Exploring some Limitations in Amateur Radio Astronomy

Dr David Morgan
Weak Signal Detection of Virgo A

Contents

- Antennas & Receiver properties
- Radio source strength & spectra
- Limitations with small antennas

3m Dish
L Band Horn
408MHz Quagis
Telescope Characteristics

- Antenna properties
Two fundamental properties of an antenna of concern to amateur radio astronomers:
- Gain
- Beamwidth

These are related – the higher the gain the smaller the beamwidth

We want both high gain and narrow beamwidth:
- Gain = sensitivity
- Beamwidth = spatial selectivity

Need Large antenna aperture
Antenna Equations

- Antenna Gain
  \[ G = \eta \left( \frac{4\pi}{\lambda^2} \right) A \]
  \( \eta = \) Aperture efficiency
  \( A = \) Antenna aperture \( m^2 \)
  \( \lambda = \) wavelength

For a reflector antenna, the area is simply the projected area.
For a circular reflector of diameter \( D \), the area is \( A = \pi \frac{D^2}{4} \) and the gain is

\[ G = \eta \left( \frac{\pi D}{\lambda} \right)^2 \]

- Antenna Beamwidth
  \( \text{HPBW} = \alpha = \kappa \frac{\lambda}{D} \)
  \( \kappa = \) a factor that depends on the shape of the reflector and the method of illumination

For a typical antenna

\[ G = \frac{27,000}{(\alpha)^2} \]

Antenna diameter drives performance
At UHF things get big

- Rare to find an amateur with a 9m antenna

John Smith (1924 -1998) with 9m dish

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Yagis vs Dishes

- Would not tend to use a small dish at **UHF**
- Yagi arrays probably cheaper and easier to build
- But – effective aperture must be similar to dish area
- So arrays will be a few metres square
- Complicated to construct and phase together

DL7APV Array (used for EME)

Part of my 408MHz Quagi Array

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Consequences

- Can have high sensitivity and good spatial resolution at 11GHz with 1m antenna
  - ~40dB gain and few degrees HPBW

- Reasonable gain and resolution with 2.4m dish at C band
  - ~ 35dB gain and <5 degrees HPBW

- Workable sensitivity and resolution with 3m dish at 1.4GHz
  - eg 30dB gain and >5 degrees HPBW

- But low gain and poor spatial resolution with 3m dish at 408MHz
  - eg 19dB gain and 18 degrees HPBW

- Impractical at VHF (space & cost)

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L band is probably most practical, useful and affordable option for amateurs

(L Band (IEEE) = 1-2GHz)
Receiver Requirements

- Band coverage
- Available bandwidths
- Detector functions
- Sensitivity
- Noise & gain stability

Discuss the last two items
LNAs and Receivers

- Receiver must have high gain and low noise
- System Noise figure ($N_F$) determined by first amplifier
- Low Noise Amplifiers (LNA) now capable of 0.2dB at 1.4GHz
- Conventional Coms receiver or SDR sensitivities are adequate when used with LNA (gains of 20 – 40dB)
- Noise & gain stability are crucial:
  - Maintain common parameters from hour to hour and day to day – to enable radio maps etc to be made.
**SDR Dongle Receivers**

- The common SDR Dongles have gaps in frequency coverage

### Frequency Coverage for FCD & RTL Dongle Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>1MHz</th>
<th>10MHz</th>
<th>100MHz</th>
<th>1GHz</th>
<th>2GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCDPro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCDPro+</td>
<td>60</td>
<td>1.1</td>
<td>1.27</td>
<td>1.27</td>
<td>1.7</td>
</tr>
<tr>
<td>RTL</td>
<td>26</td>
<td>240</td>
<td>420</td>
<td>1.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- **Coverage Gaps**

Frequency Coverage for FCD & RTL Dongle Devices
Noise /Gain Stability

- FunCube Dongle Pro +:
- Stability is better than 0.05dB over 3 hours

Cheap stable SDR receivers widely available
No important receiver limitations
Astronomical Radio Sources

- What sources are in the Northern Hemisphere?
- How strong are they? – are they detectable by Amateurs?
- What spectrum do they have?
- Are they discrete or spatially distributed?

Key parameters

Source Flux  Spectrum  Angular Size
Look at typical source signal strength

- Broadcast signals: $100 \mu V/m$
- Communication receiver: $1 \mu V/m$
- Sun storms
- Jupiter
- Supernova remnants
- Radio galaxies: $1 Jy = 10^{-26} W m^{-2} Hz^{-1}$
- Pulsars

Power Flux Density (W m$^{-2}$ Hz$^{-1}$)

Assuming 6kHz bandwidth
Radio Sources – signal strengths

In more detail

These are ‘continuous’ sources – not dealing with radio transients

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Each source has its own predominant radiation mechanism.
This determines the emission spectrum.
The source spectrum drives the telescope configuration:
- eg Frequency of operation, Gain & Antenna size

SUN: Thermal Source
SNR: Synchrotron Source
Galactic Hydrogen: Line Source

**Power flux density (10^{-26} W m^{-2} Hz^{-1})**
- SUN: Quiet sun
- SNR: Storms and bursts
- Galactic Hydrogen: Line spectrum

**Power flux density (10^{-26} W m^{-2} Hz^{-1})**
- HERCULES
- CYGNUS
- VIRGO
- HERCULES

**H Line Spectrum**
- 1420MHz
- 1421MHz
Radiation Mechanisms

- **Source Spectra**: Three mechanisms – Three spectra

1. **Semi-transparent opaque Thermal Spectrum**
   - $P = \varepsilon \frac{kT}{\lambda^2}$
   - $K =$ Boltzmann’s constant
   - $T = $ temperature

2. **Synchrotron Spectrum**
   - Charged particle
   - Magnetic field
   - $v_r$ = charged particle velocity
   - Circular polarization
   - Linear polarization

3. **Line spectrum**
   - Hydrogen 21cm
   - Methanol 4cm
   - OH 18cm
   - Hydrogen 21cm

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What can amateurs measure? – some examples

- Use microwave receiver for thermal sources
  - Few interesting objects to detect
  - Small objects < 0.5° diameter - eg SUN & Moon
  - Measurements will be HPBW limited (~2°)

- Using L band for H line
  - Measuring Doppler shifts & mapping galaxy
  - Reasonable spatial resolution achievable

- Use L Band for Synchrotron emission
  - Galactic emission can be mapped
  - Reasonable spatial resolution achievable
  - SNRs are discrete sources – smeared out by large HPBW
  - This makes SNRs difficult to detect

- Try using UHF for Synchrotron emissions
  - Higher signal but worse antenna gain – no improvement
  - HPBW rather poor – limited spatial resolution

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11 GHz Radiometer image

- School Radiometer project – show some principles of Radio Astronomy

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As amateurs we can measure the intensity, spatial distribution and velocities of Hydrogen in the galactic plane.
What is difficult for amateurs?

- Difficult to detect discrete sources at UHF / VHF
  - We are limited by using small antennas
  - Only moderate gain
  - Relatively wide beamwidths
  - Discrete sources \( \ll \) beamwidth
  - Leads to source intensity loss & spatial smearing

- How significant is the effect for discrete sources?
Wide beams & point sources

- Evaluating loss of signal and point source smearing
  - Antenna temperature relationship with source flux density

\[
T_A = \frac{A_e S}{2k}
\]

\(T_A\) = ‘Antenna Temperature’, \(S\) = Source flux
\(A_e\) = Effective Area, \(k = 1.38 \times 10^{-23} \text{ J K}^{-1}\)
\(1^{0} K = 1.38 \times 10^{-23} \text{ W Hz}^{-1}\)

\[
\Omega_A \equiv \int_{\Omega_P} P_n(\theta, \phi) d\Omega
\]

\(\Omega_A\) = Antenna beam solid angle, \(P_n\) = polar response

\[
T_A \approx T_B \frac{\Omega_S}{\Omega_A}
\]

\(T_B\) = source brightness Temp, \(\Omega_S\) = source solid angle

http://www.cv.nrao.edu/course/astr534/AntennaTheory.html
Two examples

**Example: SUN**
- For a hot source like the SUN, $TB \sim 10^4 \text{ K}$
- Angular diameter = 0.5$^\circ$
- With a 5$^\circ$ HPBW antenna beam
- Source will only add 100K to the antenna temperature.

**Example: Cass A**
Using an antenna main beam HPBW = 8$^\circ$
Angular diameter = 5 arc min, $T_B = 3792^\circ\text{K}$
Background galactic plane Temp = 86$^\circ\text{K}$
Cass A example

- For Cass A set in the galactic plane background
- Contribution from Cass A $T_{\text{temp}} = 0.411^0 \, \text{K}$
- Background GP temp = $86^0 \, \text{K}$

- So Cass A is hardly detectable against $86^0 \, \text{K}$ background with a ‘Total Power’ system

- Detection of ‘point’ sources requires very narrow beams
Discrete Source is lost in background

- Must have a larger antenna with a narrower beam to detect SNRs or extra galactic objects when using a Total Power System

- Requires Antenna HPBW of $< 1^0$ at UHF (Synchrotron Sources)

- Better than 20m diameter required.

Without access to a large antenna the only practical way for amateurs to observe point sources is with Interferometry.
This table summarises the issues when restricted to small antennas.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Performance</th>
<th>Possible Sources</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>KU Band 11GHz</td>
<td>High gain, narrow beams (&lt;2°)</td>
<td>Few of interest (thermal only)</td>
<td>‘High performance’ system but little of interest to detect</td>
</tr>
<tr>
<td>C Band 4 GHz</td>
<td>Medium gain, reasonable beam</td>
<td>As above</td>
<td>No ‘available’ sources</td>
</tr>
<tr>
<td>L Band 1.4-1.6GHz</td>
<td>Satisfactory gain, rather wide beam (5°-8°)</td>
<td>Galactic H Line</td>
<td>Low spatial resolution but OK for Galactic Hydrogen work</td>
</tr>
<tr>
<td>UHF 408MHz</td>
<td>Low gain, poor beamwidth</td>
<td>Many synchrotron SNRs, galaxies etc</td>
<td>Many sources, but poor sensitivity and resolution</td>
</tr>
<tr>
<td>VHF 150MHz</td>
<td>Need very large antenna</td>
<td>Many SNRs and Pulsars</td>
<td>Not really practical for amateurs</td>
</tr>
</tbody>
</table>

H Line is best target for amateurs
So as amateurs with modest antennas we can do a good job of measuring H Line emission - as Galactic features fill the beam

\[ T_A = T_B \] with only a little spatial smearing
Where does this leave UK amateur radio astronomers?
- Each of us is working with small antennas
- $>10\text{m}$ dia antenna too expensive for an individual

- Clubs or groups unlikely to have funds, commitment & discipline to collaborate on large scale project

However – it has been done!
- Dwingeloo telescope in Holland
- Stockert telescope in Germany
- Now in service for Amateur Radio Astronomers & EME

What are the chances of a similar UK project?
What a challenge that would be ……..
Two large dishes at Goonhilly will soon be used for professional Radio Astronomy – amateurs may be able to play a part??

Goonhilly 1 (L band)  Goonhilly 3 (C band)
Would you like to consider participating in Amateur Radio Astronomy at Goonhilly?

Put your contact details in the book

Thank You

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Cass A example

- For Cass A set in the galactic plane background
- Discrete source lost in the background with an 8° beam

\[
\text{Cass A Temp} = \frac{3792 \times 0.0153}{0.00000166} \quad T_{\text{Cass A}} \quad \Omega_A \quad \Omega_S
\]

- Cass A Temp = 0.411° K
- Background GP temp = 86° K
- So Cass A is hardly detectable against 86°K background with a ‘Total Power’ system
- Detection of ‘point’ sources requires very narrow beams

Look at a simple spreadsheet model of the situation

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Simple spread sheet model

- Use Excel to model point source in a wide beam

Create a beam profile

Generate a ‘slightly noisy’ background level

Add in Cass A ‘point source’

Sum the background noise power
Sum the noise power + ‘point’ source
Calculate % change with point source

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Observing extragalactic synchrotron objects at UHF with small antennas results in poor spatial resolution (HPBW ~18° - 3m $\lambda_E$)

- Example: M87 / Virgo A galaxy
- Only ~ 100Jy at 408MHz
- Fortunately it is out of GP – less obscured
- Still difficult to determine as a point source with Total Power receiver
So as amateurs we can do a good job of measuring H Line emission as Galactic features fill the beam ($T_A = T_B$) & only a little smearing.


Wanted to know what Galaxy looked like in Az and El.

How we would see it – if we had Radio Eyes.

1420.4MHz Image of Milky Way

13.08 GMT 28/11/2013