British Astronomical Association Radio Astronomy Group
Starbase and the Plug & Play Observatory

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21cm Spectrometer Development Team

Introduction

The British Astronomical Association (BAA) Radio Astronomy Group (RAG) originally formed when radio astronomy was largely unexplored territory for both amateur and professional astronomers. The professionals soon came to realise the immense value of observing at long wavelengths where, unlike at optical wavelengths, the dusty gas clouds that fill the spaces between the stars in our galaxy are generally transparent. A deluge of discoveries followed, while progress at an amateur level remained difficult to achieve. It is easy to speculate that this was disheartening for some experimenters. For whatever reasons, interest in amateur radio astronomy waned and despite the work of some notable individuals, the BAA RAG became dormant.

RF component and computing technology has moved a long way since those early days of valves and slide rules. It is now much easier for amateur radio astronomers to build backyard observatories that will yield detailed observations. The diehard band of radio astronomy enthusiasts in the BAA realised that interest was again building and eventually the RAG was officially reformed in 2004. Since that time a series of long-term plans have been developed and these are now being realised in the Starbase and Plug & Play Observatory projects. These projects will promote amateur radio astronomy by reducing the technical barriers to constructing a radio telescope and will build a forum for mutual support and co-operation to complete useful programmes of observation.

Radio Astronomy Basics

Sources

The Earth is constantly bombarded by electromagnetic radiation from extraterrestrial sources, although happily for us, the atmosphere filters out most of the damaging high-energy components. The electromagnetic energy that we wish to study has two basic sources; thermal and non-thermal.

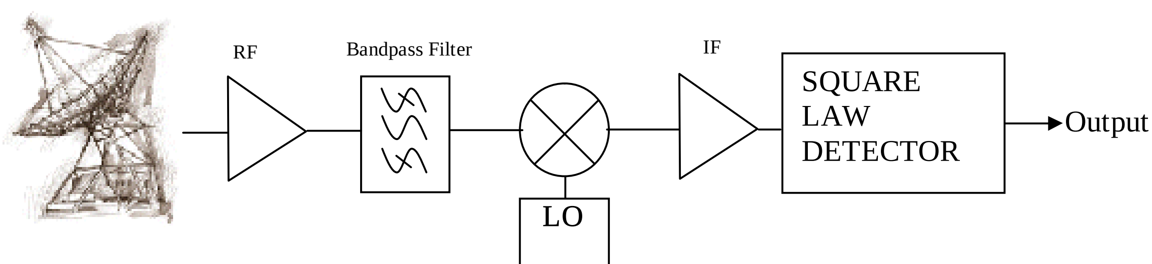
The classic thermal source is a Black Body radiator, the spectrum of which is only dependent upon temperature. The Sun and other stars are classed as blackbody radiators. Another thermal source is Free-Free radiation or Bremsstrahlung (braking radiation) that comes from the acceleration of electrons while interacting with other particles in ionised gases or plasma. There are also thermal sources with spectral line emissions that are quantum mechanical in nature. The spectrum of this radiation is specific to the type of atom or molecule originating the emission, it can therefore, yield detailed information about the components of the Inter Stellar Medium (ISM).

Non-thermal sources include Synchrotron and Geosynchrotron radiation, which are released when relativistic electrons are accelerated in a magnetic field. The spectrum of synchrotron radiation is dependent upon the speed of the electron and the strength of the magnetic field. It is polarised and the emission increases at longer wavelengths. Geosynchrotron radiation is associated with stars that collapse to become pulsars. Collapsing the mass of a star to only a few kilometres diameter causes the remnant to spin rapidly and generate an intense magnetic field that guides outgoing radiation into a narrow beam that sweeps past the Earth causing us to hear a pulse. Another non-thermal source are natural masers that can occur in molecular gas clouds or in the gaseous shells of old stars. The ‘pumping’ action of a high energy source near the gas cloud, amplifies weak spectral line emissions and they may reach solar brightness levels.

Observations

Optical astronomy studies radiation between infrared and ultraviolet wavelengths. The results are generally easy to interpret because they can be seen through the eyepiece of a telescope or in photographs. Radio astronomy looks at the longer wavelengths up to a few hundred GHz and the results are not so immediately accessible. Observations are taken as measurements and generally require processing and interpretation to extract useful information.

To detect extraterrestrial electromagnetic radiation a telescope is needed. The simplest instrument is a radiometer that measures the total energy received by the antenna at a given wavelength and within a given bandwidth.



The simple Radiometer

Although in principle the signal from the antenna could be amplified and detected, the high gains involved would make a stable system difficult to construct. The receiver is therefore normally a hetrodyne type. This type of receiver will detect continuum signals that are noise like in nature. It will detect spectral line sources but will not resolve them. Sensitivity is a function of receiver gain (including the antenna), noise performance and bandwidth. High gain, low noise antennas and RF amplifiers are therefore needed. The radiometer equation tells us that sensitivity is proportional to the square root of the bandwidth. A square law detector is used to provide a voltage output that is directly proportional to the received flux density.

$$\text{Noise} = \frac{T_{rec} + T_{sky}}{G \sqrt{BtN_p}}$$

The Radiometer Equation

The signals received by the radiometer are noise like and at a very low level. By example the increase in noise expected when pointing a practical backyard antenna towards the galactic equator will be about 0.15dB. This equates to an increase in antenna noise temperature of about 5K. Because they can be simply added together, noise temperatures are often used to characterise received signals and system parameters.

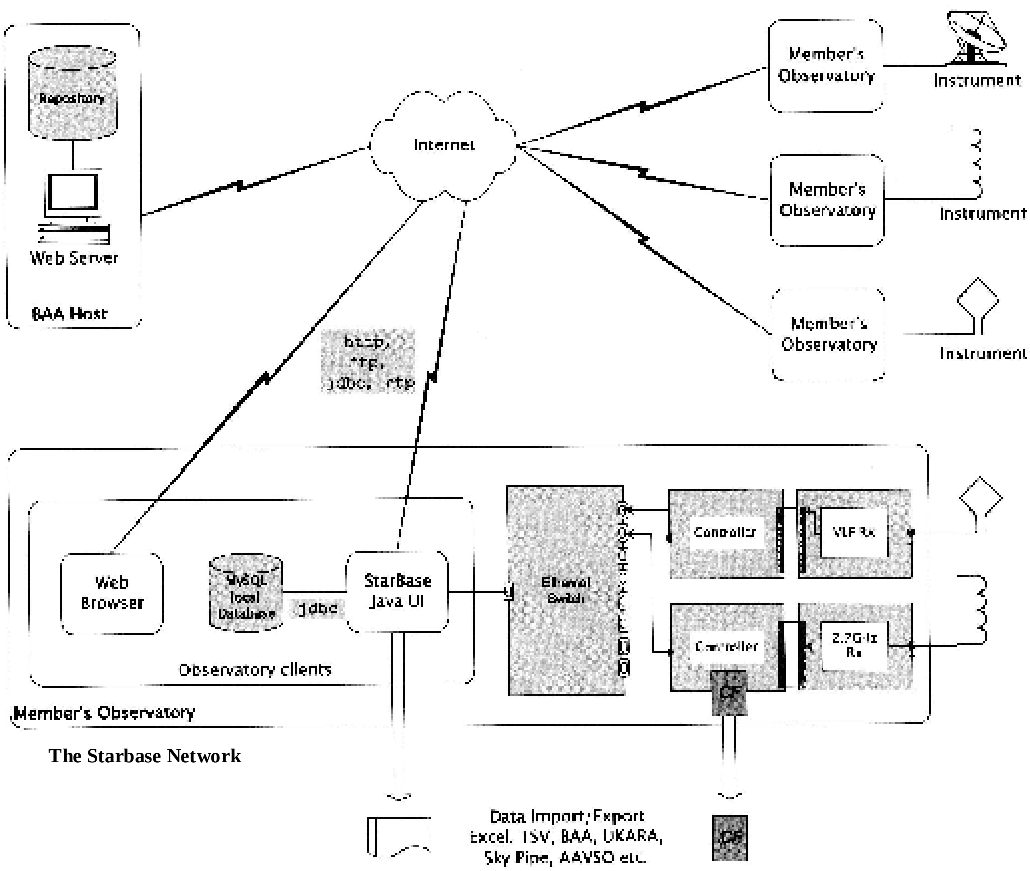
Flux densities from astronomical sources are often handled in another unit which by convention has been designated the Jansky (Jy). Where one Jy = 10^{-26} W m^{-2} Hz^{-1}.

There are a number of bright sources in the sky, but of course not all are visible from the Northern hemisphere. The Crab Nebula, the remnant of a giant star that collapsed in a supernova has emissions at 1.7GHz, with only one polarisation plane observed, of around 500Jy. This equates to an increase in noise temperature of about 1.4K producing with a typical amateur telescope, an increase in noise output at the detector of only about 0.04dB.

If the spectral line content of a source is to be measured, the bandwidth of the instrument must be narrow to reveal fine detail. This reduces the sensitivity of the instrument and requires more measurements to be taken while 'slicing' up the frequency band of interest. Banks of IF filters and detectors can be built to take simultaneous measurements, but it is more convenient today to generate I and Q signals at a low IF frequency, digitise and apply Fourier analysis using PC based DSP. Doppler shifted spectral lines reveals information about relative velocity. At 21cm a velocity of $1km^{-s}$ produces a Doppler shift of about 4.74kHz.

<u>The Starbase Project</u>

Starbase is the BAA RAG project to network the radio telescopes of its members and those operated from trusted sites. To do this a Web server running a central repository of



The Starbase Network

observational data is being set up, accessible to members via a secure Internet link. Observers will store measurements locally in their own database and then submit chosen data to the repository. In this way data can be made available to other observers and centrally archived for future reference.

The core of Starbase is an SQL database project with a Java user interface and it is largely the brainchild of Dr Laurence Newell, the RAG co-ordinator. This part of the development is well advanced but has yet to interface to the Plug & Play Observatory controller. If the grand scheme works as planned, users will be able to configure and use a number of instruments at their own location, store data and analyse it, all within the same package.

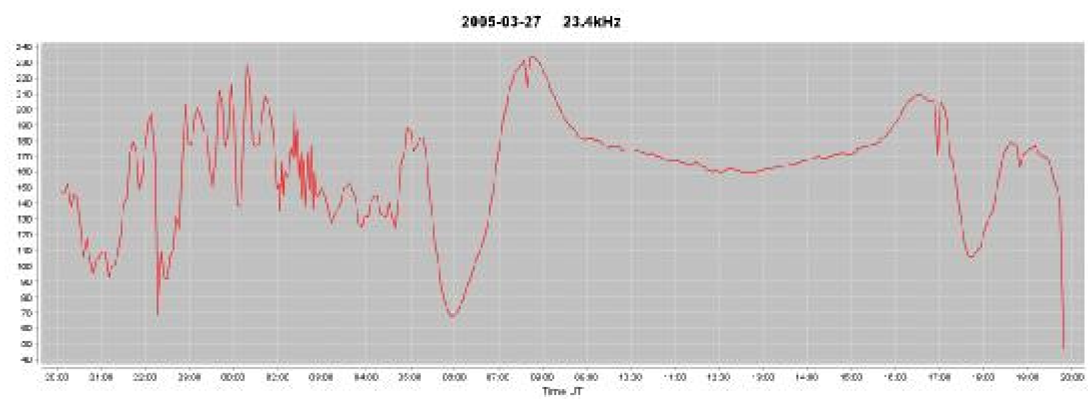
The Mullard Radio Astronomy Observatory (MRAO) at Cambridge is currently restoring a 151MHz telescope, known as the Cambridge Low-Frequency Synthesis Telescope (CLFST). Due to the efforts of a BAA RAG member Peter King, MRAO has agreed that a portion of the telescope can be used by the RAG and a Starbase interface installed. Data from this telescope should therefore be available alongside that from members' own installations. Observations at 151MHz are planned, including the study of Flare Stars.

The Plug & Play Observatory Project

Novice amateur radio astronomers are unlikely to have the facilities to build their own telescope from scratch. The goal of the Plug & Play observatory project is to provide the building blocks for a series of instruments each capable of linking to the Starbase network. A standardised controller module is being developed into which the observing instruments will connect. Currently there are projects running for the development of three different instruments:

The VLF Receiver

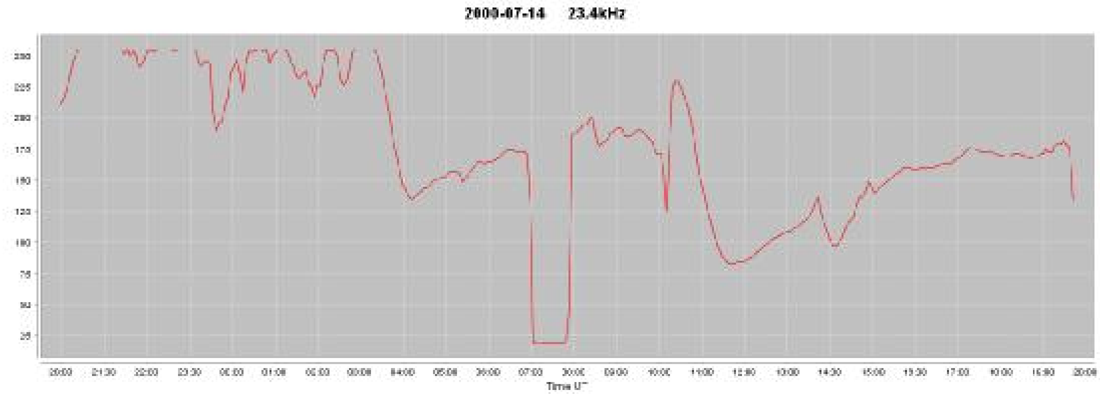
The VLF receiver is an Earth sciences instrument used to study the ionosphere. The ionosphere is sensitive to changing levels of radiation reaching it from the Sun. In particular, the D layer reacts very quickly to the X-rays associated with solar flares. Radio waves below about 30kHz will propagate as a guided wave between the Earth's conducting surface and the D layer. Any change in ionisation will therefore alter the radio transmission path and this provides a means of detecting Solar X-ray events from the Earth's surface.



A Quiet Sun (Peter King)

The RAG VLF receiver operates between 10 and 30KHz using a tuned loop antenna. Fortunately, in the frequency band of interest there are a number of high power research and military transmitters that can be monitored. A received signal is detected and integrated to remove the effects of modulation. If the DC output of the receiver is connected to a recorder or PC with logging software, the diurnal properties of the ionosphere can be plotted.

When a solar flare occurs, the effect is to increase the loss of the D layer causing the level of received signal to fall. The shape and duration of the changes in transmission path give some indication as to the nature of the flare. The first plot shows an observation for a 'quiet' Sun, where signals through the night fluctuate widely, but when the Sun rises the transmission path settles down and changes slowly as the altitude of the Sun rises and then falls towards sunset.



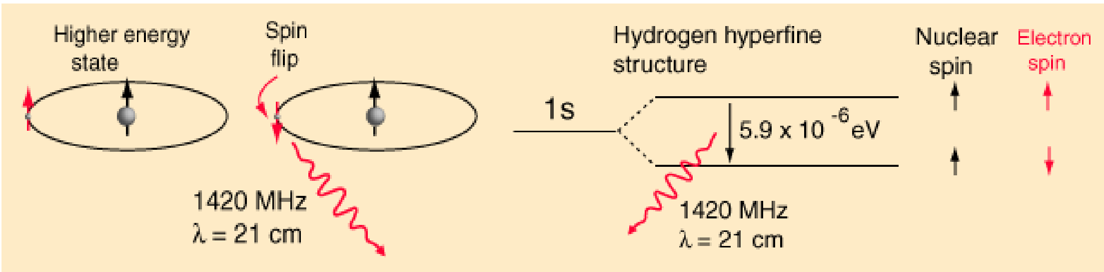
Effects of a Major Solar Flare (Peter King)

The plot of a flare event shows the transmission path being drastically affected and taking a long time to recover. The VLF receiver is a simple TRF design by Peter King who has been making observations for a number of years. Production versions of the receiver will soon be available.

The 21cm System

The Choice of Frequency

The receiver for 21cm is centred upon 1420.40575MHz because clouds of neutral hydrogen that coalesce due to gravity in our galaxy radiate a spectral line. The radiation source is a quantum mechanical effect.



Hydrogen atoms in the clouds receive little energy and are at their lowest energy state, known as 1s. Trying to achieve an even lower energy state, the spin state of the single electron in the hydrogen atom may spontaneously flip and reduce the energy of the atom by a closely spaced level in the hyperfine structure. To lose the energy, equivalent to 5.9×10^{-6} eV, a photon is emitted at 21cm. The huge volume of hydrogen in these clouds makes it possible to detect the emissions over galactic distances.

The study of the hydrogen clouds at radio frequencies is important because interstellar dust blocks UV and visible radiation. In the early part of the 20th century astronomers discovered that stars form into galaxies that may take on a variety of different shapes. The Milky Way distribution of stars gave a clue that the Sun was part of a local galaxy, but astronomers could not determine its shape.

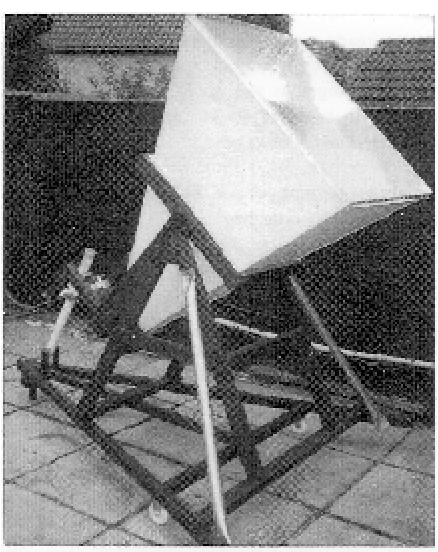
A survey of the sky at 21cm reveals not only the simple presence of hydrogen. When Doppler shift measurements of the spectral line are made, it is possible to also show that the gas clouds are moving. Our galaxy slowly rotates around its centre of gravity but the rotation is not uniform, the centre rotating faster than the outer regions. Therefore when we look in different directions from our position in one of the outer arms, we see different relative gas velocities.

M71 – A Spiral Galaxy (Courtesy NASA)

When the velocity distribution of hydrogen in clouds was mapped in the late 1950s, clues were obtained that pointed to a spiral structure for our galaxy. Later measurements of various molecular spectral lines in the gas clouds confirmed that our galaxy has four spiral arms and other short arm segments. Our sun is located on a short arm segment called the Orion Arm because it contains the Orion Nebula. The Orion arm is bordered by two major spiral arms, the Sagittarius and Perseus. The other arms are called Centaurus and Cygnus.

21cm Antenna

Antenna performance will be the main limiting factor for amateur observations. There are two obvious contenders for antennas at 21cm, the parabolic reflector and the horn. For the simplest observations the antenna does not need to track a source. It can be set in elevation and the rotation of the Earth will sweep it across the source to be measured. The gain of practical antennas is relatively low and they have a resultant wide beamwidth. Pointing accuracy will not therefore, need to be tightly constrained.



Colin Clements' Pyramidal Horn

Up to a gain of about 23dB at 21cm, the horn antenna shows some advantages in simplicity of construction. The horn has no obstructions in the aperture and should as a result exhibit a lower noise temperature than an on-axis parabolic type. Much above this arbitrary figure the conventional dish becomes more practical. Prime focus satellite dishes are available at moderate prices up to 1.8m in diameter although these generally have a solid reflector and will suffer more from the wind loading. They will therefore need stronger mounts than a mesh design, which work well at 21cm provided the mesh size does not exceed about 1/20λ. The amateur radio hobby can provide many designs for small DIY dishes and kits for a mesh design are available. The RAG will try to make a solution available for the non-technical builder, but it is an area where individuality is bound to excel.

The antenna temperature of a backyard telescope will to be affected by local thermal sources such as buildings and trees. Practical experiences show that dish spillover will limit the usefulness below about 35º elevation.

Low Noise Amplifier

The low noise amplifier (LNA) will need to be a high gain device to overcome the secondary noise contribution of the antenna feeder. Professional telescopes use cryogenic cooling to reduce the noise contribution of the amplifier but this is not feasible for the amateur. Fortunately, due to the satellite receiver and mobile telephone markets, there are many low noise microwave semiconductor devices available today. The design in development uses an ATF 54143 P-HEMT FET with a claimed noise figure of 0.3dB at 1400MHz. In a two stage design a monolithic amplifier I.C. will be used to achieve an overall gain of around 34dB. The datasheet of the ATF 54143 shows that when cooled to -40ºC the noise figure of the amplifier falls to about 0.2dB. An interesting future development would be a Peltier cooled LNA first stage.

Unless the LNA is mounted at the antenna, the carefully engineered noise figure will be compromised by feeder loss. The LNA will therefore need to be environmentally protected. To calibrate the system, it is also likely that a noise generator will be housed with the preamp.

The 21cm Receiver

The first generation BAA RAG 21cm receiver will be a conventional double conversion design with IFs at 151 and 38MHz. These frequencies have been chosen because they are protected for radio astronomy and may themselves be used for making observations in the future. Reuse of equipment is therefore a consideration.

Like all receiver systems the design of the telescope is a compromise between noise figure and dynamic range. In this case the balance is tipped heavily towards the need for a low noise receiver. It is necessary to introduce high gain at the LNA to overcome the noise contribution of the feeder. High quality foam cables are not financially viable. It would be possible to mount the downconverter(s) at the antenna, but this brings problems with thermal stability and environmental housing.

Interference may pose a problem when making measurements and this will depend to some extent upon the geographical location of the observatory. There are many terrestrial and satellite systems operating in the region of 1420MHz, GSM, GPS, Glonass, Meteorsat, Gallileo and Iridium to mention just a few. At the receiver image frequency around 1.1GHz there are some very high power radar installations operating for air traffic control and weather forecasting. Normal professional practice would be to approach a manufacturer for a good quality multi-section filter at the signal channel 1420MHz, but cost rules this approach out, as it does the normal practice of placing the filter between isolators.

When the project left the back of the envelope, a major constraint was the lack of test equipment. A signal generator, spectrum analyser and power meter were available for making spot frequency measurements, but this would be tedious when testing filters. A better solution was made available in the shape of a Wiltron 6409 scalar analyser, generously loaned to the author by Telnet in Coventry (www.telnet.uk.com). This instrument has a dynamic range of about 60dB at frequencies between 10 and 2000MHz. It is therefore an invaluable tool for testing all the filters in use at RF and IF. British Telecom (BT) has also kindly donated equipment including a 1.5GHz spectrum analyser and some industrial PCs that will be used for the data repository.

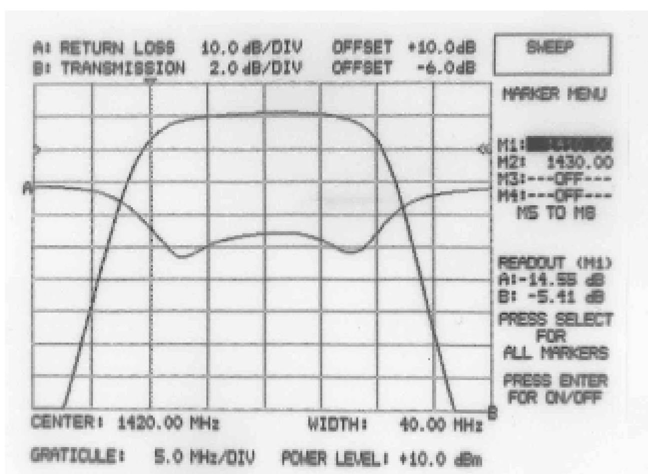
To simplify receiver construction, plans were first laid out around the use of microstrip filters at 1420MHz and a first I.F. around 400MHz to reduce the signal filter specification for rejection at the image frequency. There was a second perceived advantage that commercial filters appeared in catalogue listings for the I.F. A small number of microstrip interdigital filters were fabricated and it became clear that these low Q printed filters did not have the shape factor required. It was also a design aim for the filter to be flat to 0.1dB across the passband and with the production facilities available, this did not seem reproducible using printed filters. The proposed use of commercial 400MHz I.F. filters also suffered a setback when suppliers were approached. The filters were not readily available in small quantities and RoHS was in any case reducing the manufacturers' range of components.

The use of conventional filter engineering was then assessed and a 'proof of concept' filter constructed in a box made from 1.6mm FR4 PCB material. The filter was designed using a C++ program available on the Internet from the WA4DSY amateur radio website. The proof of concept filter performed well enough for a properly engineered version to be constructed. This filter forms part of the electrical prototype design and it is performing almost exactly as predicted by the design program.

The use of capacitively loaded air lines and the inevitable tuning required for every production device, will create the need for more resource when limited production commences, but more seriously as far as finances are concerned, it will create the need to retain suitable test equipment for an indefinite period.

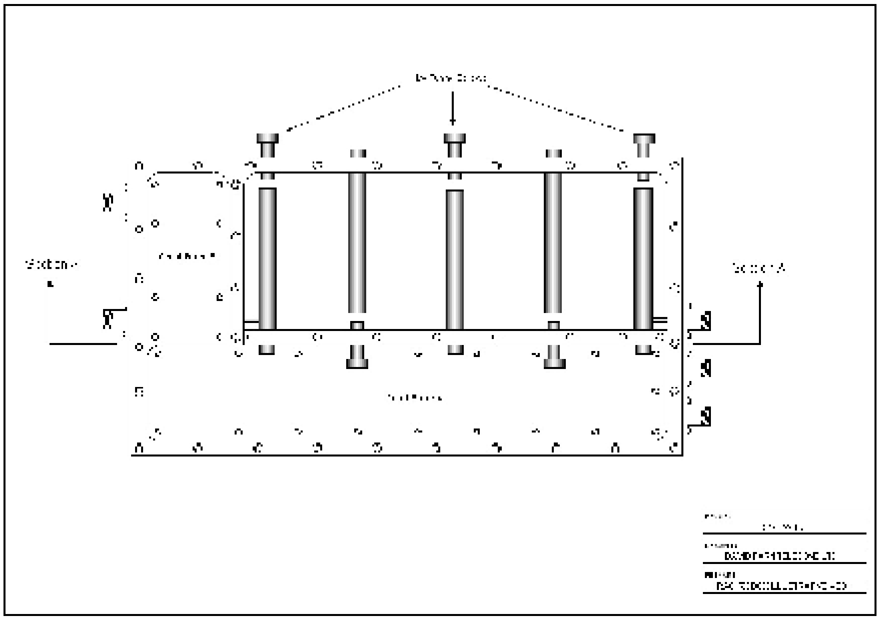
The production concept for the downconverter is a milled aluminium housing that will integrate the electronics and filters. This should improve reliability and reduce the connector count.

It was decided not to integrate the local oscillator into the same housing as the downconverter. At some stage a synthesised LO may be required and the flexibility of separate units allows for this development.



1420MHz Filter Response

It was realised that the same housing could be used for both the downconverter and the LO. This simplifies ordering of custom parts and should reduce cost. Drawings for a production version of the downconverter have been produced and quotes received for an NCM milled box. Production PCBs will be professionally produced with plated through holes for grounding, leaving only an assembly and alignment task.



The downconverter from 1420 to 151MHz is conventional, but has been designed to be reproducible in small batch quantities (10 to 15 units). It uses mainly 50 ohm MMIC amplifiers from Mini Circuits to provide gain and isolation between stages while offering good broadband impedance matching. The main channel filter is a five element interdigital design chosen to be a compromise between physical size and performance. Ideally, drop-in or SMD isolators would be placed at the input and output of the filter, but cost is prohibitive. It is hoped that the use of resistive attenuators and the good impedance match of the MMICs will prove adequate. The frequency mixer is also supplied by Mini Circuits and this is terminated by a simple diplexer.

IF Amplifier

The IF amplifier should benefit from work already done on the 2.7GHz receiver. After conversion from 151MHz to 38MHz there will be a high gain amplifier strip. A programmable attenuator will provide the gain control mechanism, the receiver does not have any form of AGC.

Detector Module

The design of the detector module is still under discussion. For the 21cm receiver a square law detector is required and has been investigated using a low barrier Schottky diode. Alternative log I.C. detectors are also under investigation.

Following the detector there will be some form of integrator with variable time constant. This is necessary to smooth the random variations of the received noise signals. Typical time constants would be between 0.1 and 100 s. The detector module will also feature a V to F converter to allow for integration by pulse counting.

The 11cm System

The Choice of Frequency

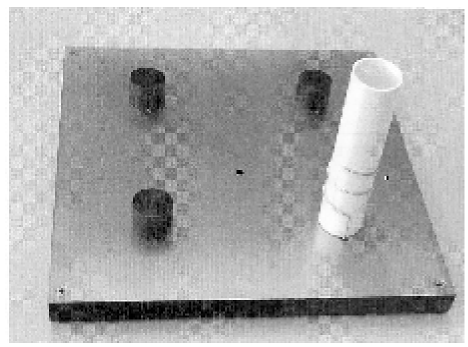
The 11cm system is being designed primarily to study solar phenomena. It will be centred on 2.695 GHz, which is a protected radio astronomy band. Solar emission at this wavelength is very bright and easily detected making it a good place to start for beginners. Measurements at 11cm give an excellent correlation with those at optical and soft X-Ray wavelengths.

Using the 11cm radiometer, it will be possible to study the 'S' component of solar radiation due to the movement of active areas through the 27day solar rotation period and microwave bursts associated with the onset of solar flares.

When the instrument is equipped to make spectroscopic studies it will be possible to study the frequency drift of the peak solar emission as the outbursts progress. The possibility exists of doing some original science in this area.

11cm Antenna

Although standard horn or parabolic type antennas may be used with the 11cm receiver, the initial purpose of the system is as a radiometer for solar observations. An array of four stacked and bayed helical antennas is being prototyped for this purpose. Using 25 turn antennas the gain should exceed 20dB and although the pattern of these antennas will not be clean, noise energy received in the sidelobes will be too far down on the signal from the Sun in the main lobe to cause significant errors. The resulting antenna should be compact and more easily steered than a horn or dish if fully motorised tracking is required.



The Prototype 11cm Antenna Array (Terry Ashton)

The 11cm Receiver

The 11cm receiver design follows a conventional format. An LNA using a low noise HEMT device will be used to set the system noise figure. Two designs of signal channel bandpass filters have been tested, a printed multi section hairpin on FR4 PCB and a capacitance tuned cavity resonator design.

The 11cm receiver is currently planned to have the same IF arrangements as the 21cm receiver with stages at 151MHz and 38MHz. A downconverter to 151MHz has been prototyped using an anti-parallel diode mixer fed by a crystal controlled local oscillator and a 38MHz IF amplifier has also been built and tested. The detector module will be the same as used for the 21cm system.

The Real World Challenges

Technical challenges besides, probably the most thorny problems that will threaten the success of these projects are financial, particularly cash flow and the impact of legislation. The designers are aware of RoSH, but it is not yet totally clear how the group can fulfil CE and WEEE. As yet undeterred, progress will continue with the various developments until working systems have been demonstrated.