Chapter 11

Calibration

This chapter is being rewritten—more soon

11.1 Efficiency Measurements

11.1.1 Calculate the Flux of a Planet

The thermal emission from a planet may be represented:

$$S_\nu = B_\nu(T)(1 - e^{-\tau})\Omega_s \tag{11.1}$$

where

$\mathbf{B_\nu(T)}$ is Planck's Law, in the Rayleigh-Jeans limit, $\mathrm{B}_\nu(\mathrm{T}) = 2\mathrm{k}\nu^2/\mathrm{c}^2\ \mathrm{T}$.

τ is the optical depth; for the planets, $\tau >> 1$,

Ω_s is the solid angle of the source, $\pi\ \theta_{eq}\ \theta_{pol}/4$,

θ_x are the polar and equatorial angular diameters.

yielding,

$$S_\nu = \frac{2kT\nu^2}{c^2}\pi\theta_s^2 \tag{11.2}$$

The planetary diameters can be obtained from The Astronomical Almanac for the current year; for 1996, they can be found on pages E52-E77. The planetary temperatures for frequencies in the range 200-500 GHz, are summarized in Table 2.1

Table 11.1: Planetary Temperatures

Planet	Frequency	Temperature
Mercury	345	501
Venus	230	275
	345	300
Mars	230	207
Jupiter	227	171
	279	170
	337	174
	392	163
	451	167
Saturn	310	135
	451	270
Uranus	230	92
Neptune	230	88

11.1.2 Measure the Atmospheric Opacity

11.1.2.1 Observing

For measurement of the atmospheric opacity, total power mode must be used. For single color bolometers (the 1.3 mm and 0.9 mm), the pre-amplifier box on top of the bolometer must be switched from INTERNAL to EXTERNAL to change from AC to DC coupling. Each receiver is then connected into two separate channels in the voltage-to-frequency converter; currently, channels 1 and 2 are designated for single channel bolometers on the left flange, channels 5 and 6 are designated for the PI SIS 460 GHz receiver, and channels 7 and 8 are designated for single channel bolometers on the right flange. The lower channel of each pair is for the switched power, the uppper is for the total power. When executing the RX verb, it selects the switched power by default. Inform the on-line data reduction software to look at Channel 2 by typing:

OBST> obs dis1 2

This tells the on-line CHEF to look at channel 2.

OBST> mbt sig1=b1

This tells the on-line CONT2 (TOOLBOX) to look at channel 2. Note: This will soon change to a simple specification of the continuum mode!

Now, take the actual skydip. The skydip procedure takes the form:

SKYDIP < azimuth > /AIRMASS max min /NUMBER_SKY np

If the azimuth is left blank, it will default to the current azimuth. The default airmass values are 2.3 and 1.1 which are "safe" for all azimuths. The default number of points is six; in most cases, typing 'skydip' at the OBST prompt will get you want.

After the SKYDIP finishes, a person is needed in the receiver room with a cold load. When the cold load is in place, take a 5 second observation of the cold load with:

OBST> ctrack /time 5

Similarly, do the same with a hot load. Record the scan numbers for the three scans (SKYDIP, COLD load and HOT load).

11.1.2.2 Reducing

Using TOOLBOX

In a FRANKE window at the DCL prompt, type:

cont2

Within CONT2, type:

co=sky.c44
read
on=scan number of skydip
end

Respond with 'ht' for all 6 subscans processed. For each subscan, an average value will be printed out. Record these values.

Next:

on=scan number of cold load
end
on=scan number of hot load
end

Next, at the DCL prompt, type:

run fdisk:[jmangum.smt]tauplt

This program prompts for the number of airmasses (typically 6), and then the corresponding values for the airmass and signal at each airmass. It then requests the temperatures and counts for the hot and cold load (hot load values are ambient for the room at the time, while cold load values seem best represented by 80 K). It will then prompt for a plot device (e.g. skydip.ps/ps (for a postscript file)). Plot this file out by typing 'plot skydip.ps'.

If you are satisfied with the skydip, it is necessary to restore both the bolometer and software to normal operating mode (switched rather than total power mode). Flip the switch on the pre-amp box back to INTERNAL. Type in OBST:

OBST> obs dis1 1
OBST> mbt sig1=a1
OBST> c_mode /phase 1 /def

Using MOPS

The reduction of a skydip scan can also be done within the Zylka MOPS software. In this case, one only needs the skydip scan (not the hot and cold load scans). From the DCL prompt, type "skydip" (if for some reason this fails, type "@[rzylka]zylka" to enable the appropriate symbols). Follow the instructions. Try to find a value for RATIO such that the smallest error for the skydip is obtained. Note: If the optical depths are very high (> 1.0), SKYDIP will not give correct fits, since the model used by this program is too simple to describe an optically thick atmosphere.

11.1.3 Measure the Antenna Temperature of a Planet

11.1.3.1 Observing

Within OBST, a CONOFF scan performs a measurement of a source alternately in the positive and negative beams of a beam-switched observation. If the wobbler is set to a 120 arcsecond separation (via "wob /w_pos -60 +60 /w_b 2 2 ") then:

OBST> conoff -120 0 az /time 10 10 will perform an on-off scan between the source and the reference position of +120 arcseconds in azimuth with 10 seconds per on/off.

In addition, you will need to obtain a calibration scan for converting the arbitrary count units to Kelvin. Put a hot load in front of the receiver and take an observation:

OBST> c_mode /phase 2 /def This tells the software not to take the difference between the two phases of a beam-switched observation.

OBST> ctrack /time 5 5 This will perform a 5 second observation on the hot load. Next, have someone put a cold load in front of the receiver and take another observation:

OBST> ctrack /time 5 5

Change the number of phases back to 1 (OBST> c_mode /phase 1 /def).

11.1.3.2 Reducing

In a window on Frankenheim (normally chose GREG or CHEF window), type 'cont2', which calls the TOOLBOX continuum software reduction package. Within CONT2:

commandfile = onoffd.c44
read
onscan = <the scan number of the CONOFF measurement>
end
onscan = <the scan number of the hot load measuremnet>
end
onscan = <the scan number of the cold load measurement>
end

You now have the measured antenna temperature in arbitrary units and values of counts for two known temperatures. The Kelvin/counts should be simply: R = (280K - 77K) / (counts(hot) - counts(cold)). Multiply the measured antenna temperature in counts by R. This is your measured antenna temperature in Kelvin.

11.1.4 Calculating Jy/K

From Equation n (Flux density in the R-J limit) and

$$\Omega_A = \frac{\lambda^2}{A_p} \tag{11.3}$$

for an ideal dish, we get:

$$S = \frac{2k}{A_p} T_R \tag{11.4}$$

where $A_p = \pi r^2$. Thus for an ideal 10 meter dish:

$$\frac{Jy}{K} = 35.15 \tag{11.5}$$

11.1.5 Calculating η_l

η_l is the hot spillover efficiency (all losses that appear to terminate at the ambient temperature, including ohmic losses and rearward scattering and spillover). In the notation of Kutner and Ulich (1981),

$$\eta_l = \eta_r \eta_{rss} \tag{11.6}$$

η_l may be directly obtained from a measurement of the atmospheric opacity, using:

$$V_h = G[T_{RX} + T_h] \tag{11.7}$$

$$V_c = G[T_{RX} + T_c] \tag{11.8}$$

$$V_{sky} = G[T_{RX} + (1 - \eta_l e^{-\tau})T_h] \tag{11.9}$$

We can set up a quantity (as in CSO guide):

$$A = \frac{ln((V_h - V_c)}{(V_h - V_{sky})} \tag{11.10}$$

Making the appropriate substitutions, we get:

$$A = \frac{\tau_z M + ln((T_h - T_c)}{(\eta_l T_h))} \tag{11.11}$$

where M = the airmass.

A is a linear function of airmass with slope, τ_z. η_l can then be found from the intercept as:

$$\eta_l = (1 - (T_c/T_h))e^{-intercept} \tag{11.12}$$

In practice, the reduction of the skydip (§4.1.2.2) lists the value of η_l.

11.1.6 Calculating η_A and η_{MB}

From Kraus,

$$\eta_A = \frac{A_e}{A_p} \tag{11.13}$$

$$\eta_{MB} = \frac{\Omega_{MB}}{\Omega_A} \tag{11.14}$$

In addition, from the derivation of the relationship between radiated power and beam solid angle of the dish, we know that λ^2=$A_e\Omega_A$. In the above equations:

η_A = aperture efficiency

η_{MB} = main beam efficiency

A_e = effective area of the telescope, taking into account the detrimental effects to the collecting area, such as deconstructive interference and tapering at the edges of the dish to minimize sidelobes.

A_p = actual physical area of the telescope

Ω_{MB} = main beam solid angle

Ω_A = total beam solid angle

λ = operating wavelength

We can obtain a relationship between η_{MB} and η_A from these relationships:

$$\eta_A = \frac{\lambda^2}{A_p \Omega_{MB}} \eta_{MB} \tag{11.15}$$

We use this expression to obtain η_{MB} after deriving η_A.

The physical area of the dish is a known quantity, but we need another expression for the effective area. In the R-J limit, the flux from a point source is given by:

$$S_{obs} = \frac{2kT_A}{A_e} \tag{11.16}$$

In this expression, S_{obs} is the observed flux and T_A is the antenna temperature of the source. Therefore:

$$\eta_A = \frac{2kT_A}{A_p S_{obs}} \tag{11.17}$$

We now have an expression based only on measured quantities. We can re-write this expression if we substitute:

$$S_{obs} = \int\int B(r,\phi) P_n(r,\phi) d\Omega \tag{11.18}$$

where:

$B(r,\phi)$ = brightness distribution of the source

$P_n(r,\phi)$ = normalized power pattern of the beam

We will assume that P_n is a gaussian of FWHM specified by the diameter of the Airy disk, and that the brightness distribution of a planet is constant over a disk of radius R. Plugging in for the form of a gaussian, we get:

$$S_{obs} = 2\pi\sigma^2 B(1 - e^{\frac{-R^2}{2\sigma^2}}) \tag{11.19}$$

Substituting the above into the equation for η_A:

$$\eta_A = \frac{2kT_A}{A_p} \frac{R^2}{2\sigma^2} \frac{1}{\pi R^2 B(1 - e^{\frac{-R^2}{2\sigma^2}})} \tag{11.20}$$

This equation states that the η_A is effectively the measured flux (equal to the measured antenna temperature (§4.1.3) times the Jy/K conversion (§4.1.4)), divided by the true flux (equal to the planetary flux (§4.1.1) times the correction for gaussian weighting over a uniform disk $(2\pi\sigma^2(1 - e^{\frac{-R^2}{2\sigma^2}}))$.

The main beam efficiency is then just:

$$\eta_{MB} = \frac{2\pi\sigma^2}{\Omega_{beam}}\eta_A \tag{11.21}$$

11.2 Useful Background Papers

For reference, we list below a number of papers which discuss the calibration of millimeter data. Where possible, we include a link to a postscript copy of the paper. We urge that the potential observer look these papers over ¡strong¿before¡/strong¿ he/she visits the telescope for the first time. Inexperienced submillimeter observers *must* discuss what calibration observations will be necessary for their program with their contact person at the HHT or any Friend of the Telescope.

11.2.1 Papers on site at the HHT

1. ”Secondary Calibrators at submillimetre wavelengths”, Sandell, G., 1994, MNRAS, 271, 75.

   The paper discusses secondary calibrators for submillimetre continuum photometry. The data are all calibrated relative to Mars and Uranus.

2. ”Observations of radio lines from unresolved sources: telescope coupling, Doppler effects, and cosmological corrections”, Gordon, M. A., Baars, J. W. M., and Cocke, W. J., 1992, AA, 264, 337.

   The paper has a nice section on T_A^* and T_R^* conversion to T_A^*

3. ”Calibration at the CSO”, Phillips, T. G., CSO Cookbook. Detailed discussion of chopper calibration.

4. ”Absolute Calibration of Millimeter-Wavelength Spectral Lines”, Ulich, B. L., and Haas, R. W., 1976, ApJ Supp., 30, 247.

   Discussion of chopper calibration.

5. ”Recommendations for Calibration of Millimeter-Wavelength Spectral Line Data”, Kutner, M. L., and Ulich, B. L., 1981, ApJ., 250, 341.

   Formal definitions for T_A^*, T_R^*, are presented. A general discussion of calibration is also included.

6. ”Calibration of Spectral Line Data at the IRAM 30m Radiotelescope: Going from backend counts to brightness temperatures”, Kramer, C., 1995, IRAM report.

   Discusses the calibration techniques used at the 30m and the OBS routines.

7. ”Main-Beam Efficiency Measurements of the Caltech Submillimeter Observatory”, Magnum, J. G., 1993, 105, 117.

   Includes a review of the broadband millimeter and submillimeter continuum emission properties of Mars, Jupiter, Saturn, and the Moon.

11.2.2 Related Papers which may be of interest

1. "On using the moon as a source with a standard intensity in the 0.1-30 cm wavelength range", Krotikov, V. D., and Pelyushenko, S. A., 1987, Astron. Zh., 64, 417.

   Spectrum of the moon is calculated in the wavelength range 0.1-30 cm.

2. "The Solar System: (Sub)mm Continuum Observations", Altenhoff, W. J., 1996, Proceedings of the ESO-IRAM-Onsala Workshop on "(Sub)Millimeter Astronomy".

   Discussion of early planet/asteroid/comet surface brightness results.

Chapter 12

Sensitivity Measurements

This Chapter is being rewritten — more soon.

12.1 Continuum

12.1.1 Calculating S_0

Follow the procedures in Section 4.1.3 for measuring the antenna temperature on a given planet, as well as a measurement of the atmospheric optical depth (section x.x). For a point source, the conversion to flux density is given by the standard equation

$$S_\nu = \frac{2kT_A}{\eta_A A_p} \exp(\tau_0 A) \tag{12.1}$$

where

k is Boltzmann's constant ($1.380662 \times 10^{-23} JK^{-1}$),

T_A is the measured antenna temperature with no efficiency or atmospheric corrections applied,

η_A is the aperture efficiency,

A_p is the physical aperture (x m^2 for the HHT),

τ_0 is the zenith optical depth, and

A is the number of airmasses.

A convenient measure of sensitivity for continuum observations is the rms flux density per root integration time outside the Earth's atmosphere, S_0. The sensitivity achieved in a given integration time t and under an atmosphere with zenith optical depth τ_0, is given by

$$S = S_0 t^{-1/2} \exp(\tau_0 A) \tag{12.2}$$

12.2 Spectral Line

Wait for AOSs, filterbanks, and cable-delay spectrometer.