The brightness temperature of the sun at 12 GHz.

1. Safety Issues

This experiment involves the use of the radio telescope on the roof of the Old Main Building. For your own safety, and that of others, it is essential that the rules below be followed. The telescope itself is a piece of heavy machinery and is remotely operated. Although moving slowly, it is very strong. If you get in its way it will simply crush you, perhaps fatally. In an emergency, the telescope can be stopped instantly by either hitting any key on the computer keyboard, or pressing the emergency stop button on the concrete slab. Note, however, that you will not be able to reach either the keyboard or the stop button if you are caught up in the telescope. Before stepping onto the concrete slab at the telescope base, **you must first disable the telescope drive by pressing the emergency stop button IN.**

z Do not attempt this experiment if there is a risk of an electrical storm, or if strong wind gusts (>50 km/h) are expected.

z Do not approach the telescope unless the emergency stop switch is “off’ (ie, pushed in). **You are not permitted to go onto the concrete slab unless this switch is off.**

z Do not lean over the edge of the roof. Do not throw yourself, or anything else, from the roof.

z **At** the conclusion of the experiment, ensure that the emergency stop switch is off, and that the coaxial cable and ribbon cables are disconnected from the receiver and interface box respectively. (This is done to protect the control-room electronics from lightning strike.)

2. Introduction

In this experiment you will use the radiotelescope to measure the brightness temperature of the sun at a frequency of 12 GHz. The term “brightness temperature” is used to indicate that this is not a unique temperature for the sun. The measured temperature of the sun varies from about 6,000 K at optical wavelengths to millions of degrees at metre wavelengths. This is basically because the sun’s temperature varies with radius, and different wavelengths probe the solar corona to different depths,

The principle of the measurement is very simple. First, the telescope is calibrated by pointing it at an object of known temperature. Then, the telescope is pointed at the sun and the ratio of the signal observed to that from the known object used to calculate the sun’s temperature. In practice, there are several important issues which complicate the calibration; issues which are also important in all modern observatories.

3. Procedure

1. In the control room, connect the coaxial cable to the Icom receiver "antenna" input. Connect the two grey ribbon cables (labelled "AZ" and "EL") to the 25-pin D connectors at the rear of the interface box.

2. Take the roof key from its hook, go upstairs to the roof, and inspect the telescope itself.

3. Check that the telescope is free from obstructions. Reset the emergency stop switch on the side of the junction box. (Twist anti-clockwise and pull.)

You are not permitted to step onto the concrete slab at the telescope base once this switch is "on".

4. Return to the control room, and switch on the:

computer
Icom receiver
"front-end" power supply
plug pack.

Do **not** switch on the servo amplifier yet.

5. Once the computer has booted, type `radtel` to start the radiotelescope program.

6. Switch on the servo amplifier. Both meters should remain at zero current. If not, switch off immediately and seek advice.

7. Type **H** to automatically "home" the azimuth and elevation axes. This operation will take a couple of minutes, during which time the motor drive current meters will make wide excursions.

8. The telescope is now ready to use. Set the receiver controls as shown in section 5 (Setting up the receiver). Provided that at least 15 minutes has elapsed since the receiver and front end were turned on, the receiving system should now have warmed up and also be ready to use.

9. Type E to set the telescope elevation. When prompted by the computer, type 45.00 to set the telescope to a 45 degree elevation.

10. Note the receiver signal strength displayed on the computer. This is the "sky", or "off-source" signal.

11. Switch off the servo amplifier. Go up to the roof, taking the Eccosorb and the ladder. **Press in the emergency stop switch to disable the telescope drive.**

12. Hang the Eccosorb on the hooks provided in front of the feed horn. Return to the control room, and note the receiver signal. This, then, is the receiver response to a 300 K blackbody.

13. Return to the roof, remove the Eccosorb, and **lay the ladder flat on the ground** well away from the telescope. Reset the emergency stop button. The telescope is now calibrated and ready to use. Return to the control room, and switch the servo amplifier back on.

14. Determine the elevation and azimuth of the sun.

15. Type **E,** then the required elevation in degrees and decimal degrees.

16. Type **A,** then the required azimuth in degrees and decimal degrees.

17. **As** the telescope moves onto position, the signal strength should rise by a factor of 10 or more. Peak the flux by using the "nudge" option in the Radtel program. Peak up by adjusting first one axis, then the other, then peaking the first axis again. Note the signal strength displayed on the computer screen. This is the "on-source" signal. If the signal strength does not rise, go to the roof and check that the telescope is in fact pointing at the sun. When the telescope is correctly pointed, the feedhorn will cast a shadow exactly onto the vertex of the dish.

18. ## needs some work ## The next step is to make a **drift scan** of the sun. Note the present time, and add ten minutes to it. Using Ephem, adjust time. Note **Az** and El of the sun. return to radtel, and point the telsecope to the position where the sun will be in ten minutes. set gchart going. select sample time, 512 samples. **As** the sun moves through the telescope beam, the computer will record the signal. If all works well you finish up with a symmetrical plot, roughly gaussian in shape. You can make a print-out of this plot by ##

19. Before finishing for the day, ensure that the telescope is properly shut down. You **must** follow this procedure, and complete the checklist. Sign the completed checklist, and hand it, together with the control room key, back to Barry before you leave.

Shutdown procedure

z Park the telescope by typing **Park.** This places the telescope in the “bird-bath” position, greatly reducing the risk of wind damage. Wait until the computer has signified that it has completed the “park” operation.

Done......

z Turn off all electronics in the control room and switch off at the power point.

Done......

z Unplug the coaxial cable from the back of the Icom receiver.

Done......

z Unplug the two ribbon cables (labelled “AZ” and “EL”) from the back of the interface box.

Done......

z On the roof, switch off the emergency stop (push in).

Done......

z Return the ladder to the control room.

Done......

z Lock the roof, and return the roof key to the hook in the control room.

Done......

All shut-down items properly carried out:......

Signed...

Date.............................

4. Analysis

The flux emitted by a blackbody at temperature T is given by the Planck function:

$$B = 2h\nu^3/c^2(e^{h\nu/kT} - 1)^{-1}$$

Unless the temperature of an object is very low, $h\nu << kT$ at radio wavelengths. (Exercise: At what temperature does $kT = h\nu$ in this experiment?) Substituting $h\nu << kT$ into the Planck function leads to the Rayleigh Jeans approximation,

$$B = 2kT\nu^2/c^2 = 2kT/\lambda^2$$

(Exercise: Derive the Rayleigh Jeans approximation from the Planck function.) Because the flux (and hence the received power) is proportional to temperature, it is common for radioastronomers to talk in terms of **antenna temperature,** rather than "received power". The antenna temperature, T_A, is the signal that the receiver would see if the antenna were illuminated from all directions by a blackbody at that temperature.

By placing an absorber at temperature T directly in front of the antenna feed horn, we achieve the same effect as if we placed the whole antenna in an absorbing box at temperature T. From conservation of energy we know that an absorber must also be an emitter: the Eccosorb is thus our standard "blackbody" source of 300K radiation.

When the telescope is pointing at blank sky, it sees a background temperature of around 20K. This made up of several components: the 2.7K cosmic background radiation, diffuse radiation from the galaxy, and stray 300K radiation from the ground. The difference between the signal seen with the Eccosorb and that from blank sky thus corresponds to an antenna temperature difference of about 280K. This measurement can thus be used to calibrate the receiver output exactly in terms of T_A.

When the telescope is pointed at an object of small angular extent, the signal will be less than if the object were radiating at the telescope from all directions. The simplest way to account for this is to introduce the concept of **antenna beam solid angle,** Ω_A. This quantity can be best visualised by considering the antenna as a transmitter, rather than a reciever. The principle of reciprocity (which in turn comes from the time-reversal symmetry of Maxwell's equations) ensures that the spatial distribution of the transmitted signal (or "radiation pattern") is identical to the sensitivity response of the antenna when used as a receiver. Ω_A can be thought of as the solid angle through which all the transmitted power would be radiated if it were constant over this solid angle and equal to the power/unit solid angle radiated at the maximum point of the antenna's beam. (See figure 6-2 in Kraus.)

From antenna theory, we find that

$$A_e\Omega_A = \lambda^2,$$

where A_e is the effective aperture of the antenna. The antenna temperature that will result from a source of angular extent Ω_S small compared to the antenna beam is then

$$T_A = \Omega_S/\Omega_A \, T_{source}$$

You should thus be able to derive a brightness temperature for the sun (assume its angular size is 30 arcminutes).

From your drift scan, you should be able to derive an estimate of the half-power beamwidth of the telescope. The diameter of the sun is 30 arcminutes, which is not negligible compared to the telescope beam. A simple way to proceed is to assume that both the sun's brightness and the telescope beam have a gaussian angular distribution. You can then use the fact that the convolution of two gaussians is yet another guassian, whose half-power width is the square root of the sum of the squares of the widths of the original guassians. Compare the result you get with that expected from diffraction theory.

5. References

J.D. Kraus, *Radio Astronomy* (McGraw-Hill, New York, 1966).
K. Rohlfs, *Tools of Radio Astronomy* (Springer, Berlin, 1990).
W.T. Sullivan 111, *Classics in Radioastronomy* (Reidel, Dordrecht, 1982). This book is a compilation, with comentary, of many of the early radio astronomy papers. Facinating stuff!

5. Setting up the receiver

The following are brief instructions which are sufficient for this experiment. If you wish to learn more about the receiver, or to use it for general-purpose listening (eg for receiving weather satellites, aircraft, amateur radio transmissions etc.), a copy of the manual is available in the control room.

Refer to figure 1. Identify the various controls, and set them as follows:

1. **Power on.** Press this now to give the receiver time to warm **up.** Leave on for the duration of the experiment.
2. **AF Gain.** Otherwise known as a volume control. Adjust according to taste.
3. **Squelch.** Set fully anticlockwise.
4. **Receiving mode.** Press "FM".
5. **Tuning knob.** In this experiment we will enter the frequency directly, using the small keypad (8).
6. **Tuning Step.** Sets the rate at which the tuning knob changes the frequency. Ignore.
7. **1 GHz.** Adds 1 GHz to the displayed frequency. Press in.
8. **Frequency keypad.** To enter 234 MHz, press **2,** 3, *4*, ***Enter,*** in that order. With the 1 GHz button pressed in, the receiver is then tuned to 1,234MHz.
9. Ignore.
10. **Tuning lock.** With this pressed in, the tuning knob is disabled, preventing any change of frequency if the tuning knob is accidentally bumped. Press in.

11 - 13. Ignore

14. **Display dimmer.** Adjust as appropriate.
15. **Noise blanker.** Must be out.
16. **Attenuator.** Must be out.
17. **Remote.** Enables the infrared remote control. Must be out.
18. **Infrared remote control sensor.**
19. Ignore.

20 - 32. These buttons put the receiver into a scanning mode. Don't touch them!

33. **Signal strength meter.**
34. Selects meter display as "signal strength" or "centre tuning". Must be out.

35 - 36. Ignore.

Now refer to the back panel (figure 2). The relevant items are:

49. **Antenna input.**
50. **USB/LSB.** Leave in the out position (ie, USB).
51. **FM(1)/FM(2).** Leave in the up position (ie, FM2).
55. **Remote.** Connects to the computer RS232 port via the CI-V interface.
57. **AGC out.** Connects to the A/D converter in the computer.
59. **AGC on/off.** Must be on.

Description of the radio telescope.

1. Antenna

The dish itself is a 3.7 metre diameter spun aluminium paraboloid with a focal length of 1.35 m (ie, f/d = 0.375). The **physical aperture,** A_p, is simply the physical collecting area of the dish, and is given by

A, $= \pi D^2/4$.

The incoming plane wavefront from a distant source is reflected from the dish surface and is collected by the feedhorn, which passes the signal along a very short piece of waveguide to the preamplifier. The preamplifier is mounted right on the feedhorn itself to keep signal losses to an absolute minimum.

If the dish were a perfect paraboloid, and if the feedhorn responded equally to parts of the wavefront from all portions of the dish, the antenna response to a distant point source would be an Airy function. In reality, the feedhorn is designed to be less sensitive to signals from near the edges of the dish than to those from the inner sections. (The reasons for this are central to the design of all communications, space and radioastronomy antennas, and will investigated in a later experiment.) Additionally, some parts of the dish contribute nothing to the signal response - eg those in the shadow of the feedhorn and its support legs. The net result is that the antenna is less than 100% efficient at collecting radiation. The ratio of the power it receives from a distant point source to the power which actually falls on the aperture is known as the **aperture efficiency,** η_a. The **effective aperture,** A„ can thus be defined as

$$A_e = \eta_a A_p.$$

The aperture efficiency, η_a, of this particular antenna is stated by the manufacturer to be 65%.

Again, if the feedhorn responded equally to signals reflected from all parts of the dish, the antenna response to a distant point source would be an Airy function. The spatial resolution would then be given by the familiar Rayleigh criterion, which gives the diffraction-limited resolution of a circular aperture as

$$\Delta\theta_r = 1.22\lambda/D.$$

This is in fact a reasonably good approximation for our antenna. We can go further, and calculate the full-width-at-half-maximum response of the antenna as

$$\Delta\theta_{fwhm} \sim \lambda/D.$$

2. Servo system

The telescope can rotate 360 degrees in azimuth and 90 degrees in elevation, thus covering the entire hemisphere of sky. (Exercise: What are the other possible arrangements for a telescope mount? What advantages and disadvantages do these have?) The two axes are independent, and are driven by small (90 watt) DC motors. The position of each axis is recorded by an incremental encoder. These devices produce 3,600 pulses per revolution of the motor shaft. The pulses pass on to up-down counters in the computer, which can then derive the current position of the telescope by seeing how far it has moved since the counters were reset. The azimuth motor drives the telescope via a toothed-belt reduction, and a worm and worm wheel. Elevation drive is accomplished via a toothed-belt reduction and a lead-screw.

Before the telescope can be used, it must be moved to some reference position and the counters set to zero: this is done by using the “home” command on the computer. Once “homed” the counters keep track of the telescope position until it is switched off or the wiring disconnected.

The telescope must be prevented from moving beyond the safe limit of its travel. This is done by the use of mechanical limit switches. There are four such switches on each axis - two “inner” limits, and two “outer” limits. **As** the telescope approaches the extreme of, say, its clockwise azimuth rotation, it first trips the inner clockwise limit. This notifies the computer, which stops the motion and inhibits further clockwise travel. In the case of a failure (either software or hardware), the telescope might nevertheless continue moving and cause serious damage. This is prevented by the outer clockwise limit. This switch is wired directly in series with the motor, and stops the telescope dead in its tracks. Under normal operation the outer limits are never reached.

At the present time the telescope pointing software allows the telescope to be moved to any desired position in the sky. It cannot, however, continuously “track” an object such as the sun that is moving across the sky. Instead, the user must update the telescope position sufficiently often to keep the object within the telescope beam.

The earth rotates once on its axis every 24 hours, ie, at a rate of 15 arcseconds per second of time. (Exercise: calculate how long it will take the sun to move through the telescope beam if the telescope position is not updated.)

3. Signal Path

Signals in the range 12.25 - 12.75 GHz are received by the feed horn and amplified by a very low noise preamplifier (noise temperature = 80K). They then pass to a mixer, together with a 11.3 GHz signal from the local oscillator. By a process known as heterodyning, the mixer creates a new signal called the intermediate frequency, or IF. This IF signal is at a frequency given by the difference between the incoming signal fequency and that of the local oscillator:

$$\nu_{IF} = \nu_{input} - \nu_{local\ osc.}$$

The IF signals thus lie in the range 950 - 1450MHz. Each frequency component in the IF signal is an exact representation of the corresponding component at the original signal frequency.

The IF signal is further amplified, then sent down the coaxial cable to the control room. The power supply voltage (+18 V) for the preamplifier is sent up from the control room on the inner conductor of the coax.

In the control room, the coax connects to a bias-T, which passes the IF signal onto the receiver, and connects the +18 V from the power supply to the coax innner conductor. The receiver selects a slice of spectrum centered on the frequency (25 - 1,999MHz) to which it is tuned. The width of this slice, or IF bandwidth, depends on the receiver mode, and in this experiment is 150kHz.

The signal strength is indicated on the S-meter (note that this scale is logarithmic), and is also available by monitoring the receiver AGC (Automatic Gain Control) voltage. The AGC voltage is passed to the computer, where it is sampled by a 12-bit A/D (Analog-to-digital) converter. Because the voltage is a non-linear function of signal strength, it must be calibrated by means of a look-up table which has previously been generated with a precision signal generator. This calibration is done automatically by the computer, and so the signal it displays is in units of power.

4. What is a solid angle?

Well, first of all, what is a **radian?**

##insert figure##

An angle θ of one radian subtends an arc, L, of length L = r. Thus, in general, $\theta = L/r$, where θ is measured in radians. Clearly there are 2π radians in a circle.

Now for the **steradian.**

##insert figure##

The solid angle, Ω, of the cone is given by the area, A, on the surface of the sphere divided by r^2. Solid angle is measured in steradians. One steradian subtends an area, A, equal to r^2. Clearly there are 4π steradians in a sphere.

For small Ω, the area of the surface on the sphere is approximately that of a disc at distance r, ie.

##inset figure##

If θ is the apex angle of the cone, $A_{disc} = \pi(r.\theta/2)^2$.

$\therefore\ \Omega \cong (\pi/4).\theta^2$ steradians (for small θ, and θ in radians).

5. Library collection.

A small collection of relevant books and manuals is maintained in the control room.

ARRL Handbook
ARRL Antenna Handbook
Icom R7000 receiver manual
Icom CI-V reference manual
Icom CT-17 reference manual
Miscellaneous satellite TV manuals