Weak Signal Detection of Virgo A

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In this paper I will show how amateur radio astronomers can detect extragalactic objects, such as the peculiar object known as Virgo A. In presenting this at the 2012 EME Conference I hope to encourage those who already have the skills and equipment to operate on EME to consider using their equipment to make observations of radio astronomical objects.

This paper has two components:

1. **Astronomy** – where Virgo A is in the sky, its physical nature and the expected signal strength and radio frequency spectrum.
2. **Measurement Equipment** – how to choose the frequency at which to observe, what antenna to use, the receiver, setting up an interferometer and finally the measurements made of Taurus A and Virgo A.

The Nature of the Virgo A Source

Virgo A is a giant elliptical galaxy more than 3 times the diameter of the Milky Way. It is one of the most remarkable objects in the sky, as it has a very large and strange jet of ionised matter projecting from it. Virgo A is also very massive, estimated to be 200 times the mass of the Milky Way. It is suspected to have an active galactic nucleus (AGN) where some extremely energetic process is producing the plasma jet in which particles are travelling at relativistic speeds – in other words, close to the speed of light [1].

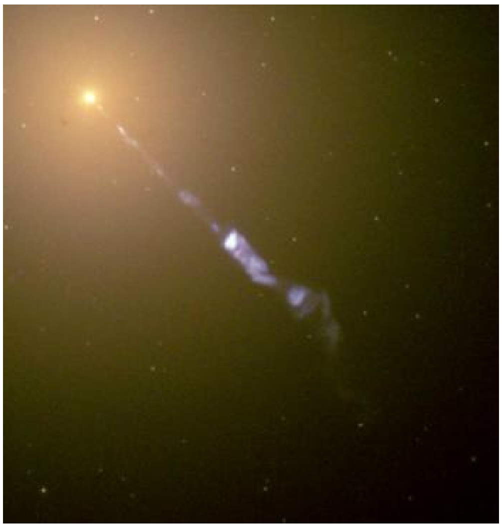

Figure 1: Virgo A with its plasma jet

The plasma jet is responsible for the bulk of the radio emission from Virgo A and has been mapped extensively by professional radio astronomers using sophisticated instruments such as the Very Large Array situated in New Mexico. The energy source for the jet is thought to be a super massive black hole (SMBH) near the centre of the galaxy.

There is considerable speculation about super massive black holes, and the physics of jet generation is not yet well understood. However some indications of its mass and size have been published. The Virgo A SMBH is thought to have a mass of ~6 billion solar masses and to have an accretion disc diameter larger than the orbit of Pluto. It is rotating very fast at a rate of roughly 1,000 km per second and may be displaced from the galactic centre of mass by about 82 light years. It has been conjectured that this offset has been produced by reaction from the jet. The rotation of the SMBH drags a strong magnetic field around with it and this creates very strong electric fields in the jet, which in turn accelerates particles (electrons & positrons) to relativistic speeds. The relativistic particles in these very strong E and H fields radiate by the synchrotron emission process.

Synchrotron emission has been widely understood for many years and is one of the main mechanisms by which astronomical objects radiate electromagnetic energy – including radio waves. It is a special case gyro-cyclotron radiation, where the charged particles that encounter a magnetic field do so with velocities close to the speed of light.

In this situation the normally dipolar radiation pattern of a charged particle is swept forward in the direction of the particle velocity and the magnetic field. This results in an intense beaming of radiation along the direction of the field. The radiation is polarized (circular or linear) depending on the observer's line of sight to the direction of the field. This feature is often used (together with the spectrum of the radiation) to confirm that the radiation has been produced by the synchrotron.

The synchrotron emission spectrum of Virgo A falls with increasing frequency and when plotted on a log-log graph we can define a near constant spectral index (x). For Virgo A, x is 0.79. The choice of the best frequency to observe this source is interesting, but very familiar to EMEers: the source produces more signal at low frequencies, but the antenna gain increases with frequency for a given antenna size. The choice is often determined by practical considerations of available antennas, or the cost of constructing them.

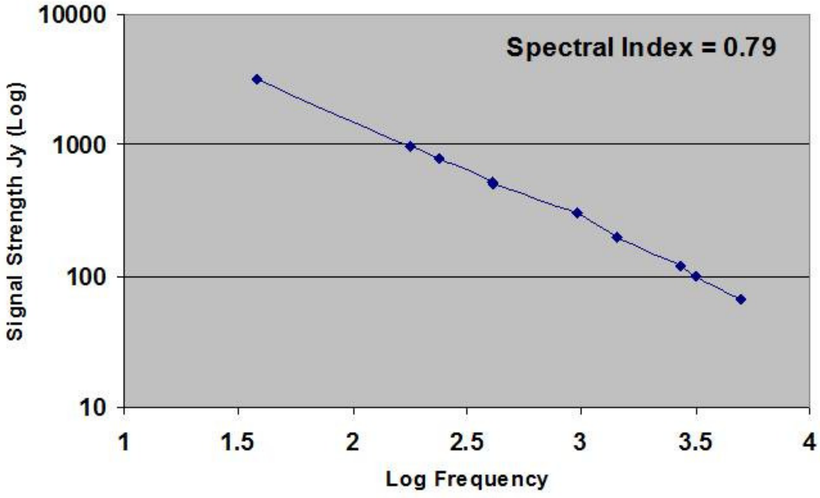

Figure 2: Virgo A spectrum

The expected signal strength of Virgo A at about 408 MHz is 519 Jy. One jansky (Jy) equals 10^{-26} W m^{-2} Hz^{-1} so the power density is about –203 dBm m^{-2} Hz^{-1}.

Measurement Equipment

Having looked at the nature and radio characteristics of the Virgo A source, we now turn to the choices of a suitable observing frequency and antenna. The solution is probably not clear cut, as the signal from the source increases at lower wavelengths, but the gain available from an antenna of a fixed physical size falls with wavelength. Thus the two trends act to neutralise each other. The choice of frequency for the observations reported here rested purely on the cost of developing suitable antennas. As the intention was to observe Virgo A with an interferometer, two similar antennas were needed. A couple of 3 m dishes operating at around 1.4 GHz would have been viable, but only one dish / feed was available.

It was decided to build four Yagi type antennas based on the Society of Amateur Radio Astronomers (SARA) ‘Quagi’ design [2] at 408 MHz, as these are relatively cheap to construct. The two interferometer antennas were made by stacking two Quagis for each element. Stacking the two Quagis reduced the beamwidth from ~33° to 18° and increased the gain. Several experiments were made to determine the optimum stacking distance.

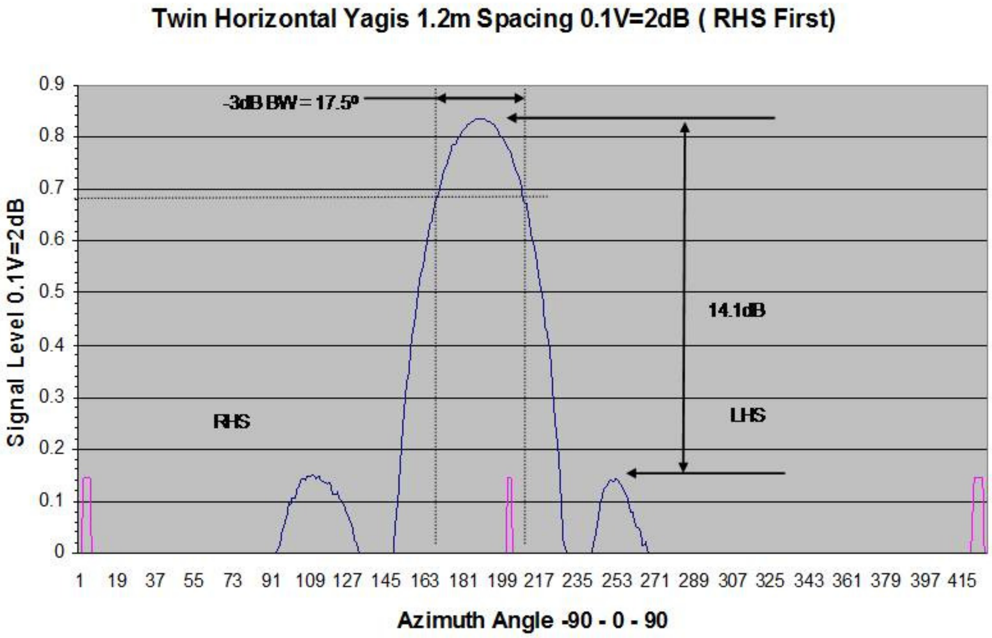

Figure 3: Polar diagram of stacked Quagis

The performance of each single SARA Quagi antenna was measured over a range of 200 m on open ground at 408 MHz, using an automatic rotator and data logging system. A typical stacked beam profile is shown in Figure 3 and has a HPBW of ~18° and side lobes at -14 dB. Following a number of experiments to find the optimum stacking distance that gave the narrowest beam with the lowest side lobes, a figure of 1.2 m was arrived at. At an operating wavelength of 74 cm, this gave a spacing of 1.6 λ. This 1.2 m spacing is close to an ‘optimum’ suggested by VK2ZAB [3] from the formula (52 / 3dB beamwidth) yielding a figure of 1.16 m separation. The Quagis were combined with simple coaxial cable λ/4 transformer combiners to present approximately 50 Ω to the preamplifier input.

The preamplifier used at each pair of antennas was obtained from Radio Astronomy Supplies (designed by WD5AGO) with noise figure of 0.33 dB [4]. This was followed by a ‘line driver’ amplifier with a gain of 18 dB manufactured by Mini circuits (ZX60-33LN) with a 1 dB noise figure. The total head amplifier gain was 44 dB and this drove the signal down 20 m of URM 67 to the interferometer combiner.

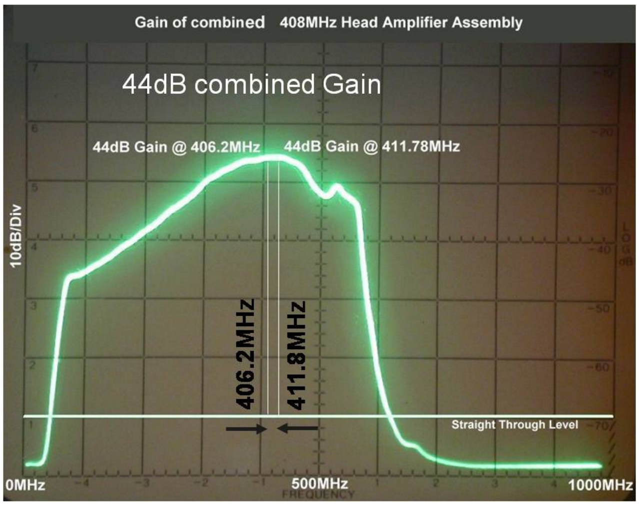

Figure 4: Head amplifier gain vs frequency

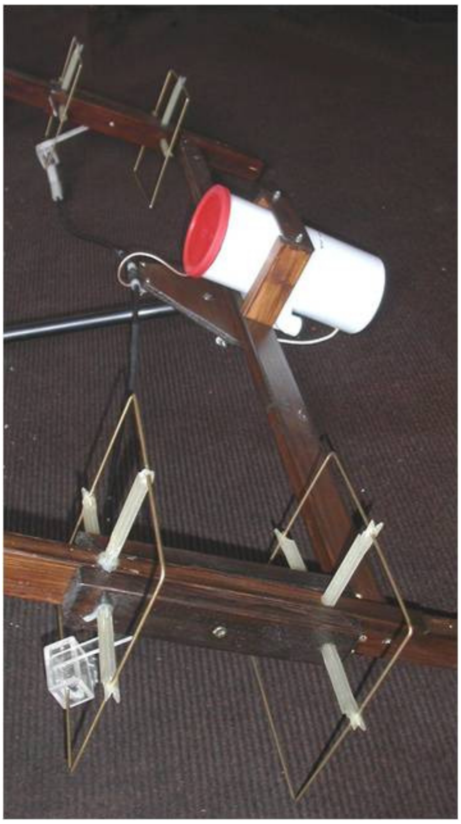

Figure 5: Stacked Quagis and head amplifier

It had already been established when using single Quagis for radio astronomical observations, that it is important to stabilize the head amplifier gain and noise against temperature variations. Without this, the measured signal strength from a source could vary over the course of some hours, particularly at dawn and dusk when large temperature changes occur. Heating from direct sunlight can also be a problem and on cloudy-bright days could introduce signal variations on the order of minutes. An active temperature control system was therefore built into the head amplifiers using Peltier cooling elements. The temperature of the head amplifier was recorded along with the signal level during every measurement. The compact unit was housed inside an insulated aluminium and polystyrene wrap inside a white waterproof casing as shown in Figure 5.

Figure 6: Antennas on East tower

The principles of an interferometer are well known and they are only summarised here. See reference [5] for a full description. When two antennas separated by several wavelengths are receiving an incident EM wave, the phase difference between the combined outputs gives rise to constructive and destructive interference as the angle of incidence changes. The angular separation of the constructive interference peaks is a function of the separation of the antenna (the baseline) measured in wavelengths. In the interferometer used for these measurements of Virgo A, the wavelength was 0.74 m and with a 30 m separation this gives a baseline of 40.6 λ.

The interferometer forms a series of 'beams' with an angular width determined by the length of the baseline in wavelengths. In the arrangement used here, the angular separation of beams was 1.4°. For transit measurements the baseline is orientated East-West, so that the source passes through these beams giving rise to a cyclic variation in output known as 'fringes'. The amplitude of these fringes falls off either side of the central beam as a result of the beam profile of the individual antennas at each end of the baseline. In this case we have the fringe pattern of 1.4° modified by the 18° HPBW of the stacked Quagi antennas (see Figure 7 below).

During transit scans of the sky, with the Earth rotating at 15° per hour and a beam separation of 1.4°, we have a fringe frequency of ~ 5.6 minutes. With the stacked Quagi HPBW of 18° and the first nulls at ±25°, the fringes will rise and fall away again over the period of less than 3 hours. Thus during a transit scan we may expect to see about 35 fringes in the pattern. It is then possible to verify the shape of the interferometer beam pattern and the fringe frequency by using a relatively strong astronomical radio source such as Taurus A (The Crab Nebula, M1) to produce a clear and noise-free recording.

It so happens that Taurus A and Virgo A lie at similar declinations and the antenna will scan across each source in turn during a transit measurement. Figure 7 is a recording of a scan across Taurus A and nicely shows the multiple interferometer beams rising and falling away lasting a few hours. The HPBW of the main central beam is estimated to be 0.6°.

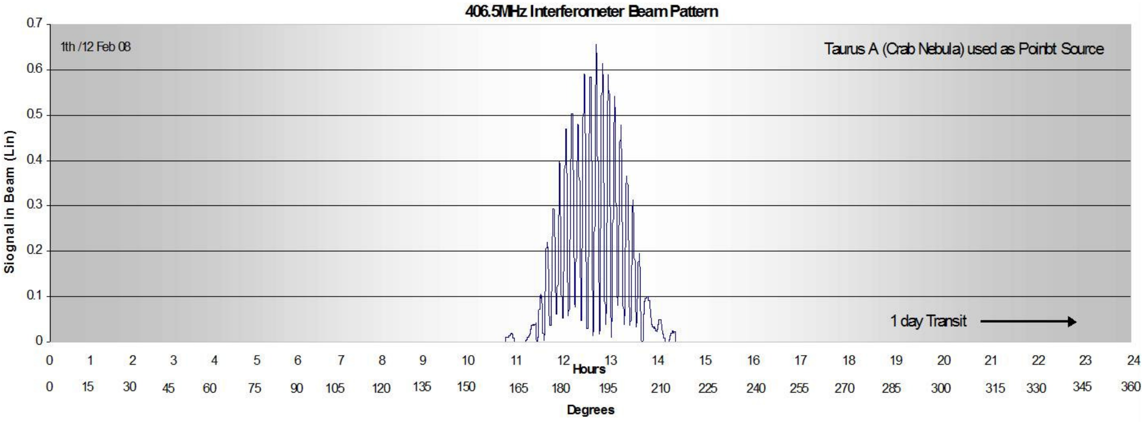

Figure 7: Taurus A interferometer response

In Figure 8 we see the resulting signal level as a function of time, plotted over 17 hours of Right Ascension. The location of the two sources Taurus A and Virgo A are defined by the interferometer fringes. The location map at the base of the figure is a section of the *Radio Eyes* [6] plot used to set up the measurement.

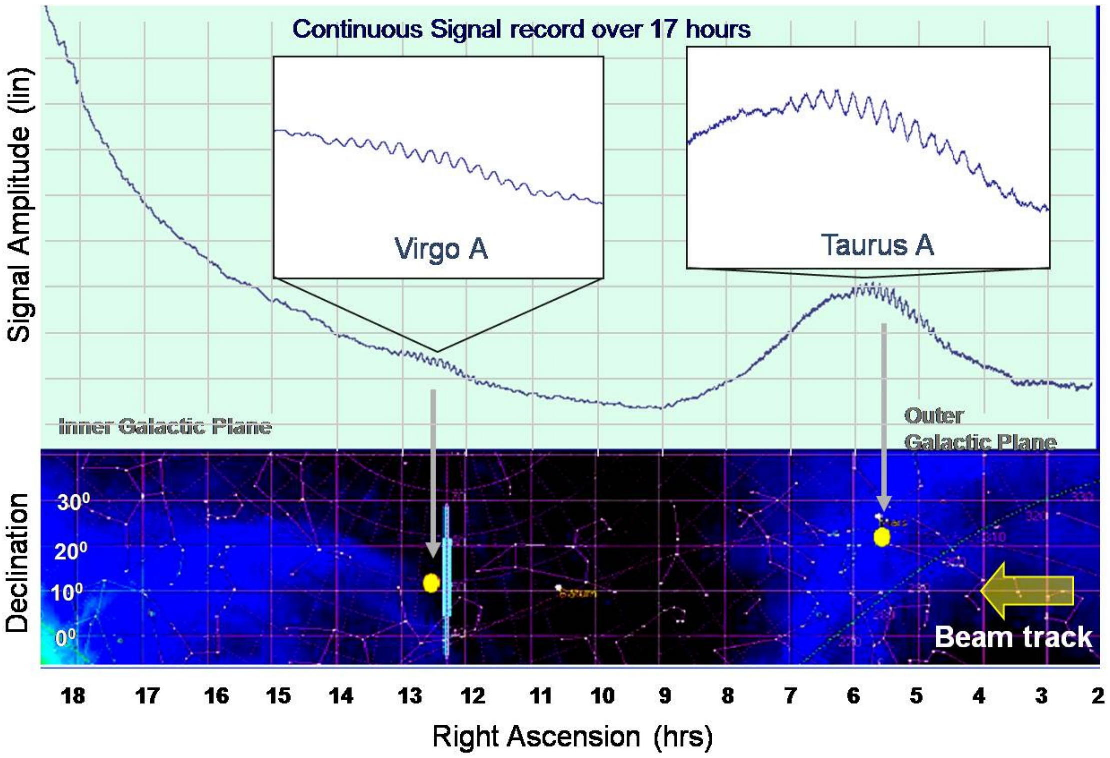

Figure 8: Interferometer fringes from Virgo A and Taurus A

The beam tracks from right to left in this plot and several features can be identified: The first ‘hump’ on the right is the signal from the diffuse background as the beam passes through the outer element of the galactic disc ((looking away from the centre of the Milky Way). The fringes embedded in this are due to Taurus A (Crab Nebula). For clarity, the fringe plots are magnified in separate ‘windows’.

The background signal then falls as the beam sweeps out of the galactic plane toward the north galactic pole, before encountering the galactic plane again looking inward to the galactic centre. The steady rise in signal level is the background radiation from the inner galactic plane. The small set of fringes one third of the way up this curve is produced by Virgo A. It can be seen that they are smaller – by approximately 3x – than the fringes from Taurus A. This is due to the difference in source strengths: 1200 Jy for Taurus A and only 500 Jy from Virgo A.

If we extract the numerical data that includes the Virgo A fringes, these can be manipulated in Microsoft *Excel* to show the fringes more clearly – see Figure 9 (next page). Within the fringe pattern we also see a hump in the average, compared with the smoothly rising background on either. This may be because the angular size of this source is large enough to be partially resolved by the interferometer beams, which are only 36 arc-minutes wide.

Finally, by subtracting the average signal level from the total signal we can achieve our objective: Figure 10 is the resolved interferometer fringe pattern generated by Virgo A.

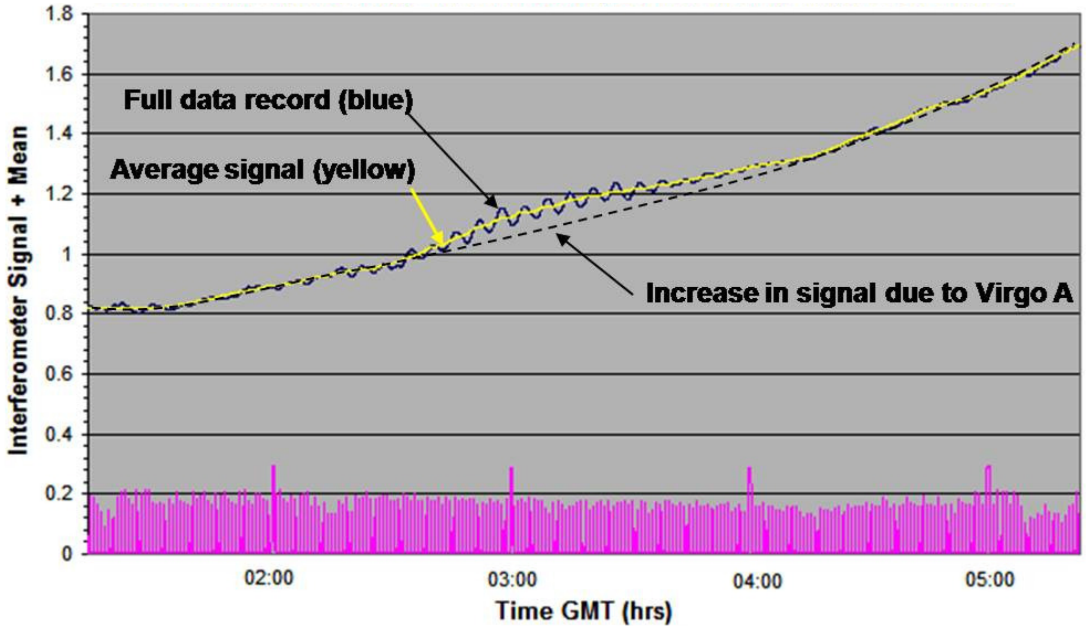

Figure 9: Virgo A partially resolved signal

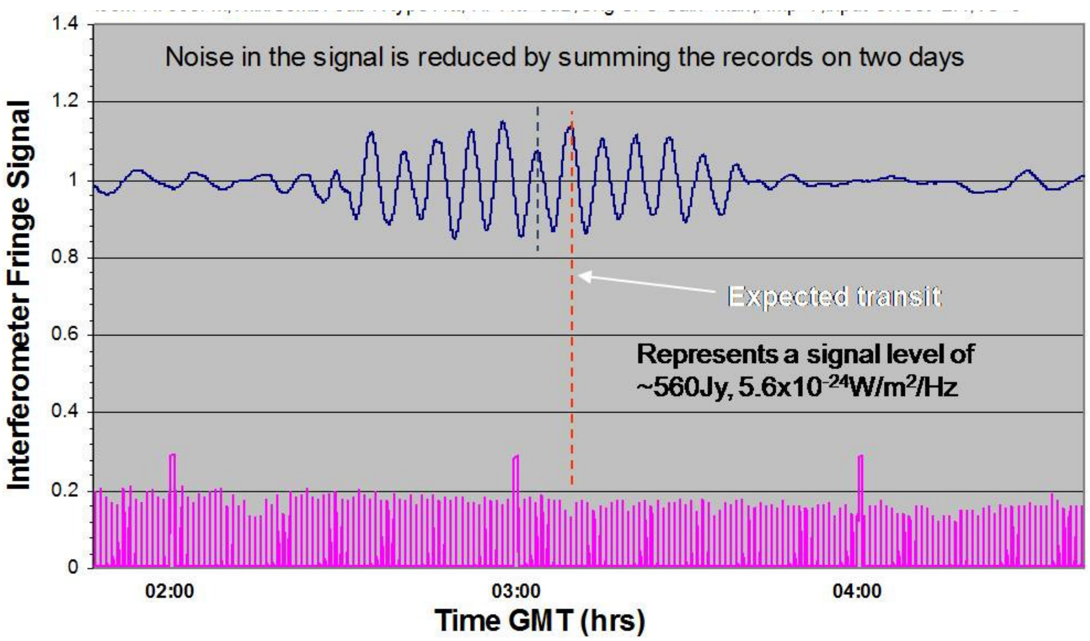

Figure 10: Virgo A fringe pattern

Conclusion

It is clear that the EME community has members who are very capable in the fields of communications, electronics and software, with receiving equipment sensitive enough for use in radio astronomy.

Some attention may be required to ensure long-term noise and gain stability of the receivers, but members of the EME community could readily undertake detection and measurement of radio astronomical sources.

If you have never seriously considered this, I would urge you to try your hand at this interesting activity.

References

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