Various Methods for Measuring System Temperatures on Individual Elements of the Allen Telescope Array

Ronald J Maddalena
August 8, 2020

Introduction

One of the goals for the current program for upgrading the Allen Telescope Array (ATA) is to measure with sufficient accuracy the frequency-dependent values for system temperature, T_{SYS}. The current method involves lab-type measurements using a hot load that covers the feed, the sky as a cold load, and a spectrum analyzer as a broad-band power detector. These measurements can provide excellent results, but they are labor intensive and require taking a dish out of routine observing. We are interested in devising ways to make T_{SYS} measurements that can be taken as part of routine observing, using the Observatory's standard backends, maybe with some sacrifice in the accuracy of the results. At this stage, we are restricting ourselves to methods that will have sufficient accuracy when using each ATA element as a single dish.

Here I describe three possible methods. The first uses the Moon as a 'hot' load and blank sky as a 'cold' load (a method that has been used before with the ATA). The next method uses more point-like astronomical sources as 'hot' loads and blank sky as a 'cold' load. The final method uses the Earth's atmospheric emission at low and high elevations as 'hot' and 'cold' loads. No one method is perfect. I will discuss the restrictions and inaccuracies of each, along with observing and processing tactics. Probably we will need to iteratively try each method, compare results, and then revise tactics. The final section gives a suggestion on how the products of the atmospheric method could slightly improve the current hot-cold load tests.

On-Off Measurements Using the Moon

The Moon is potentially a great source to use for measuring T_{sys} as it is radio-bright, is a near-perfect black body (like most rocky planets), and is above the elevation limits of the ATA on the average of about 9 hours a day. Essentially, if one can estimate the antenna temperature, T_A, produced by the Moon at the time and frequency of an observation, then moving the ATA on and off the Moon should be a useful method for measuring system temperatures.

At the observing frequencies of the ATA, the Moon's effective brightness temperature is roughly 220 K but can vary with phase and wavelength from this value by 10-15%. Since we might want Tsys estimates that are better than 10%, we might need better predictions for brightness temperature than the canonical 220 K. There are a few reasons for the variation. The temperature of each surface point changes in a semi-sinusoidal pattern as the Moon goes through its monthly phases in solar illumination. Since the Moon's surface is not a perfect conductor, temperature changes beneath the surface lag behind the changes at the surface, with the lag getting longer with depth. At depths where the lag exceeds the Moon's synodic period, one finds a near constant temperature with phase. Since radio telescopes probe different depths when measuring different observing wavelengths, the observed brightness temperature at long wavelengths will lag behind the Moon's phase more than at short wavelengths. Moreover, the magnitude of the temperature changes will be less at long wavelengths than at short. There are various models in the literature that we can use to estimate the frequency- and phase-dependent brightness temperature.

More importantly, to derive the Moon's T_A, one must convolve the brightness distribution of the emission across the face of the Moon with the beam shape of the ATA. At 1 GHZ, the Moon's diameter (approximately 0.5° but varies by 12% due to the Moon's orbit), is smaller than the ~3.5° FWHM beam of the ATA – The Moon at 1 GHz with an ATA element is almost a point source and has a T_A that varies by 20% due to its orbit. Above 7 GHz, where the ATA's FWHM is about the same as the Moon's diameter, the Moon becomes an extended source. At 1 GHz with the ATA, I estimate that the Moon will produce T_A/η_A ~ 10 K while at 15 GHz the ATA will see T_A/η_{MB} ~ 220 K, where η_A and η_{MB} are the aperture and main beam efficiencies of the ATA. Because of the wide range of possible values for T_A, errors in forming the convolution will produce significant systematic errors in the derived system temperatures, especially near 7 GHz where the FWHM is close to the size of the Moon.

In short, if we want better than ~15% accuracy we will need to derive brightness temperatures using models in the literature, the Moon's phase at the time of the observations, and the observing frequency. However, it is more important that we use the Moon's diameter, the details of the ATA's beam shape and aperture efficiency at the observing frequency to derive T_A from brightness temperature.

The observations could consist of moving on and off the Moon, repeating the cycle about five times. Since the expected T_A is rather large, even at 1 GHz, the dwell time on each position need not be more than a few seconds. Sampling need not be any faster than about 10 Hz, but must be faster tha n 1 Hz so as to provide some ways to excise broadband RFI or receiver compression from RFI. The observing frequencies should be those that have been established as having a good chance of being free from RFI. The bandwidth can be relatively narrow as the observations will be limited by 1/F receiver instabilities.

On the sky we would separate the *on* and *off* observations by a few degrees, a few FWHM beam widths (for the lowest observing frequency), or whichever is larger. One should try to keep the atmospheric and spillover contributions to T_{SYS} the same for both observations by having the *off* position at the same elevation as the Moon. If that is not possible, we might need to correct for the differences in spillover and atmosphere. It is also highly preferable to avoid low elevations and bad weather days to minimize atmospheric affects and corrections.

When observing on and off the Moon, the measured powers will be:

$$P_{\text{Moon}} = g\left((T_A + f \cdot T_{CMB}) \cdot e^{-\tau \cdot A_{\text{Moon}}} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau \cdot A_{\text{Moon}}}) + T_{Spill}(\text{elev,Moon})\right)$$

$$P_{\text{Off}} = g\left(T_{CMB} \cdot e^{-\tau \cdot A_{\text{Off}}} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau \cdot A_{\text{Off}}}) + T_{Spill}(\text{elev,Off})\right) = g \cdot T_{SYS}$$

Then,

$$T_{SYS} = \frac{P_{\text{Off}}}{P_{\text{Moon}} - P_{\text{Off}}}\left((T_A - T_{ATM} + f \cdot T_{CMB}) \cdot e^{-\tau \cdot A_{Moon}} - (T_{CMB} - T_{ATM}) \cdot e^{-\tau \cdot A_{Off}} - \Delta T_{Spill}\right).$$

If the elevations for the Moon and off observations are approximately the same, then:

$$T_{SYS} = \frac{P_{\text{Off}}}{P_{\text{Moon}} - P_{\text{Off}}}\left((T_A - (1 - f) \cdot T_{CMB}) \cdot e^{-\tau \cdot A}\right).$$

Here g is the gain, in units of power/K; τ and T_{ATM} are atmospheric opacity and effective atmospheric temperature as derived from weather forecast models for the time and frequency of the observations (see below for more details). T_{CMB} is the 2.7 K cosmic microwave background and f is the integrated fraction of the beam not covered by the Moon (f is ~1 at 1 GHz and zero above ~7 GHz). T_{Rcvr} is the receiver's noise temperature, A is the air mass at the two observing elevations (approximately 1/sin(elev)); and T_{Spill} and Δ T_{Spill} are the spillover temperature at the two elevations and the difference in spillovers.

Note that the derived T_{SYS} is for the elevation of the observation. To derive T_{SYS} for the zenith, subtract $T_{ATM}(e^{-\tau} - e^{-\tau \cdot A_{\text{Off}}})$. Or, to derive T_{SYS} for the best weather days at the Observatory at the zenith, subtract $T_{ATM}(e^{-\tau_{Best}} - e^{-\tau \cdot A_{Off}})$.

On-Off Measurements Using Other Astronomical Sources

The established list of calibrators for radio astronomy are given in Perley & Butler (2017ApJS..230....7P). Unfortunately, when observed with the 6.1 m dishes of the ATA, most of these sources will have T_A well under 1 K at ATA's lowest frequencies. Furthermore, most have synchrotron spectra, making them weaker as one goes up in frequency. Thus, the standard calibrators probably would not produce sufficient sensitivity when using a single ATA dish.

Instead, we might have to use sources with suitably high, but less accurate and sometimes variable, flux densities. Some of these are point sources for the ATA, others will be extended with respect to the beam size at the higher ATA frequencies. Sources to consider are Cas A, Cyg A, Tau A, and Virgo A.

The observations could consist of moving periodically on and off the source with the location of the *off* being a few FWHM beam widths away for the lowest observing frequency. The number of times we repeat the on-off cycle depends upon the strength of the source, but should probably be no fewer than five. We should use the same dwell time, sample time, observing frequencies, and bandwidths as described above for the Moon observations. As with observations of the Moon, one should try to keep the atmospheric and spillover contributions to T_{SYS} the same for both observations by having the *off* position at the same elevation as the *on* position. If that is not possible, we might need to correct for the differences in spillover and atmosphere. It is also highly preferable to avoid low elevations and bad weather days to minimize atmospheric affects and corrections.

The frequency-dependent T_A for point sources is proportional to the best available estimate of the frequency-dependent flux density of the source, S(ν) and the aperture efficiency, η_A(ν):

$$T_A(\nu) = \frac{\eta_A(\nu) \cdot S(\nu) \cdot Area \ \cdot e^{-\tau \cdot A_{on}}}{2k}$$

Here, k is Boltzman's constant and Area is the geometric projected area of the ATA's primary. To derive T_A for extended sources, one must convolve the frequency-dependent brightness distribution of the source with the (potentially) frequency-dependent beam pattern of the ATA.

$$P_{\text{On}} = g\left((T_A + T_{CMB}) \cdot e^{-\tau \cdot A_{\text{On}}} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau \cdot A_{\text{On}}}) + T_{Spill}(\text{elev,On})\right)$$
$$P_{\text{Off}} = g\left(T_{CMB} \cdot e^{-\tau \cdot A_{\text{Off}}} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau \cdot A_{\text{Off}}}) + T_{Spill}(\text{elev,Off})\right) = g \cdot T_{SYS}$$

And

$$T_{SYS} = \frac{P_{\text{Off}}}{P_{\text{On}} - P_{\text{Off}}}\left((T_A - T_{ATM} + T_{CMB}) \cdot e^{-\tau \cdot A_{on}} - (T_{CMB} - T_{ATM}) \cdot e^{-\tau \cdot A_{Off}} - \Delta T_{Spill}\right).$$

If the elevations for the *on* and *off* observations are approximately the same, then:

$$T_{SYS} = \frac{P_{\text{Off}}}{P_{\text{On}} - P_{\text{Off}}} T_A \cdot e^{-\tau \cdot A}.$$

To derive T_{SYS} for the zenith, subtract $T_{ATM}(e^{-\tau} - e^{-\tau \cdot A_{\text{Off}}})$ and to derive T_{SYS} for the best weather days at the Observatory at the zenith, subtract $T_{ATM}(e^{-\tau_{Best}} - e^{-\tau \cdot A_{Off}})$.

Measurements Using the Emission from the Earth's Atmosphere

One can also use the emission of the Earth's atmosphere to derive an estimate of T_{SYS}. There is one intriguing advantage to using the atmospheric emission. Unlike the previous two methods where objects need to be above the ATA's elevation limit to be useful, the atmosphere is always available. The method also has the possible advantage over the previous two of measuring T_{SPILL}, which, in turn could be used by the first two methods.

The Earth's atmosphere has a low, but non-zero opacity at radio wavelengths with the trend that higher frequencies have higher opacities. On clear days, opacity is roughly proportional to the total column of atmospheric water vapor (i.e., precipitable water vapor). On cloudy or rainy days, opacity increases through a process akin to Mie scattering from hydrosols or raindrops. Since precipitable water, clouds and rain are time variable, so is the opacity. The total opacity is higher at low elevation since the path length through the atmosphere is longer. From Kirchhoff's law, if the atmosphere absorbs radiation it must also emit. Lower elevation emit more than higher due to the higher total opacity. From radiative transfer theory, the emission from the atmosphere is $T_{ATM}(\upsilon)\left(1 - e^{-\tau(\nu) \cdot A}\right)$. Here, A is the air mass of the observation (~ 1/sin(elevation)), τ the frequency-dependent atmosphere opacity at the zenith, and T_{ATM} is the frequency-dependent effective atmospheric temperature.

I can already derive accurate T_{ATM} and τ from vertical weather profiles provided by the National Weather Service (NWS) using the methods and software described at www.gb.nrao.edu/~rmaddale/Weather. I have begun archiving the necessary data products for a suitable location near the Observatory.

Observations would consist of measuring the power as a function of elevations. At low frequencies on reasonable weather days, we can expect a 6 K change in T_{SYS} from the lowest to highest elevation observable with the ATA. That is a fair fraction of the best available values for T_{SYS} of about 40 K, and, thus should be easily detected with sufficient sensitivity. At high frequencies, where the best values for T_{SYS} are above 100 K, we can expect a 15 K difference in T_{SYS} between low and high elevations. To boast sensitivity at high frequencies, it might be best to schedule these measurements during moderate weather days with no forecasted clouds and rain as the weather models are less accurate during those poor weather times. We should use the same dwell time, sample time, observing frequencies, and bandwidths as described above for the Moon observations.

Since emission increases with air mass, the sampling should be in steps of air mass, not elevation. For example, elevations of 17.9° (or the ATA's minimum elevation), 19.4°, 21.3°, 23.6°, 26.4°, 30. °, 34.8°, 41.8°, 53.1°, and 87° (the ATA's maximum elevation) are separated by ~0.25 air masses. We should repeat observations about five times to provide us with a sense of the consistency of the results.

The elevation-dependent detected power for each observing frequency is:

$$P(A) = g \cdot \left(T_{CMB} \cdot e^{-\tau A} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau A}) + T_{Spill}(A)\right) = g \cdot T_{sys}(A)$$

Using the measured powers at the various air masses, and the atmospheric model values for T_{ATM} and τ, one could use a linear least-squares fit to derive the two unknowns, g and the sum of T_{Rcvr} plus any elevation-independent part of T_{Spill}. The residuals of the fit would be the elevation-dependent part of T_{Spill}, which can be compared to previous estimates and models for spillover T_{SYS}, as a function of elevation, is simply P(A) divided by the least-squares result for g.

It is important to note that the derived T_{Spill} does not include any elevation-independent (i.e., constant) component. One should only use the derived T_{Spill} when one needs just the change in spillover between two elevations. That is, the ΔT_{Spill} as used in the first methods above.

This method will not work well in the unlikely case that both the elevation-dependent and frequency dependent part of T_{Spill} has a functional form close to $e^{-\tau(\nu)\cdot A}$. Since spillover is weather independent, but the atmospheric terms are weather dependent, maybe two sets of observations taken under different weather conditions would help resolve any doubts on the results for T_{SPILL}.

Suggestions that might slightly improve accuracy of hot-cold load measurements

The current hot-cold load tests use a hot load that completely covers the feed and a cold load that is the sky. The detected power for the hot and cold parts of the tests are:

$$P_{\text{Hot}} = g \cdot (T_{Load} + T_{Rcvr})$$
$$P_{\text{Cold}} = g \cdot \left(T_{CMB} \cdot e^{-\tau \cdot A} + T_{Rcvr} + T_{ATM}(1 - e^{-\tau \cdot A}) + T_{Spill}(\text{elev})\right) = g \cdot T_{SYS}$$

Where T_{Load} is the physical temperature of the absorber used as a hot load. Then,

$$T_{SYS} = \frac{P_{\mathrm{Cold}}}{P_{\mathrm{Hot}} - P_{\mathrm{Cold}}}\left(T_{Load} - T_{ATM}(1 - e^{-\tau \cdot A}) - T_{Spill}(elev) - T_{CMB} \cdot e^{-\tau \cdot A}\right)$$

Instead of the weather-independent values currently being used in the hot-cold measurements, we can now provide weather-dependent values for τ and T_{ATM} by applying existing atmospheric models and software to the forecasts that I am now archiving.