Using a Satellite Dish as a simple Radio Telescope

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Introduction

A satellite dish can be used as a temperature remote sensing device, relying on the fact that the radio emission from most objects occurs in the Rayleigh-Jeans tail of the black body brightness distribution, so that measured power is proportional to temperature. In particular, a satellite dish can be used to measure the temperature of the Sun.

Equipment required

A standard small satellite dish for DSTV. That used at HartRAO is 47cm diameter - it does not need to be large. This operates at 12GHz / 2.5cm wavelength. The output is fed to a radiometer. A "radiometer" means a "radio-meter" – i.e. a device that measures the strength of the radio signal coming from the receiver on the dish. A commercial "Satellite Finder" (cost ~R200) provides a simple radiometer, but a disadvantage is that the meter has a dB scale rather than a linear scale. If used, the satellite finder needs 15V DC to power the satellite finder and the microwave amplifier. At HartRAO we built a radiometer using spares from the 26-m radio telescope. The HartRAO radiometer supplies the 15V DC needed by the amplifier on the satellite dish.

If the output can be recorded digitally, and if the dish can be mounted on a tripod on which the elevation or azimuth can be measured accurately (better than 1°), then the beamwidth of the dish can be measured and not just inferred from simple arguments (see later).

Also needed, for measuring the angular diameter of the visible Sun, is a sheet of card or paper, a tape measure and ruler (see later).

Targets at which to aim the satellite dish and record the output

1. Sky – shows lowest signal level. Note that when aimed at different parts of the sky the signal level hardly changes. This means that it is not sensitive enough to detect stars.
2. Sun – how to aim the dish is shown in the pictures – look past receiver horn to see the sunlight reflecting off the surface of the satellite dish – see Fig. 1.
3. Fluorescent lamp – representing an ionized gas cloud such as the Orion Nebula (demo only)
4. The ground
5. Buildings
6. People; hand over feed horn
7. DSTV satellite(for interest only, not used in calculations).

The radiometer

The radiometer uses a detector whose output voltage is proportional to the input radio power (i.e. a "square-law" detector). The output voltage from the detector is displayed on a meter. This meter has an arbitrary scale. The output voltage is also fed to a loudspeaker to provide an audio output, which is a hiss of varying levels of intensity. The hiss is "white noise" - the radio equivalent of white light that we see with our eyes.

On the HartRAO demonstration radiometer, the meter reading is proportional to the noise level from the receiver and the object at which it is pointing. The noise level depends on the temperature of the object. Typical meter readings are:

- 10 aimed at the sky
- 30 aimed at the ground
- 24 aimed at the Sun.

How do we translate these numbers into temperatures?

The measured signal comes not only from the object at which the dish is pointing, but also from the radio receiver itself. A rough calibration of this system as a radio telescope can be achieved by comparing the reading pointing at the sky and the ground. We have to use absolute temperatures for this calculation.

- The noise temperature of the sky at the operating frequency of the satellite dish is called T_{sky} and is about 5K. The (cloudless) sky is nearly transparent and we are seeing the Cosmic Microwave Background and a small contribution from the atmosphere.
- The ground temperature T_{ground} ~ 300K on a sunny day.
- The effective temperature of the receiver is called the receiver temperature T_{rec}.

If V1 and V2 are the two meter readings and c is a constant of proportionality, then:

$$cV1 = T_{rec} + T_{sky} \qquad (1)$$
$$cV2 = T_{rec} + T_{ground} \qquad (2)$$

We can solve for c and T_{rec}:

$$10c = T_{rec} + 5 \qquad (3)$$
$$30c = T_{rec} + 300 \qquad (4)$$

hence from (3) - (4)

$10c - 30c = -300$ (approximately, as 300 >> 5)

$20c = 300$

$c = 15$ Kelvins per division

and substituting for c in (3)

$150 = T_{rec} + 5$

$T_{rec} \sim 145$ Kelvins

As each division on the meter is equal to about 15 Kelvins, the measured temperatures go from 150 K pointing at the sky to 15x24 = 360 K on the Sun to 15x30 = 450 K pointing at the ground. Hence the temperature we measure from the Sun is 360 – 150 = 210 K. But the Sun is much hotter than this! To understand this, and to work out the real temperature of the Sun, we have to figure out how much of the sky the dish "sees" (or more technically, the beam solid angle).

The telescope beam

The satellite dish is sensitive to radio waves coming from a small circular area of the sky. This is called the "beam" of the antenna. What is the diameter of this beam? As the radio emitter moves away from the middle of the beam, the angle of the waves hitting the dish changes. When all the waves coming from each part of the dish are in phase, we get the strongest signal, when the emitter is in the centre of the beam. Moving away from the centre, the waves from different parts of the dish start to become out of phase with each other, causing destructive interference. The telescope sensitivity falls to a minimum when the incoming wave is tilted at an angle so that there is a phase difference of approximately one wavelength across the diameter of the dish. This minimum is called the "first null" in the antenna beam pattern. We normally use the points at where the response of the antenna has fallen to half that in the centre of the beam to define the “half-power beamwidth”, hereafter just “beamwidth”.

The beamwidth ~ wavelength / diameter, in units of radians (1 radian = 57.3 degrees). A more detailed calculation for typical antennas leads to:

beamwidth ~ 1.2 x wavelength / diameter.

Try calculating the resolving power of your eye (2 mm pupil) and of a 20cm optical telescope, using this measure.

The beamwidth of the satellite dish in radians = 1.2 x wavelength / diameter (in units of radians)
= 1.2 x 2.5cm / 47cm
= 0.064 radians
= 3.7 degrees approximately.

If the dish can be pointed accurately using a tripod, the beamwidth could actually be measured, by scanning across the Sun or letting it drift through the beam.

Estimating the temperature of the Sun using the beam size

Now we need to know how many times the Sun would fit into the beam of the telescope. Use pinhole projection to measure the angular diameter of the Sun. You will need two pieces of paper or card, one pierced with a small hole (~ 2 mm), and a tape measure. The hole need not be circular, and indeed it is instructive to make it triangular. The card with the hole is used to project an image of the Sun onto the second card. The two cards need to be separated by a distance 'D' of around 2 metres, measured by tape measure. The linear diameter 'd' of the projected Sun is measured with the ruler. The angular diameter of the Sun is d/D radians (see later for more detail).

The Sun should be measured to be 0.5^o in diameter, so we could fit $(3.7/0.5)^2$ = 55 Suns into the beam of the dish.

Hence the temperature of the Sun is about 55 x 210 = 11500 K.

This does not allow for the “aperture efficiency” of the dish (its efficiency in receiving radiation from a small source in the centre of the beam), which is probably about 60 percent of the maximum possible for an ideal antenna. Correcting for this, the Sun's temperature is about 11500 / 0.6 = 19 000 Kelvins.

This temperature will vary during the 11 year solar cycle (2007 = solar minimum), but it reasonably matches the value given in standard references for this observing wavelength, and is about three times higher than the value measured at visible wavelengths (5800 Kelvins). Hence we cannot treat the Sun as a perfect blackbody radiator – other mechanisms must be enhancing the amount of radiation at radio wavelengths. What could they be?

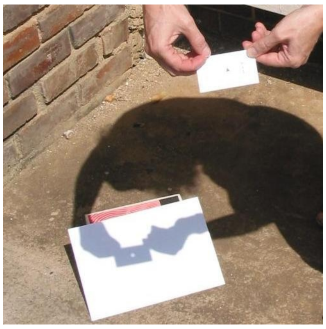
Worksheet: Calculating the Diameter of the Sun

(taken from HartRAO manual for teachers)

Work in groups of three.

You will need:

- 2 pieces of plain paper 10cm x 10cm to A4 in size
- A ruler
- A piece of string , cotton or wire



Projecting the Sun through a pinhole.

1. Stand up and hold the string in one hand. Stretch your arm straight up, let the string touch the ground. Tie a knot in the string where it touches the ground. Use the ruler to measure the length of the string up to the knot.

2. Record the length: ______________________mm

3. Make a hole in the centre of one of the pieces of paper. The hole should be between 2 and 4mm in diameter.

4. Stick the second piece of paper to the outside cover of a hardcover book. This will allow the paper to stand on it's own on the ground.

5. Set the distance between the two pieces of paper as the length of string to the knot.

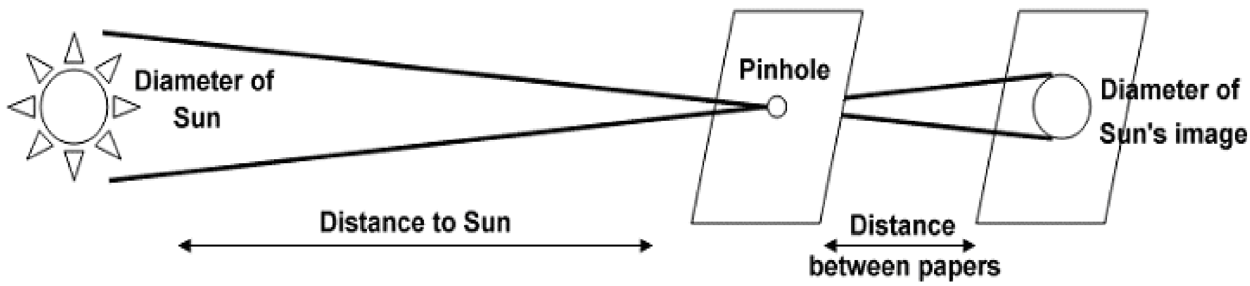
6. Let the Sun shine through the pinhole onto the second sheet.

7. Draw a circle around the Sun's image on the second sheet. Use the ruler to measure the diameter of the Sun's image: ____________________mm.

8. Divide the answer from number 2 by the answer from number 7.____________

This gives us the number of Sun images that when placed end to end, would fit in the distance between the pinhole paper and the graph paper.

9. Using the answer from number 8, we can say that the distance from the Earth to the Sun is _____________ times the diameter of the Sun. We are using the principle of simple proportion to do this – see the diagram on the next page.



Given that the Sun is 150 000 000 km from Earth, we can calculate the diameter of the Sun, by simple proportion:

$$\frac{\textbf{Actual Diameter of Sun (km)}}{\textbf{Diameter of Sun's image (mm)}} = \frac{\textbf{Actual Distance to Sun (km)}}{\textbf{Distance between the pieces of paper (mm)}} \qquad \textbf{(1)}$$

so:

$$\frac{\textbf{Diameter of Sun (km)}}{\textbf{your diameter (mm):}} = \frac{\textbf{150 000 000 km}}{\textbf{your distance (mm):}} \qquad \textbf{(2)}$$

We can rearrange equation (1) to give us:

$$\textbf{Diameter of Sun} = \frac{\textbf{Diameter of Sun's image (mm)} \quad \textbf{x} \quad \textbf{Actual Distance to Sun (km)}}{\textbf{Distance between the pieces of paper (mm)}}$$

Therefore we can rearrange equation (2) in the same way, filling in your numbers:

$$\textbf{Diameter of Sun} = \frac{\textbf{Your diameter (mm):} \qquad \textbf{x 150 000 000 km}}{\textbf{Your distance (mm):}}$$

Do the calculation with your numbers, to get:

Diameter of Sun = __________________________ **km**

Figures

Fig. 1 Looking past the feed to see the reflection of the Sun off the dish surface

Fig.2   Commercial “satellite finder”

Fig. 3 Satellite dish and HartRAO radiometer

Block Diagram of Demonstration Radio Telescope and Radiometer