High Precision Calibration of Data from Single-Dish Radio Telescopes

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The traditional methods for calibrating data from cm-wave single-dish telescopes has problems in that the methods seldom obtain an accuracy better than 10%. Higher accuracy usually requires a significant outlay of telescope time and someone very familiar with the instrument. Also, the traditional assumption that the telescope has a narrow bandwidth no longer works when calibrating data from today's wide bandwidth receivers and backends. Any scientific project that needs to compare data from multiple radio telescopes is compromised at some level by the inaccuracy of the calibration. The high dynamic range, high fidelity data from telescopes like the NRAO-GBT beg for better calibration.

We have modified and developed calibration methods that can obtain an accuracy of well under 5%. The new methods require very few ancillary observations but does not require of the observer any special expertise. The techniques include better models for atmospheric opacity and air mass; better models of the calibration noise diodes used in cm-wave radio telescopes.

Calibration Uncertainties

- The fractional error in the calibrated flux of a source that is observed at cm-wavelengths can be summarized by:

$$\left(\frac{\Delta S}{S}\right)^2 = \left(\frac{\Delta T_{CAL}}{T_{CAL}}\right)^2 + \left(\frac{\Delta\eta}{\eta}\right)^2 + (A\cdot\Delta\tau)^2 + (\tau\cdot\Delta A)^2$$

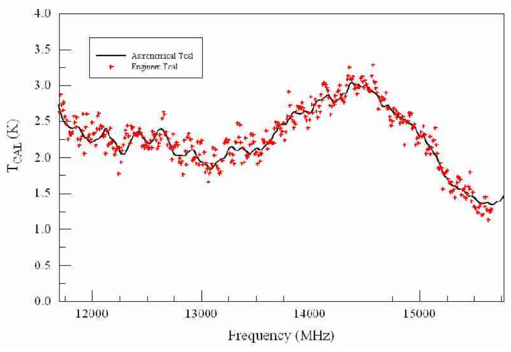
  where S = source flux density, T_{CAL} = temperature of the receiver's calibration noise diode, τ=atmospheric opacity, and η= telescope efficiency.
- Traditional calibration tables provided by the receiver engineer have a typical accuracy of only 10-15%. Observers are required to use observing time to determine high accurate values for T_{CAL}
- Wide bandwidth observations of multiple spectral lines require accurate T_{CAL} values at a finer frequency resolution than can be provided by the hot-cold load measurements performed by the receiver engineers..
- Variable weather, combined with low elevation observing, usually requires an antenna tipping to provide an estimate of τ.
- Most techniques for estimating τ use atmospheric models based on ground-level values and standard lapse rates and not the true vertical distribution of atmospheric conditions.
- Separating atmospheric effects from gain and T_{CAL} errors can be daunting for even experienced observers.
- Wide bandwidth receivers and backends require the new twist of using frequency-dependent opacities and efficiencies.

Noise Diode Values

- Traditionally, T_{CAL} values are measured by the receiver engineer using hot and cold loads -- a laborious process which achieve low frequency resolution results and an accuracy of about 10%.
- Observations of astronomical sources can produce more accurate, repeatable results with high frequency resolution over wide bandwidths with significantly less effort.
- The technique involves spectra line observations with the GBT Spectrometer of calibrators from Ott et al (1993, A&A, 284, 331). The method uses:

$$T_{CAL}(\nu) = \left(\frac{\eta\cdot A_P}{k\cdot e^{\tau\cdot A}}\right)\left(\frac{P_{REF\_ON}(\nu) - P_{REF\_OFF}(\nu)}{P_{SIG\_OFF}(\nu) - P_{REF\_OFF}(\nu)}\right)S(\nu)$$

  where A_p is the area of the telescope's dish and P_{REF_ON} P_{REF_OFF} are the detected powers on blank sky with the noise diodes on and off and P_{SIG_OFF} is the detected power on the calibrator with the noise diode off.
- The frequency resolution is that of the spectrometer (typically < 1 MHz); the bandwidth covered in a single observation can be up to 3 GHz
- The stochastic errors for a 2 minute observation produce results that are better than 1%.
- The limitations of the method is set mostly by systematic errors in the catalogs, by the accuracy of both the opacity correction and the telescope efficiency.
- With such a wide bandwidth, one must compensate for the frequency dependence of both opacity and, at high frequencies, efficiencies.
- If the engineers can measure an accurate T_{CAL} at a few frequencies across the receiver's band, then combining those T_{CAL} values with astronomical measurements can provide accurate efficiencies. These efficiencies then allow one to calculate T_{CAL}.



http://www.gb.nrao.edu/~rmaddale/GBT/Commissioning/Rcvr_Tcal/memo22_NoiseDiode.pdf

Vertical Weather Data

- The data used in this modeling are derived from forecasts of vertical weather profiles supplied by the national weather services. The forecasts, which are updated twice a day and look ahead 60 hours, are based on balloon and GOES satellite soundings.
- Each forecast consists of a time series of ground or gross weather conditions, (e.g., ground pressure, clouds, total precipitable water, …) and, most importantly here, pressure, temperature, humidity, … as a function of height and time above the observatory..
- Unlike most attempts at calculating weather effects for cm- and mm-wave observations, there is no assumed pressure heights or temperature lapse rates. Rather, calculations of the index of refraction and absorption coefficients are performed on each layer of the atmosphere, thereby eliminating any assumptions concerning the atmospheric profile above the observatory.
- Using ray tracing, one can estimate quantities like : (1) Refraction for any elevation and time; (2) Air mass for any elevation and time.
- Using radiative transfer, one can estimate: (3) Opacities for any time and user-chosen frequency; (4) System temperatures for any elevation, time, and frequency; (5) Atmospheric temperatures for any time and user-chosen frequency.

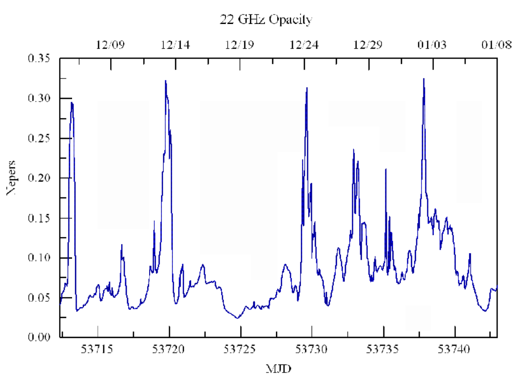
http://www.gb.nrao.edu/~rmaddale/Weather

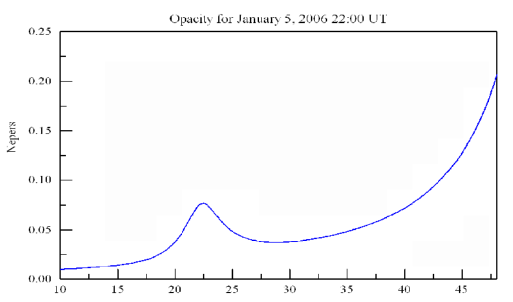
Atmospheric Opacities

Opacities are derived via the MWP model of Liebe (1985), with some modifications by Danese and Partridge (1989). Opacities are calculated based on the contributions from 40 O_2 resonance lines, three H_2O resonance lines, H_2O continuum, and the dry air. The model should be accurate for most purposes up to 120 GHz. The contributions to opacity from hydrosols (fog, cloud water droplets, etc.) is modeled after Schwab and Hogg (1989), combined with the Liebe hydrosol continuum model.

The opacity results are:

- A time series of τ values at user-selected frequencies
- An estimate of τ as a function of frequency for any time





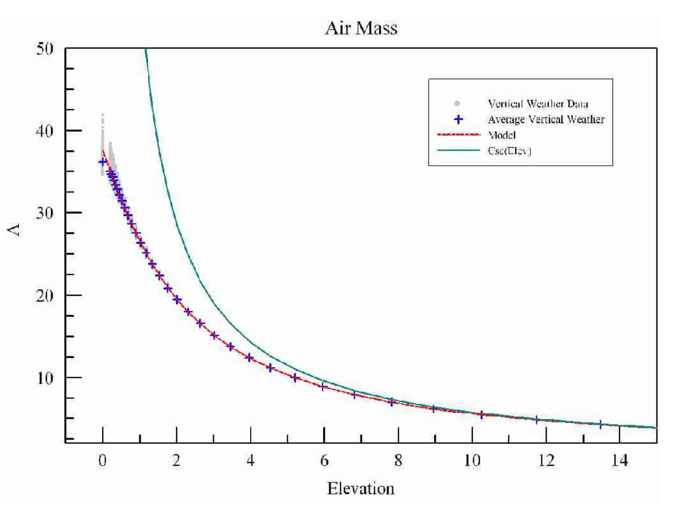
H.J. Liebe, "An Updated model for millimeter wave propagation in moist air", 1985, *Radio Science*, 20, 1069

L. Danese and R.B. Partridge, "Atmospheric Emission Models: Confrontation between Observational Data and Predictions in the 2.5-300 GHz Frequency Range", 1989, *AP.J.* 342, 604.

F.R. Schwab and D.E Hogg, "Analysis of Radiosonde Data for the MMA Site Survey and Comparison with Tipping Radiometer Data" (1989), from the IAU Symposium on "Radio Astronomical Seeing"

Air Mass

- The frequently-used csc(elev) approximation for Air Mass can lead to calibration errors of a few to 20% at low but still reasonable elevations.
- Vertical weather data, combined with ray tracing using radio frequency refraction, allows us to accurately model air mass down to the horizon under all weather conditions.
- Above about 1 degree, one can ignore the changes due to variable weather and, instead, use a simple, fast analytical approximation that is more accurate at lower elevations than the model presented in K. Rohlfs and T.L. Wilson, *"Tools of Radio Astronomy, 2nd edition"*, 1996, pp. 165-168..



$$A = -0.0234 + \frac{1.014}{\sin\left(Elev + \frac{5.18}{Elev + 3.35}\right)}$$

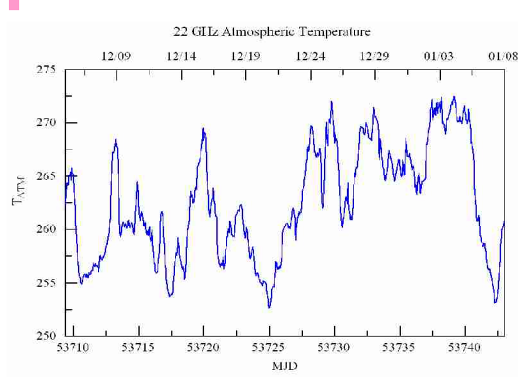
Atmospheric Temperatures

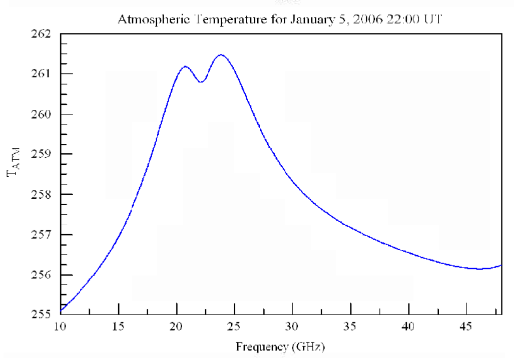
To derive atmospheric opacity, observers typically use 'tipping' to measure values of the System Temperature (T_{SYS}) over a wide range of air masses . A simplistic model of T_{SYS} is:

$$T_{SYS} = T_{Instrument} + T_{ATM}\cdot(1 - e^{-\tau\cdot A})$$

One usually has to assume a representative atmospheric temperature (T_{ATM}). The degree to which the assumed T_{ATM} is wrong is directly reflected in the inaccuracy of the derived opacity. Now, one can determine T_{ATM} from radiative transfer calculations using vertical weather data. The analysis produces:

- A time series of T_{ATM} values at user-selected frequencies
- An estimate of T_{ATM} as a function of frequency for any time





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