of sight with a town of 30,000 people, lying to the south and east. In both designs the baseline was about 50 feet, with each antenna comprising two 14-element yagis, a 2-to-1 signal combiner (a device that combines two signal channels into one while minimising mismatch and loss) and a GaAsFET (Gallium Arsenide Field Effect Transistor) preamplifier. The amplified signals are carried to the rest of the receiver by buried coaxial cable of type RG/8 [3]. Burying the cable is important for a number of reasons. The most important are: (1) The soil attenuates any leakage of signal from the cable. This could otherwise radiate into the antennas and degrade the stability of the receiver. (2) it reduces the temperature ranges to which they are exposed, reducing expansion, contraction and the consequent phase variations, and (3), it keeps the solar ultraviolet radiation away from the cables. Ultraviolet radiation breaks down the polymers in the plastics, causing crosslinking and making them brittle. The terrain made it impossible for the antennas to be in a precise east-west line, and the east antenna is about 10ft lower than the west one.

**Figure 1: The eastern end of the interferometer. The signals from the two yagis are combined in a 2:1 combiner. The box attached to the elevation axis contains a filter and the first GaAsFET amplifier. Mounting the yagis so that the axis is behind the reflector elements reduces the interaction between the antennas and mount.**

Each antenna of the interferometer consisted of a pair of yagis, coupled via a 2-port combiner to a low noise amplifier. The signals were fed by buried RG/8 coaxial cable to the rest of the receiver, where there was some additional RF amplification. Filters are included to minimize the amount of interference reaching the mixers. The IF frequency was 30 MHz and the bandwidth was a little more than 1 MHz. Since the first RF amplifier was to be outside, exposed to the elements, too much gain was to be avoided. A little feedback from the output cable run back to the antenna would be devastating to the gain stability and could even make the amplifier oscillate, especially with the likelihood of the amplifier characteristics varying with temperature. Another reason for not making the gain too high was to avoid adjacent-band interference driving the amplifier into non-linearity. It is not easy or desirable for the first amplifier to have too narrow a bandwidth or many tuned circuits because of the effects of temperature variations. However, the preamplifier had to have enough gain so that its noise output, reaching the rest of the

[3] This is a North American cable type; the nearest UK equivalent is UR-67. It is a 50-ohm impedance cable with a solid polyethylene dielectric, with a diameter of about half an inch, and uses Type N connectors

receiver through the 6dB loss in the cable, was still much larger than the noise generated in the rest of the system. That is, turning off the power to the preamplifers should cause the noise output from the detector to fall by a factor of at least ten. A preamplifier gain of 25dB gain was decided upon. The block diagram of the 30MHz IF version of the receiver is shown below:




To make it possible to avoid interference, the local oscillator is tunable. The mixers are commercial double-balanced mixers. They perform excellently but have a high noise temperature. The input signal has to be high enough to exceed (often referred to in radio astronomical circles as "swamping") this noise by at least several dB. Mixers are inherently and essentially non-linear. They therefore produce interaction products from all the signals reaching them. It is therefore essential to stop unwanted signals from reaching them; it becomes far harder to eliminate their effects after frequency mixing has been done. Additional 408 MHz amplifiers and two filters were installed at the receiver to filter the incoming signals and ensure that mixer noise was thoroughly swamped. Each antenna has essentially its own receiver. A common local oscillator feeds the two mixers. The 30 MHz (IF) amplifier had a gain of about 80dB (adjustable), and a bandwidth of a little over 1 MHz, but with very steep skirts at the edges of the band.

The output from each receiver is split three ways. One output from the splitter goes to a detector. This voltage is displayed on a meter; it gives a measure of the total-power output and is useful for setting up the system, for adjustments as needed, and for maintenance. Another output from each channel goes to a double balanced mixer that is being used as an analogue multiplier. The output is labelled "cosine fringes" in the diagram. This is the output that is recorded for usual observations. The "sine fringes" output is optional. Its use is discussed later, in the section of system calibration. The total power detector is used for setting levels.

The diodes in detectors and double-balanced mixers can give a square-law (output voltage proportional to input power) for signal levels up to around of –20 dBm[4] (10 μW). Typical diode detectors give about 1mV out per μW input. The baseline (quiet sky - well away from the Sun, Milky Way or other bright radio sources) detector voltage was set to between 10 and 25mV, which allows some headroom for observing strong sources while having a high enough voltage to avoid problems with hum and other low frequency interference in the post-detector stages. The power fed to the detector (between 10 and 25 μW) is given by:

$$kT_{sys}BG = P_{out}$$

or

$$G = \frac{P_{out}}{kT_{sys}B}$$

where $T_{sys}$ is the system noise temperature, $B$ is the bandwidth in Hz, $G$ is the net pre-detection gain in dB and $P_{out}$ the desired power fed to the detector and correlators. The detector voltages are indicated on panel meters.

If the antenna temperature is around 50 K, coming from the sky and ground, the total noise temperature at the input of the receiver is about 75 + 50 = 125 K. If the bandwidth

[4] A dB is a way to express a ratio. It is common to express power levels as the ratio with some reference power level. When this is done, dB's are used, with the reference unit added after the dB. The most common reference unit is the Watt (dBW) and the milliwatt (dBm). For example, 10dbW is 10 Watts, and -30 dBm is a microwatt (a thousandth of a milliwatt)..

is 1 MHz, and we want an input to the detector of (say) 15 μW, a net pre-detection gain of about 98 dB is required. Considerably more than this is needed in practice because of losses in cable and filters, conversion losses in the mixers, and the need to put 3dB attenuators between devices where interaction could degrade equipment stability or create other problems. For example, filters need to "see" a matched load at their inputs and outputs, but, somewhat hypocritically, may themselves present a matched load to the devices connected to them only in their designed operating band. This situation can easily be addressed by inserting a 3dB attenuator at the filter input and output. Mixers are notorious for presenting really complex (sic) impedances at their inputs and outputs, and should therefore never be connected directly to a filter. A 3dB attenuator should be included. This application of attenuators as buffers between devices has led to their also being referred to as "pads". Therefore, the gain budget has to include a gain margin to make up for the presence of perhaps several 3dB attenuators. The gain and power budget going through the receiver stage by stage is given below, including the presence of some attenuators:

| | | |
|---|---|---|
| **Noise Temperature** | **75 K** | **Boltzmann's Const** |
| **Antenna Temp.** | **50 K** | **1.40E-23 J/K** |
| **Bandwidth** | **1.00E+06 Hz** | |

| **Device** | **Gain (dB)** | **In (dBm)** | **Out (dBm)** |
|---|---|---|---|
| Low Noise RF Amplifier | 25 | -118 | -93 |
| RG/8 Cable Lead-In | -6 | -93 | -99 |
| Low Noise RF Amplifier | 25 | -99 | -74 |
| 3 dB Attenuator | -3 | -74 | -77 |
| Band-Pass Filter | -1 | -77 | -78 |
| 3 dB Attenuator | -3 | -78 | -81 |
| Mixer | -8 | -81 | -89 |
| IF Amplifier (Adjustable) | 80 | -89 | -9 |
| Power Splitter | -9 | -9 | -18 |

=================================================

**Net System Gain** **100 DB**

**Estimated Input to Detector** **18 μW**
**Estimated DC output from Detector** **18 mV**

Chart recorders have seen many years of use by amateur and professional radio astronomers. They are very convenient for making the data quickly visible and are simple to operate and maintain. However, unless one is lucky at an electronics junk store, chart recorders can be very expensive. The prices of ink, charts and other things one needs can also be rather high. Data analysis can be very tedious. They are excellent for equipment testing and development, but computer data logging systems are now inexpensive to set up, and the information is recorded in a way that makes it much easier to analyse, combine with other data, and to present in many different ways. Moreover, the data logging demands for radio astronomy are so undemanding that relatively old computers are perfectly suitable. In this project an ancient (genuine) IBM PC-AT, driven by an 8MHz 80286 has proved more than adequate. A compatible 12-bit A/D card was found in a junk box. All the software was written in Microsoft Quickbasic 4.5, which is a very potent language for applications like these.

The input voltage range for the analogue-digital (a/d) converter is –10 to +10 volts, which fits nicely with the output range of typical op-amps. One a/d bit is therefore equivalent to about 5 mV. The sampling filters used are 5 Hz, 5-pole Bessel[5] types. Suitable filter designs can be found in the various handbooks for amateur radio. For a post-detection bandwidth of 5 Hz and a predetection bandwidth of 1 MHz, the fluctuations at the detector or correlator output are about 0.002 of the average detector output. If this is 18 mV, the rms amplitude of the noise from the correlator or detectors is about 40 μV. It is good practice to sample with a resolution sufficient to resolve the output fluctuations by at least 2:1. To do this, the random fluctuations have to be amplified to about 10 mV before feeding them to the analogue/digital converters. Therefore, a voltage gain of about 250 is needed in the post-detection system of the receiver. This was done using a multi-stage DC amplifier. This uses an op-amp with a gain of about 20 and a time constant of about 0.01 seconds, followed by a 5-pole 5 Hz Bessel filter, and then another DC amplifier with a gain of around 12. The final amplifier has a switched gain adjustment and an output offset to make it possible to set the signal level in the middle of the operating range of the analogue/digital converter.

The initial tests looked encouraging. Successful observations of the Sun were immediate, but the interference was horrible, especially when the antennas were at low angles of elevation. Observations made using a borrowed spectrum analyzer showed very strong signals lying just outside the radio astronomy band, and small peaks of emission within the band. The skirts of the frequency response of the IF amplifier were just not steep enough to keep out the adjacent band signals, and, despite the excellent linearity of GaAsFET amplifiers, the adjacent band signals were too strong, and there were some signs of intermodulation. In addition, there were some narrow-band interfering signals present inside the band. It was obvious that although radio astronomy in the 408-410 MHz band might be possible at this location, overlooking the town of Penticton, one would have to live with strong adjacent band signals and 1 MHz Bandwidth was out of the question, and the preamplifiers needed additional protection.

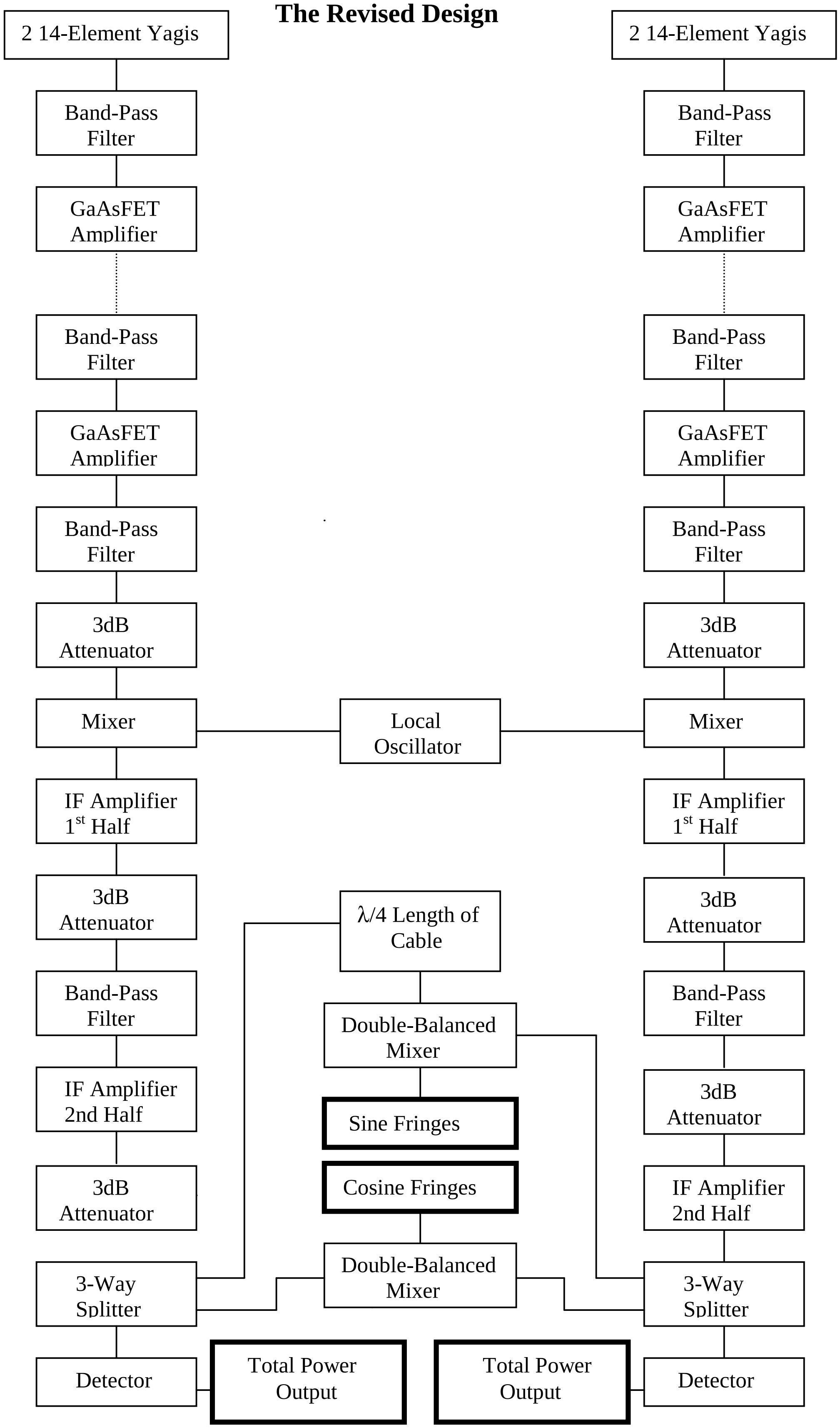
### Version 2

The solution had two main parts: the bandwidth of the IF had to be reduced, and additional filtering would be needed to ensure a really steep rolloff in sensitivity at the band edges. The second measure was installation of filters to protect each GaAsFET amplifier from adjacent-band signals. Putting a filter before the first amplifier in the system would be unfortunate in that it would degrade the noise temperature, but it looked highly advisable in this case.

The frequency of 408 MHz corresponds to a wavelength of 74 cm, which is a very convenient band for making filters. Several filters were made, each consisting of a brass rod a little less than half a wavelength long, grounded at both ends with a trimmer

[5] There are many kinds of filter, including Butterworth, Elliptical and Bessel, depending upon the mathematical approach to their design. Different types give flatter responses, or more constant phase shift across the pass-band, or other properties. A simple exponential (RC integrating circuit) is usable, but because these never really "cut off", one should have a time constant at least 10 times the shortest variation period in the input signal.

## The Revised Design



capacitor mounted at the centre. Input and output connections were made at opposite ends of the rod, about 1.5 inches from the end. The filters were mounted in some old, plated brass chassis, 12" x 2.5" x 1.5", originally intended for use in IF amplifiers. Half-wave, trough-line filters of this kind are described in detail in the handbooks of the American Radio Relay League and the Radio Society of Great Britain. Two were installed between the antenna and the preamplifiers. This is not good practice since it degrades the sensitivity, but was necessary.

Rather than modify a working IF amplifier, an old 10 MHz IF amplifier system was dug out of the junk box. Each amplifier consists of two units, a front end unit with about 45 dB gain, and a back end with adjustable gain, as high as about 55dB. The half-power bandwidth is about 250 kHz. Breaking the amplifier into two units made it possible to add additional filtering in between them. Two filters were made, each consisting of three loosely-coupled parallel LC resonators. The bandwidth was 250 kHz and the insertion loss about 1dB. Each filter is bracketed between 3dB attenuators. The addition of the filters before the preamplifiers degraded the sensitivity. Their loss was about 0.3dB. Since they are at ambient temperature the new noise temperature is:

$$T_{sys} = (L - 1)\, T_0 + LT_r$$

where $L$ is the attenuation (0.1dB gives $L$ = 1.08). If the ambient temperature of the filter, $T_0 = 300$K and $T_r$, the noise temperature of the preamplifier is 75K, we get

$$T_{sys} = 25 + 1.08 \times 75 = 106 \text{ K.}$$

The gain/power breakdown for the modified system is shown below.

| | | |
|---|---|---|
| **Noise Temperature** | **106 K** | **Boltzmann's Const** |
| **Antenna Temp.** | **50 K** | **1.40E-23 J/K** |
| **Bandwidth** | **2.50E+05 Hz** | |

| **Device** | **Gain (dB)** | **In (dBm)** | **Out (dBm)** |
|---|---|---|---|
| Low Noise RF Amplifier | 25 | -123 | -98 |
| RG/8 Cable Lead-In | -6 | -98 | -104 |
| Band-Pass Filter | -1 | -104 | -105 |
| Low Noise RF Amplifier | 25 | -105 | -80 |
| 3 dB Attenuator | -3 | -80 | -83 |
| Band-Pass Filter | -1 | -83 | -84 |
| 3 dB Attenuator | -3 | -84 | -87 |
| Mixer | -8 | -87 | -95 |
| IF Amplifier | 45 | -95 | -50 |
| 3db Attenuator | -3 | -50 | -53 |
| Band-Pass Filter | -1 | -53 | -54 |
| 3dB Attenuator | -3 | -54 | -57 |
| IF Amplifier (Adjustable) | 47 | -57 | -10 |
| Power Splitter | -9 | -10 | -19 |

==================================================

**Net System Gain** **104 DB**

**Estimated Input to Detector** **14 μW**
**Estimated DC output of Detector** **14 MV**

Reduction of the bandwidth by a factor of 4 halves the theoretical sensitivity. A further degradation comes from making the system noise temperature about 25% worse (106 + 50)/(75 + 50) = 1.25), making the sensitivity a factor of 2.5 times worse than the theoretical sensitivity of Version 1. Further degradation can be caused by the bandwidth of the filter at the receiver input being smaller than the bandwidth of the RF amplifier. To avoid this, the amplifier is followed by another, identical filter. With single yagis for the east and west antennas, the weakest detectable sources would have flux densities of about 4000 flux units. Using two yagis for each antenna reduces this by a factor of about two, to between 2000 and 3000 flux units. It is unfortunate that sensitivity has to be sacrificed in this way, but it is typical of amateur and other systems, where the location could not be chosen for minimum interference.

Success was immediate. It was possible to adjust the local oscillator to get between the strongest and most persistent interfering signals. The loan of a spectrum analyser really helped here, although it was not a necessity. There were, and are still, a few spikes each day from some unidentified local transmitter. The Sun produced an immense response, with little noise, and it was found possible to detect other cosmic sources, which, at 408 MHz are much weaker than the Sun.

## Observations

At 408 MHz, the brightest radio sources are as follows:

| **Source** | **Identification** | **RA (2000)** | **Dec (2000)** | **Flux Density (f.u.)** |
|---|---|---|---|---|
| Sun | Star | Varies | Varies | >250000 |
| Cassiopeia A | Supernova Remnant | 23h 23.4m | 58° 49′ | 4500 |
| Cygnus A | Radio Galaxy | 19h 59.5m | 40° 44′ | 4000 |
| Taurus A | Supernova Remnant | 05h 34.5m | 22° 01′ | 1250 |
| Virgo A | Radio Galaxy | 12h 30.8m | 12°23′ | 450 |

The first serious observations were of the Sun. In each case an observation consisted of the source drifting through the antenna beam and fringe pattern, which is directed towards the southern meridian. Only the antenna declination is adjustable.

If the rms noise fluctuations in the receiver output are around 3000 flux units, sources stronger than that should be detectable. The transit of the Sun shown below, taken in December, 2000, illustrates the enormous signal to noise ratio obtained when observing the Sun. The large sidelobes indicate that the pair of yagis used for each antenna are a little too far apart. Moving them closer would make the sidelobes smaller, but the main lobe a little broader. The sidelobes are no particular problem, so things have been left as they are.

In a normal multiplying interferometer, one would expect the narrowest fringes to occur close to the middle of the main beam, and the fringes in the sidelobes broader. The fringes in the sidelobes on either side of the main beam should be the same. For the interferometer discussed here, this is clearly not so. The cause is the interferometer baseline not being oriented east-west. The terrain available makes that out of the question. The east antenna is a few feet further north and about 10ft lower.

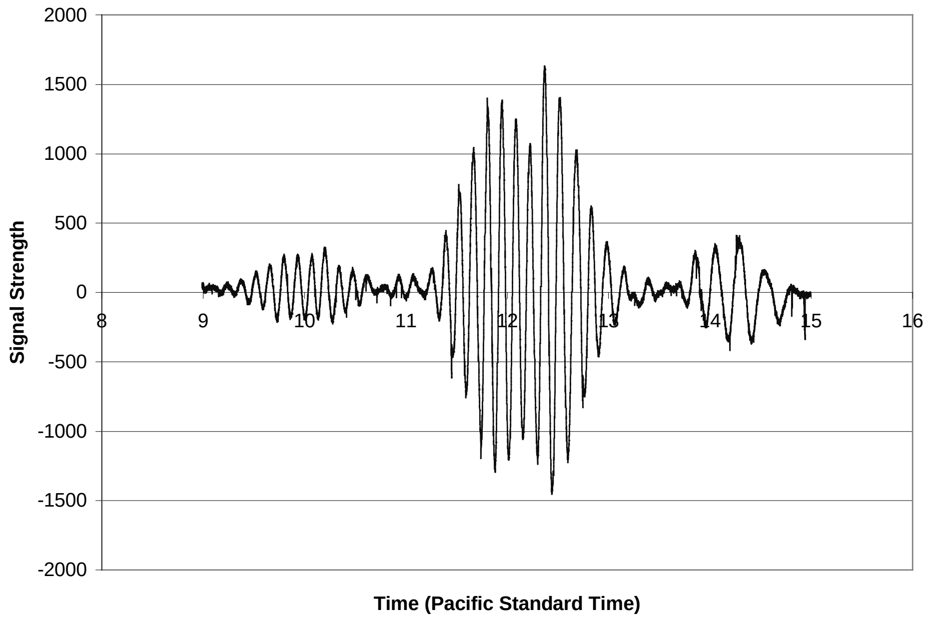



**Figure 2: An observation of the Sun. That the fringes in the two sidelobes have different rates indicates that the elements of the interferometer, although pointed south to catch the sources as they cross the meridian, are not on an east-west line. The terrain in the garden just didn't allow a conventional interferometer arrangement. The eastern antenna is north of the east-west line and about 10ft lower. Note the high signal to noise ratio. The time constant is about 0.2 seconds. The flux density scale is arbitrary.**

An additional problem with inclined baselines is that the fringes are not parallel with the meridian. Which particular fringe lines up with the centre of the antenna pattern will be a function of the declination. If one were making serious position measurements of sources, this could be a problem. There are two possible solutions. The most logical is to do some surveying and set up the baseline so that it is truly horizontal and oriented east-west. This is easy to do roughly, but very difficult to do accurately. Errors in baseline orientation are usually estimated by measuring the apparent position of sources of known position, and calculating the errors. These are then applied to correct the measured positions of other sources. Since the positions of the brightest sources have been established to high accuracy over decades of measurements made with the world's largest radio telescopes, this would be an academic exercise only. It is not necessary to do this unless the baseline is (unavoidably) so far from being horizontal and east-west that there are problems with identifying sources.

The radio telescope was obviously well-capable of making solar observations, but the design goal was to get other sources too. At 408 MHz, the strongest non-solar source in the sky is Cassiopeia A, a supernova remnant. An observation of this source is below.

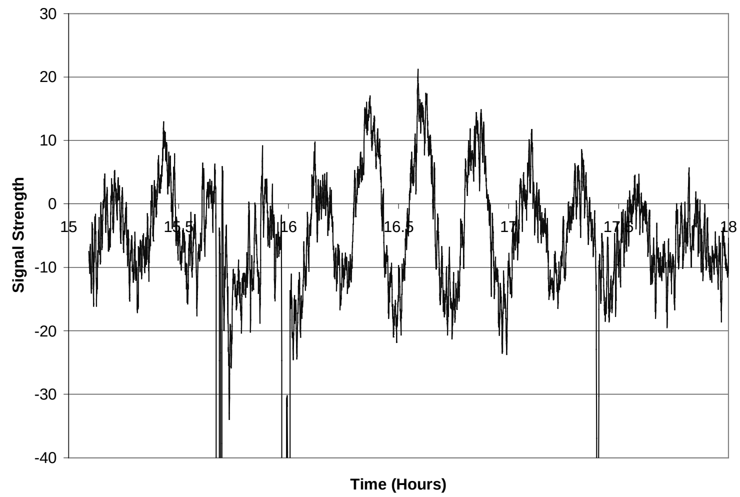



**Figure 3: A transit observation of the supernova remnant Cassiopeia A. Note the lower signal-to-noise ratio. The negative-going spikes are interference.**

The signal to noise ratio for Cassiopeia A is much poorer than was the case for the Sun. However, the fringes are clearly visible and would appear consistently in repeated daily observations. For the two-yagi interferometer design, the design objective was to detect the radio emissions at 408 MHz from Taurus A, the Crab Nebula. This source has only about a quarter of the flux density of Cassiopeia A, and would be more of a challenge. The figure below shows a typical observation of the Taurus A. The source was successfully detected. One of the records are shown below. The source record is the chain of weak fringes at the right-hand side of the figure.

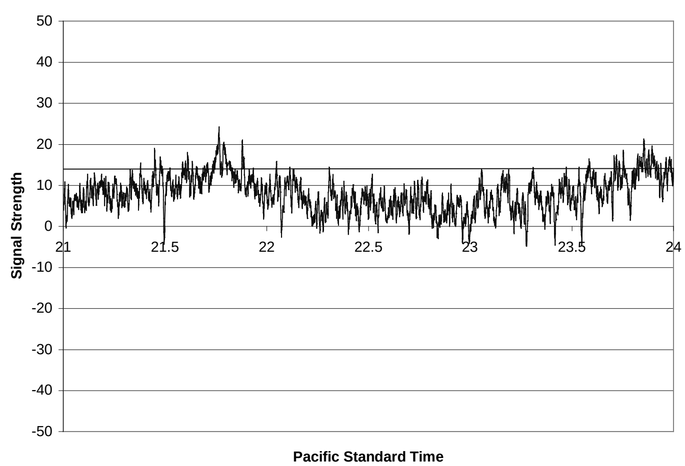



**Figure 4: One of several similar observations of the Crab Nebula. Note the scarcely-distinguishable fringes towards the right-hand side.**

After observations were made of the sources within reach of the interferometer, a longer-term programme was needed, one that could be highly automated. It was decided to make daily observations of the solar flux density at 408 MHz. This raised two issues: firstly, how would the observations be calibrated, and secondly, how would the flux density be extracted from the digitized fringe records, without any human intervention.

## Calibration

The simplest way to calibrate a radio telescope observation is to compare the radio emission from the source under study with that of a standard, known source that can be used as a calibrator. The problem with applying that technique to solar observations at 408 MHz is that there are no sources of comparable brightness. The brightest non-solar radio source, Cassiopeia A, is typically about 100 times fainter than the Sun. Taking into account the noisiness of the Cassiopeia A observation and the huge scaling factors involved, a calibration of the solar radio emission using Cassiopeia A would be scarcely better than a guess. A possible method is to switch in a 20dB attenuator whenever the Sun is observed, and switch it out when the antennas are pointed at Cassiopeia A. This is certainly possible, but is rather tedious and will need to be done often.

The standard calibration process used for single-antenna radio telescopes is to use calibration sources in conjunction with a noise generator installed at the receiver input which injects as required and small, known amount of noise into the receiver. This calibration noise source is calibrated periodically in an intensive comparison with celestial sources and then used as the calibration reference for observations.

Such a method could be used here, but there is the added problem of the radio telescope being an interferometer. The signal from a common noise generator would have to be split and then distributed, through identical lengths of cable to the two antennas, where they would be injected into the receiver inputs. However, to work, the signals have to arrive at the correlator in the receiver in phase. Taking into account temperature variations, the expansion and contraction of cables and other effects, getting and then keeping the injected noise signals in phase would not be easy. However, there is a way out.

The standard multiplying interferometer produces "cosine" fringes, having maximum amplitude when the signals arrive at the antenna in-phase

$$S_{\cos} = \sqrt{W_E G_E W_W G_W}\,\cos\phi$$

However, by adding a piece of semi-rigid cable a quarter of a wavelength long to one of the IF channels, so that there is an additional 90° phase switch to one of the IF channels compared with the other,

$$S_{\sin} = \sqrt{W_E G_E W_W G_W}\,\sin\phi$$

If we record these two signals, we can calculate the source flux density:

$$S = \sqrt{S_{\cos}^2 + S_{\sin}^2} = \sqrt{W_E G_E W_W G_W} \cdot \sqrt{\cos^2 \phi + \sin^2 \phi} = \sqrt{W_E G_E W_W G_W}$$

The quantity *S* is easily calculated in the computer. The record should look like the response of a source going through a single-antenna system, like the envelope of the positive fringes in the solar transit in Figure 2.Of course, this theory is based upon a true 90° phase shift between the channels, that the signals are of similar amplitude, and that the linearities of both channels are more or less the same. The result of errors in any of these quantities is the presence of fringes being superimposed upon the total power record computed from the sine and cosine components. The errors were diagnosed by simulating the correlation process using a computer while putting in amplitude and phase errors until the result looked like what was coming out of the radio telescope.

The noise injection system was installed so that with a 20dB attenuator in series with the noise generator (a solid-state device), the deflection was compared with Cassiopeia A almost every night over a month. This provided the opportunity to average the data to reduce the error, and also to look for thermal and other effects. Then, with the 20dB attenuator taken out, the noise source could be used to calibrate the total-power solar transit. The noise source is re-calibrated in terms of Cassiopeia A every few weeks or so.

**Observing Programmes**

Once one has got a radio telescope working successfully, and established what it can do by way of detecting sources, one has to consider two options for the future: (1) to modify the hardware and software to achieve better performance, and/or (2), to undertake some kind of long-term observing programme. Doing (1) delays the inevitable, but, at some point, unless one wants to scrap the instrument or give it away, one arrives at (2).

Single-antenna radio telescopes can be used to make maps of the Milky Way. It would indeed be possible to mount two dipoles and reflectors at the focus of a dish (at right angles and with one mounted a quarter of a wavelength behind the other), to form a single-antenna correlation radiometer. In this case, an initial step will be to point the antenna at the Sun and then add additional lengths of cable to one or other of the IF channels to maximize the output from the correlator (making sure the signals are in phase). This note is included here for completeness. Doing this would really be the subject of a separate project.

Interferometers are not good for mapping the Milky Way, they work best with discrete sources of small angular diameter. If using a small radio telescope of the kind described here, there are two projects that are feasible: monitoring the annual decay in the strength of the Cassiopeia A radio source (a couple of percent a year), or to monitor the day-to-day variability of solar radio emissions. The first project requires accurate calibration and precise measurements made from a relatively low-interference environment. If the interferometer described in this article were to be dedicated to such a project, larger antennas would be needed, to get a better source emission to noise ratio.

The most feasible long-term observing project available to amateurs is monitoring the Sun. Solar radio emissions are complex, highly variable, and very interesting. For that reason, a long-term programme of monitoring solar radio emission was decided upon. These started in 1998, when the first version of the interferometer started operation.

This project consists of observing each noon transit of the Sun and deriving an estimate of the solar flux density. This is added to a file. The actual transit is not recorded. The observations are handled by the computer. The only manual intervention is in occasionally changing the declination setting of the antennas, and in transferring data for analysis. A plot of the daily measurements is shown in Figure 5. In hindsight it might have been better to record each transit fully, then a permanent record of bursts and flares would also be available. However, additional hindsight has shown that if one records complex or large amounts of data, the analysis may not get done regularly or in a timely fashion, or perhaps at all.

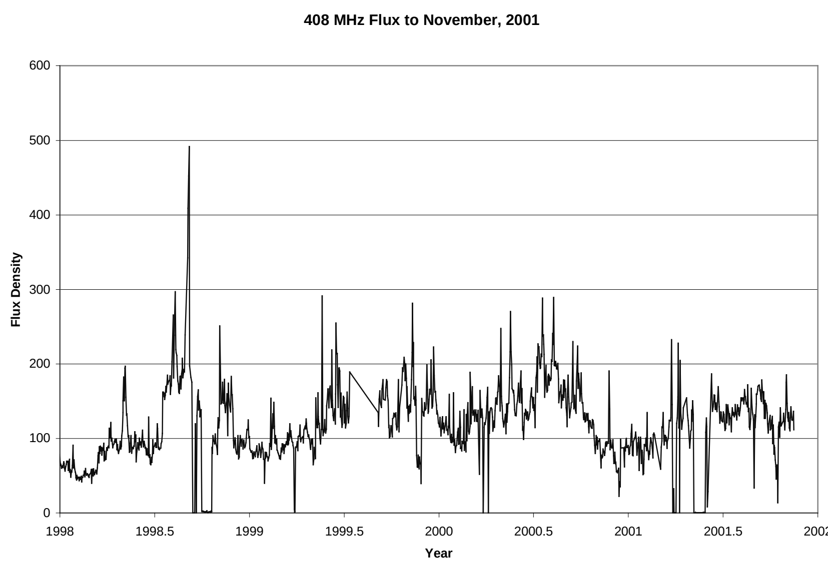



**Figure 5: Daily measurements of the solar flux density from 1998 to the present. The negative spikes are mainly hardware problems. The units of signal strength are solar flux units. A solar flux unit is $10^{-22}$ W.m$^{-2}$.Hz$^{-1}$.**

## The Next Phase

It is clear that the current system is more than adequate for making solar observations. However, the small antennas make reaching fainter radio sources a challenge, and the wide beamwidths of the yagis (about 35 degrees) make the system more vulnerable to interference. I recently acquired two 10ft satellite TV dishes. At 408 MHz they would offer a beamwidth of about 15°. The sensitivity using these dishes would be about

$(35/15)^2$ = 8.5 times higher than is the case with the yagis. The signal to noise ratio obtained on source Taurus A (1250 fu) would be obtained on sources with flux densities in the region of 150 fu. Virgo A would be a very easy source to detect, and Hercules A might be in reach. However, on the downside, to make a proper measurement, the antenna should be pointed within about a tenth of a beamwidth of the source being observed. Pointing a large antenna to about a degree is not a trivial exercise.

Replacing the yagis at some point is an attractive proposition. They are made of a mixture of copper, brass and aluminium, with some components soldered. This is a good situation for cathodic corrosion. Periodically stripping, cleaning, greasing and reassembling the antennas provides some protection. However, in the long term a simpler, less corrosion prone antenna system would be a good idea.

Correlation interferometers have the performance of phase-switched interferometers but without the complication of a phase switch and synchronous detector. The disadvantage is that essentially two receivers are needed, and that the detector output contains DC voltage components that carry important signal information (in a phase switched interferometer this information is carried at the switching frequency, and DC voltages can be ignored or rejected using capacitor coupling). Attention has to be made to electrical contacts in the low-level signal lines to avoid contact potential problems. Also care has to be taken to avoid hum and other pickup of spurious signals. However, these difficulties can be overcome and the correlation interferometer type as described here is worth trying in other radio telescopes.

## More Possibilities

Not everyone has access to the space and tolerance to set up radio telescopes with large antennas. The instrument described in this article can be used with much smaller antennas. A dipole and reflector for 408 MHz can be made out of 1/8" rod and be small and almost invisible. An interferometer using one of these for the east and west antennas would have a sensitivity about an order of magnitude less than is the case with the yagi pairs used here. This would still be enough for serious solar observations to be made. An advantage will be also that since the beamwidth of the antennas roughly 90 degrees, they could be set up to the declination of the celestial equator and left alone. They don’t need to be easily accessible. We once lived in a flat in Ottawa, and wanted to operate a small, 408 MHz interferometer. I screwed a dipole and reflector to the wall outside the kitchen window; this formed the east antenna, which I never touched after installation (we were on the 11th floor and I didn't like leaning out too far). The western antenna was mounted on the balcony, and was a 10-element yagi. This makes use of the property of interferometers, as can be seen in the formulae earlier in the article, that the net antenna gain is the geometric mean of the gains of the two antennas, i.e.:

$$G_{interferometer} = \sqrt{G_{East} G_{West}}$$

This offers the option of putting a dipole reflector at the end of the baseline that is inaccessible or conspicuous, and a larger antenna at the easier to get at, less conspicuous end. In this way one still gets much of the benefit of using a large antenna.


## Acknowledgements

The first version was built with the help of John Smith, who was visiting at the time. He also showed me how to deal with corrosion problems in antennas using his famous grease technique. It works. Thanks also to Phil Beastall for checking the draft. I must also thank my wife, Jacqui, for putting up with this and various other projects.


## References

### Books


*Radio Astronomy*, by J.D. Kraus, Cygnus Quasar Books, Powell, Ohio, USA, 1986.

*Radio Astronomy Projects*, by Bill Lonc, Radio-Sky Publishing, PO Box 3552, Louisville, Kentucky, USA, 40201-3552. ISBN 1-889076-00-7, 1996.

*Radio Astronomy for Amateurs*,by Dave Heiserman, Tab Books, Blue Ridge Summit, Pennsylvania, USA. ISBN 0-8306-4714-7, 1975.

The *VHF Handbooks* published regularly by the American Radio Relay League and the Radio Society of Great Britain.


### Magazine Articles


An excellent series of articles on the construction and use of a small radio interferometer were written by Swenson, and published in *Sky and Telescope*, in 1978, on pages 55, 385 and 475.


### Published Articles in Astronomy Journals


Smith J.R.: "A Radio Telescope for 136 MHz", *Journal of the British Astronomical Association*, **Vol. 75**, No. 4, 1965.

Smith J.R.: "Reduction of Radio Telescope Flux Density Recordings", *Journal of the British Astronomical Association*, **Vol 79**, 5, 1969.

Smith J.R.: "Amateur Radio Telescopes - Their Design and Adjustment. Part 1: Design", *Journal of the British Astronomical Association*, **Vol. 80**, 5, 1970.

Smith J.R.: "Amateur Radio Telescopes - Their Design and Adjustment. Part 2: Adjustment", *Journal of the British Astronomical Association*, **Vol. 80**, 5, 1970.

Tapping K.F. "Radio Astronomy for Amateurs", *Journal of the Royal Astronomical Society of Canada*, serialized in **Vol 72**, Parts L5, L22 and L38, 1978.