MILLIMETER ARRAY
MEMO NO. 108

Single Dish Observing and Calibration Modes

D. T. Emerson & P. R. Jewell

December 1, 1993.

The following describes some of the more common observing modes and calibration techniques in use at the 12-m telescope. These are fairly typical for mm-wave single-dish instruments.

The observing modes are divided into spectral line and continuum techniques.

1. Spectral Line Observations

All observing techniques use an "on-source" and "off-source" measurement. The "off-source" signal may be derived by moving the telescope itself, typically by 0.5 degrees, but sometimes as much as 2 degrees in complex fields. A typical repeating observing sequence consists of 30 seconds on and 30 seconds off-source. The off-source measurement may be obtained by nutating the subreflector at a few Hz, with a beam throw of +/-1' to +/-3'. For spectral line beam switching, a switch rate of 1-2 Hz is usually sufficient; faster rates (4 to 15 Hz) are desirable for continuum observations. Finally, the off-source spectrum may be derived by frequency-switching; the local oscillator is switched typically 2 - 10 MHz, with a switching frequency of about 1 Hz.

Calibration:

If **S** represents the average on-source (Signal) spectrum
R represents the average off-source (Reference) spectrum
G represents a calibration (Gains) array,

the final spectrum is formed by:

$$G * [(S - R)/R]$$

The Gains array gives the variation of system noise across the spectrometer passband, and is found from a separate calibration measurement, which is typically performed every few minutes, say at the start of each on-off-on-off sequence. In poor weather conditions, a calibration measurement is needed more often to allow for the instability in the atmospheric opacity. Usually, the calibration is carried out by measuring the difference in power received by the receiver from blank sky (in the neighborhood of the source) and a dummy load. Simple assumptions are made about the atmospheric temperature and telescope loss factors (see the 1990 12-m Users' Manual, and MMA memo No. 35 (1985)). This then enables an absolute calibration of system noise across the passband. Specifically, for a single-sideband receiver system:

$$G(i) = Tc * Tload(i)/(Tload(i) - Tsky(i))$$

The value of the calibration scale factor, Tc, depends on accurate knowledge of the antenna rear and forward spillover efficiencies; it is also a weak function of the atmospheric optical depth. Tc is defined by Ulich and Haas (1976) and Kutner and Ulich (1981), and has a value of ~400 K for a single sideband system. This technique is valid as an absolute calibration technique within about 5 %. At the 12-m telescope, the load is a sheet of absorbing material which is physically inserted in the beam between the receiver feed and the subreflector. Another assumption is that the receiver gain and atmospheric opacity are adequately stable for the few minutes between the end of a vane-calibration measurement and the completion of the on-off source observing sequence.

This has calibrated a spectrum in terms of "Tr*", which is the antenna temperature which would be observed with a loss-less radio telescope above the earth's atmosphere. Note that this temperature scale does not include a correction for beam losses near the main diffraction beam, and most notably the error-pattern loss. In many cases, Tr* is as far as the calibration can (easily) be corrected. In some circumstances, a further correction to main beam brightness temperature, Tmb, is possible. Tmb is defined as the temperature resulting from a convolution of the main diffraction beam and the source. Sources smaller than the main beam are generally easier to calibrate than more extended ones. The intensity of small sources can be expressed, ultimately, in Janskys/beam, using measured efficiency factors. For radio sources less extended than the telescope beam, this becomes a telescope-dependent parameter.

2. **Continuum Observations**

Essentially all continuum observations use the beam-switching technique, nutating the subreflector at a few Hz. For observations of extended sources, a restoration algorithm is used to go from the beam-switched map to the equivalent single-beam map. The calibration technique is slightly different for low frequencies (< 120 GHz) and higher frequencies.

Three possibilities exist for continuum calibration: noise tube, vane, or direct scaling.

At the lower frequencies, the 12-m telescope uses a switched noise tube as a calibrated standard. The noise source is a gas discharge tube located behind the subreflector, radiating through a horn feed directed towards the main secondary focus receiver feed. In use, the noise tube is left turned on, but is modulated at a few Hz by a ferrite switch before the feed horn. This is sufficient to inject about 6 K of additional noise into the receiver. The noise tube gives insufficient signal to be useful at 150 GHz or higher frequencies.

For absolute calibration, a strong source (e.g. a planet) is observed. At low frequencies, the switched noise source can then be calibrated absolutely in terms of Janskys, or in terms of corrected antenna temperature Tr*. This requires knowledge of the atmospheric opacity in the direction of the planet, and in the direction of the source. The zenith opacity is usually derived from a sky-tip observation; the 12-m antenna is moved in elevation, ideally at the same azimuth as the planet and the source. The difference in apparent temperature between blank sky and a dummy load (the absorbing vane) as a function of air-mass is recorded. This permits derivation of the zenith opacity, and hence the correction to be applied at the elevations of the source and of the planet. Again, it is assumed that the atmosphere is stable between the two measurements.

At higher frequencies, where a switched noise source is not available, the vane calibration method, described above for spectral line observations, can be used. Alternatively, if the vane were not available, the receiver detected power output can be calibrated directly in terms of Volts/Jansky, or Volts/Kelvin, by observation of a standard source. It is then assumed that receiver gain remains constant when the unknown source is observed, but still taking into account the atmospheric opacity and air mass towards each source. This direct calibration is the least satisfactory method.

The flux density from a planet is derived from the known disk temperature, and angular size. Some planets (especially Jupiter and Venus) may be substantially resolved by the telescope beam, so an assumed telescope beamwidth has to be applied in deriving the apparent flux density from the planet. One of the largest sources of uncertainty in this method is the absolute temperature of the planet.

3. Antenna Absolute Calibration

The above procedures are repeated for each observation. For the conversion between flux density and antenna temperature, an assumed telescope efficiency factor has been used. Although this is normally fairly constant with time, it does need to be redetermined for a new receiver, for each frequency, and for any substantial change in telescope optics. NRAO staff normally perform this calibration.

The technique is to observe a strong planet, to calibrate the receiver response in terms of Janskys from a point source. The receiver itself is then calibrated in terms of degrees Kelvin, by placing a warm load, and then a cold load, in the telescope beam. For the warm load we normally use the vane absorber, at ambient temperature. The cold load is a piece of absorber at liquid nitrogen temperatures. The loads are placed in turn above the receiver and its feed optics, intercepting the beam on its way to the subreflector.

Aperture efficiencies are best determined by observing a planet smaller than the main beam. Beam efficiencies are ideally measured against a planet extending to the first nulls of the beam. Rear spillover efficiencies, needed for vane calibration, can be derived from well-calibrated tipping scans. Forward spillover must be measured against the moon.

4. Mapping procedures

The techniques used to map extended sources, both in continuum and in spectral line, are extensions of the above. All continuum observing, and some spectral line observing, use the nutating subreflector.

For continuum maps, the observing is usually carried out in an Azimuth-Elevation frame, so that the direction of beam nutation (which is fixed E-W on the 12-m) is along the scanning direction. Usually several beam-switched coverages of the same area are made, then restored to the equivalent single-beam observation, and interpolated and averaged in to a common RA-Dec grid. The observer tries to map an area sufficiently large that there is no significant emission at the edge of the coverage. The ends of each linear scan are then used to define and subtract a linear baseline level. If independent coverages with nearly orthogonal scanning directions are available (which is often the case), various algorithms (e.g. "Basket Weaving" due to Chris Salter, or "Plait" from DTE) can be applied to optimize the baselines, partially removing the requirement for zero emission at the edge of the field.

For spectral line mapping data, spectral baselines can be fitted to the raw data, removing the necessity for spatial baselines and removing the constraint of zero emission at the edge of the field.

Summary of Special Calibration Hardware:

(1) Nutating subreflector. This could also be implemented with a chopper wheel. Frequency of nutation needs to be a few Hz. Maximum beam throw is limited by optical aberrations, but is probably a few arc min.

(2) Noise tube calibration sub-standard. Should ideally be injected as early in the r.f. chain as possible (in the 12-m, from a hole in the subreflector). Probably limited to 3mm or longer wavelengths.

(3) Absorbing vane. Needs to be switched into the optical path between the feed and the subreflector, typically for a few seconds every few minutes. Temperature needs to be monitored closely, but need not be constant. An absolute cold load is also advantageous.

(4) If the receiver frontend and backend are to be used for single dish measurements, the instrumental gain stability needs to be much higher than would be required for interferometric observations alone. A 1% change in gain would at worst affect interferometer absolute calibration by 1%, or introduce ~1% sidelobes into the synthesized beam. A 1% gain change in a single-dish system would be disastrous, introducing a spurious signal perhaps 1000 times bigger than the desired signal.

References:

(1) **12m User's Manual**, P.R. Jewell (ed.), 1990, NRAO-Tucson.
(2) **MMA Memo No. 35**, P.R. Jewell, 1985.
(3) Kutner, M.L., and Ulich, B.L. 1981, **Ap. J.**, **250**, 341.
(4) Ulich, B.L., and Haas, R.W., 1976, **Ap.J.Suppl.** **30**, 247.