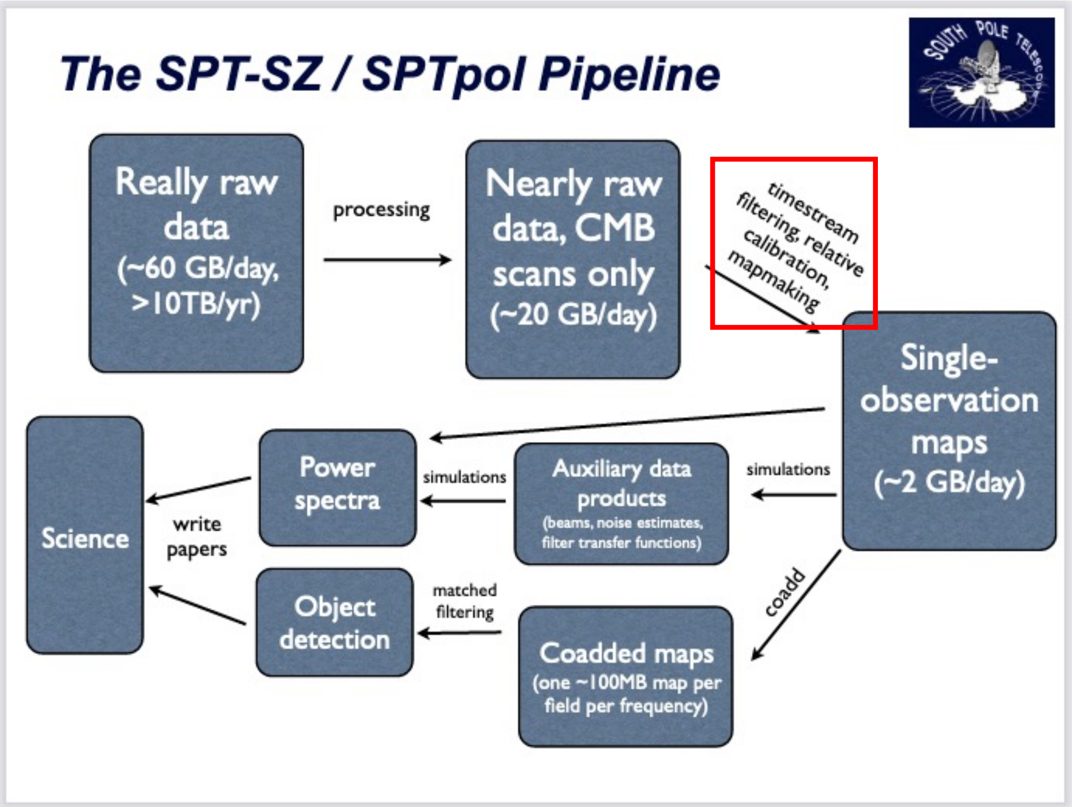
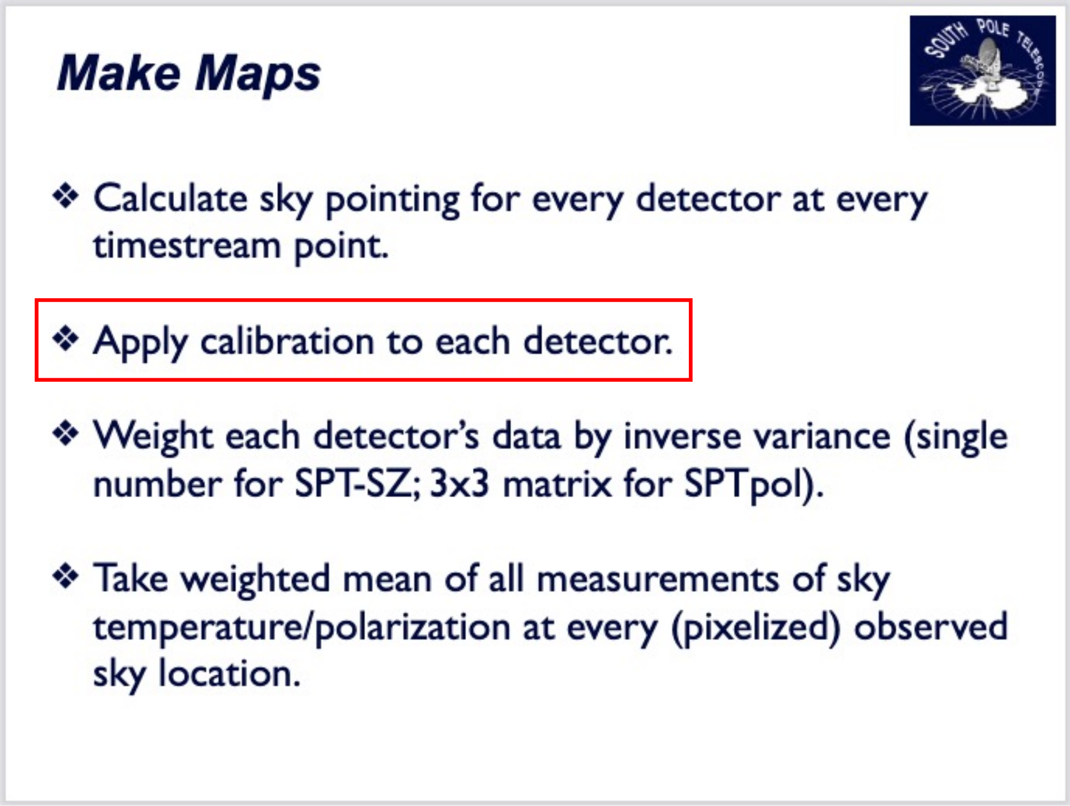
Detector timestream processing and calibration

Hello! My name is Wei, a graduate student @ UChicago working on SPT-3G.

In this presentation, I am going to expand on something Tom mentioned briefly, which is, as part of the mapmaking process, we want to calibrate timestreams in units of CMB fluctuation temperature, ΔT_{CMB}.





Contents of this presentation

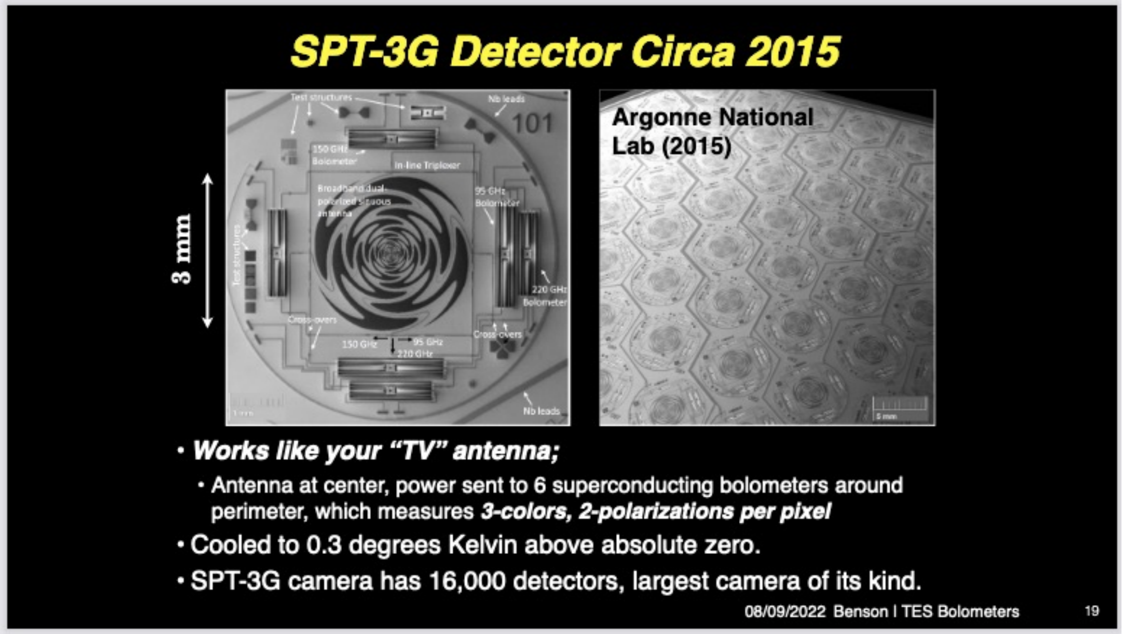
Since I have been working on SPT-3G, I will talk about what I am most familiar with: the specific calibration procedure used by SPT-3G. I think it still contains some elements that are generally useful to know, though!

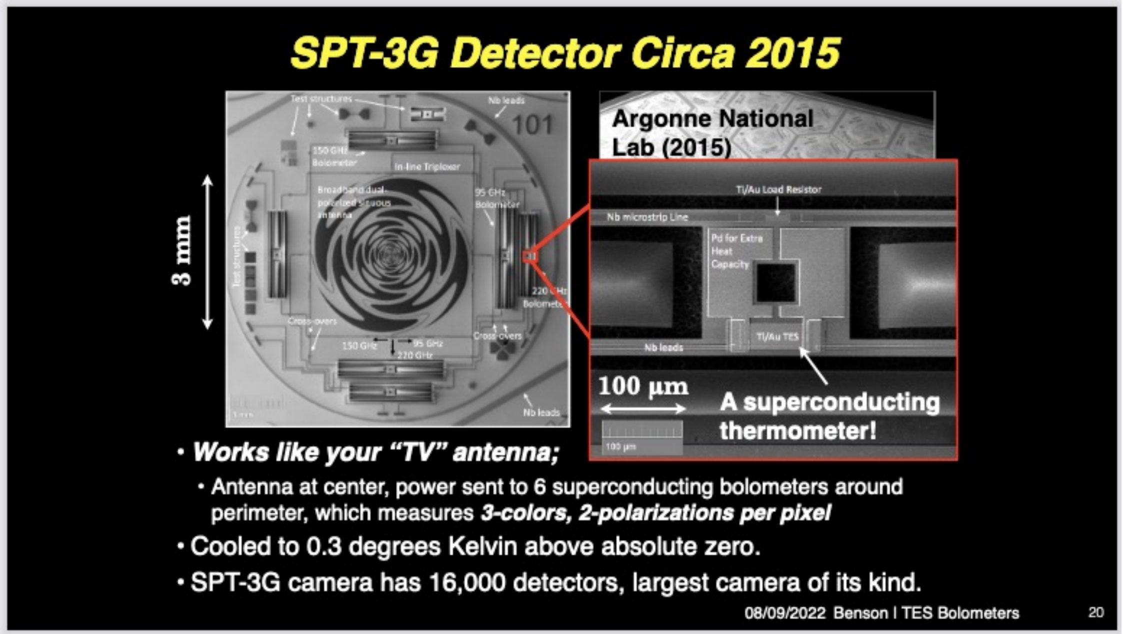
So, I will talk about

1. a few important concepts about TES bolometers (brief review)
2. four types of calibration observations used by SPT (main discussion)
3. a typical SPT observing schedule (miscellaneous things)

1. A few important concepts about TES bolometers

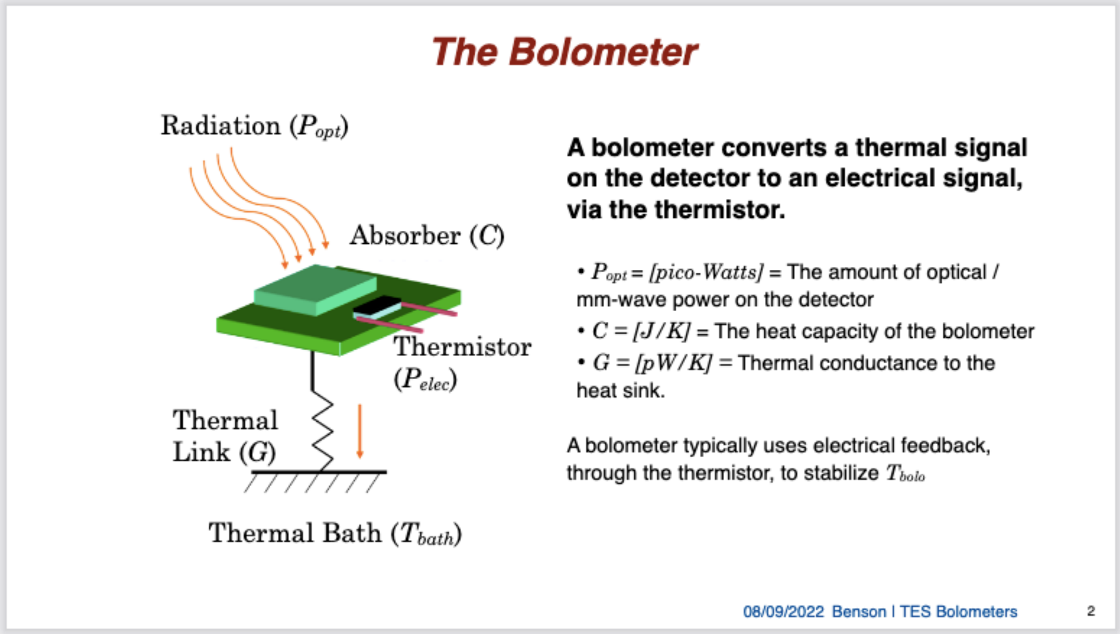
As Brad mentioned earlier this week, an SPT-3G TES bolometer lives in an island that is weakly thermally connected to the the wafer substrate.

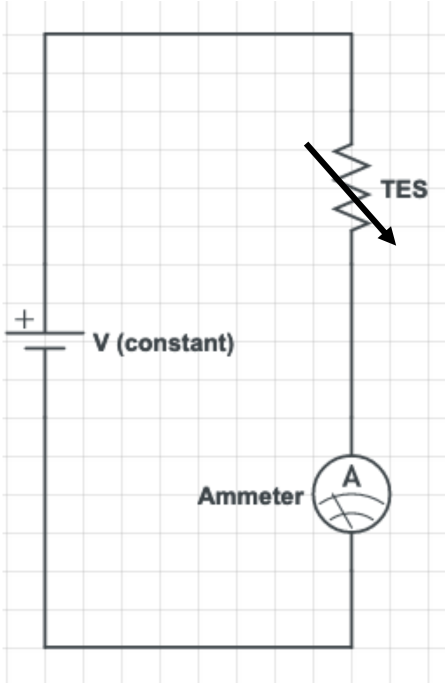


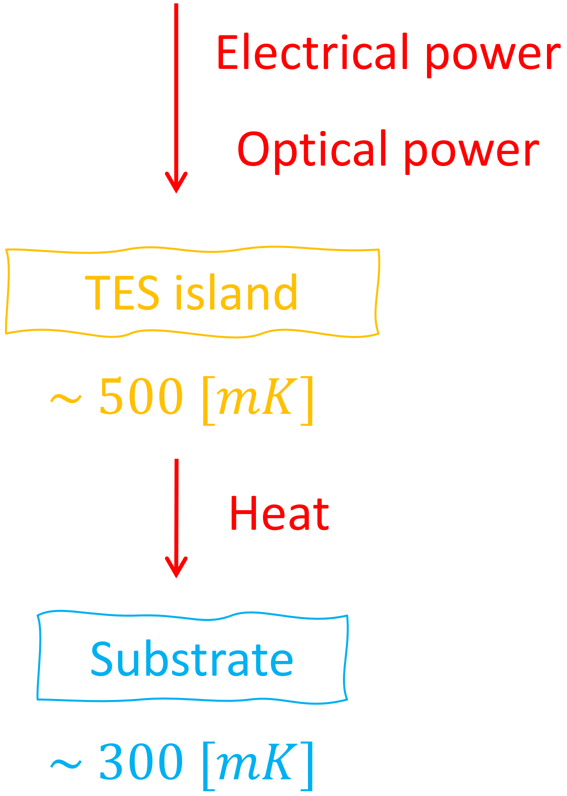


1. A few important concepts about TES bolometers

Represented in a simplistic circuit diagram, the electrical part corresponds to a variable resistor connected to a battery. The electrical power (Joule heating) dissipated on it and the optical power it receives through the antenna balance the heat flowing from it to the colder substrate.







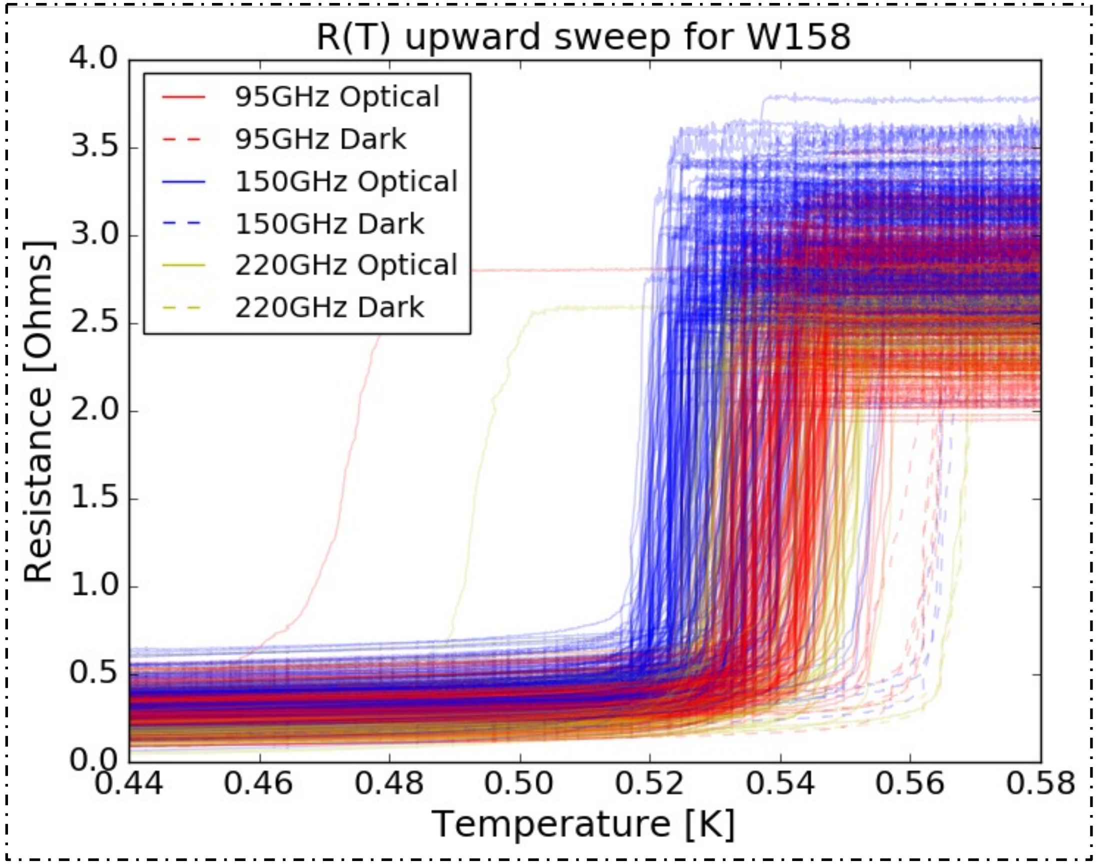
1. A few important concepts about TES bolometers

Given the constant voltage bias, an increase (decrease) in the optical power leads to a decrease (increase) in the electrical power. It will be important to keep this in mind when we look at some timestreams shortly!

$$P_{elec} = V^2/R(T)$$

$$P_{opt} \uparrow \implies T \uparrow \implies R(T) \uparrow \implies P_{elec} \downarrow$$

$$P_{opt} \downarrow \implies T \downarrow \implies R(T) \downarrow \implies P_{elec} \uparrow$$



Everett et al., Design and Bolometer Characterization of the SPT-3G First-Year Focal Plane, Journal of Low Temperature Physics 193 (2018) 1085

2. Four types of calibration observations used by SPT

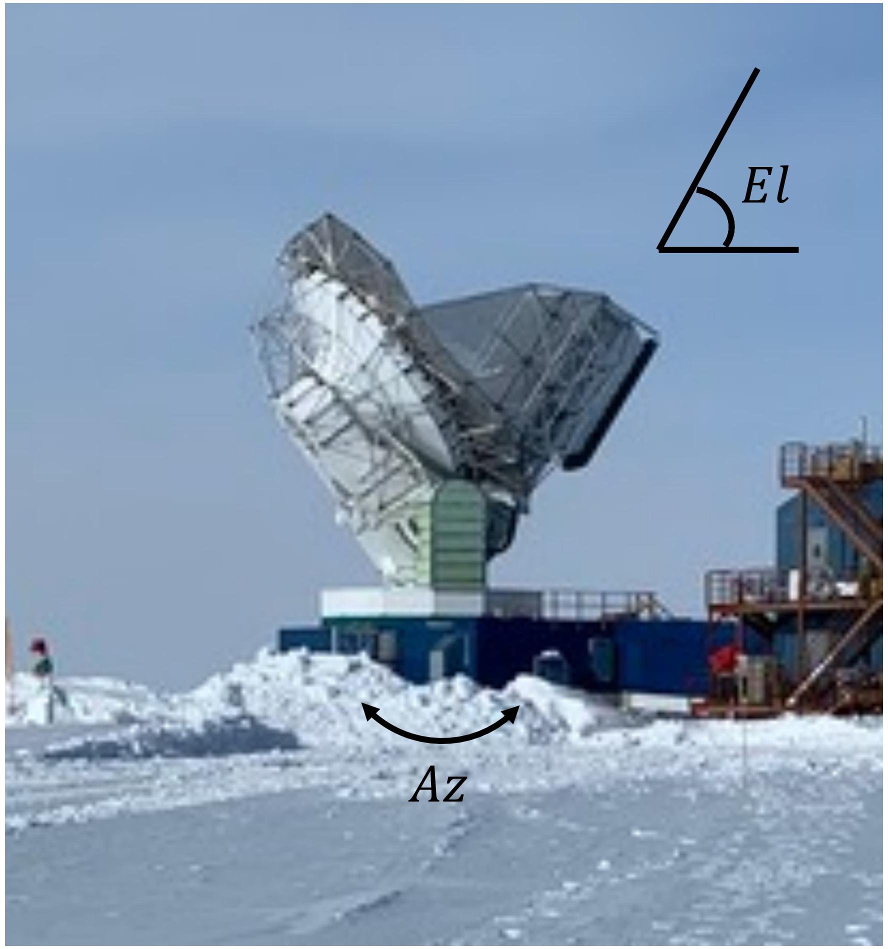
Now we can get to the main part and talk about what SPT does to calibrate timestreams.

In the mapmaking process, at some point before we bin timestreams into map pixels, we want to convert each bolometer's timestream's units from ΔP_{elec} to ΔT_{CMB}.

In order to get this conversion factor for each bolometer, we take four types of calibration observations, analyze the timestreams from these observations, extract useful quantities, and combine the quantities to obtain the conversion factor.

2. Four types of calibration observations used by SPT

Before we take a look at the first type of observation, let me quickly mention how the telescope moves… It has two degrees of freedom, El (elevation angle) and Az (azimuth angle).



2.1. A thorough observation of an astrophysical source whose flux is known

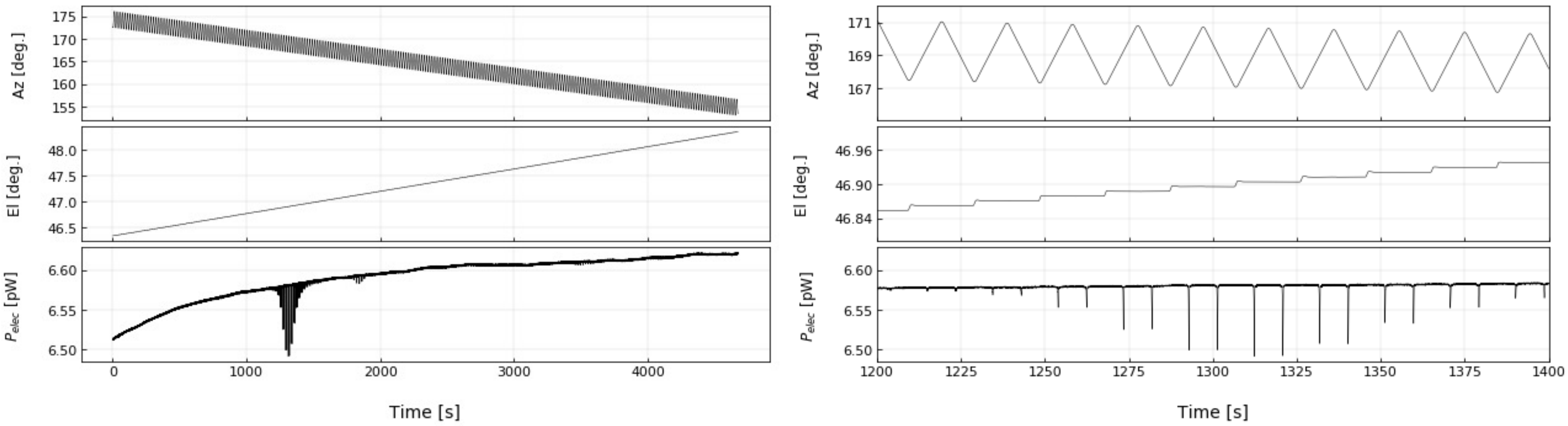
The first type of observation, perhaps the most important one, is a thorough observation of an astrophysical source whose flux is know. For this source, we use some galactic star-forming regions (HII regions) such as RCW38.

In this thorough observation, we make sure the telescope scans across a sufficiently large area on the sky so that every bolometer, whether located near the center or the periphery of the focal plane, sees the full extent of the source.

Let’s take a look at some real data from this type of observation!

2.1. A thorough observation of an astrophysical source whose flux is known

The figures below show the Az and El of the telescope and the data from one bolometer during an RCW38 observation (left: the entire observation, right: a small portion).

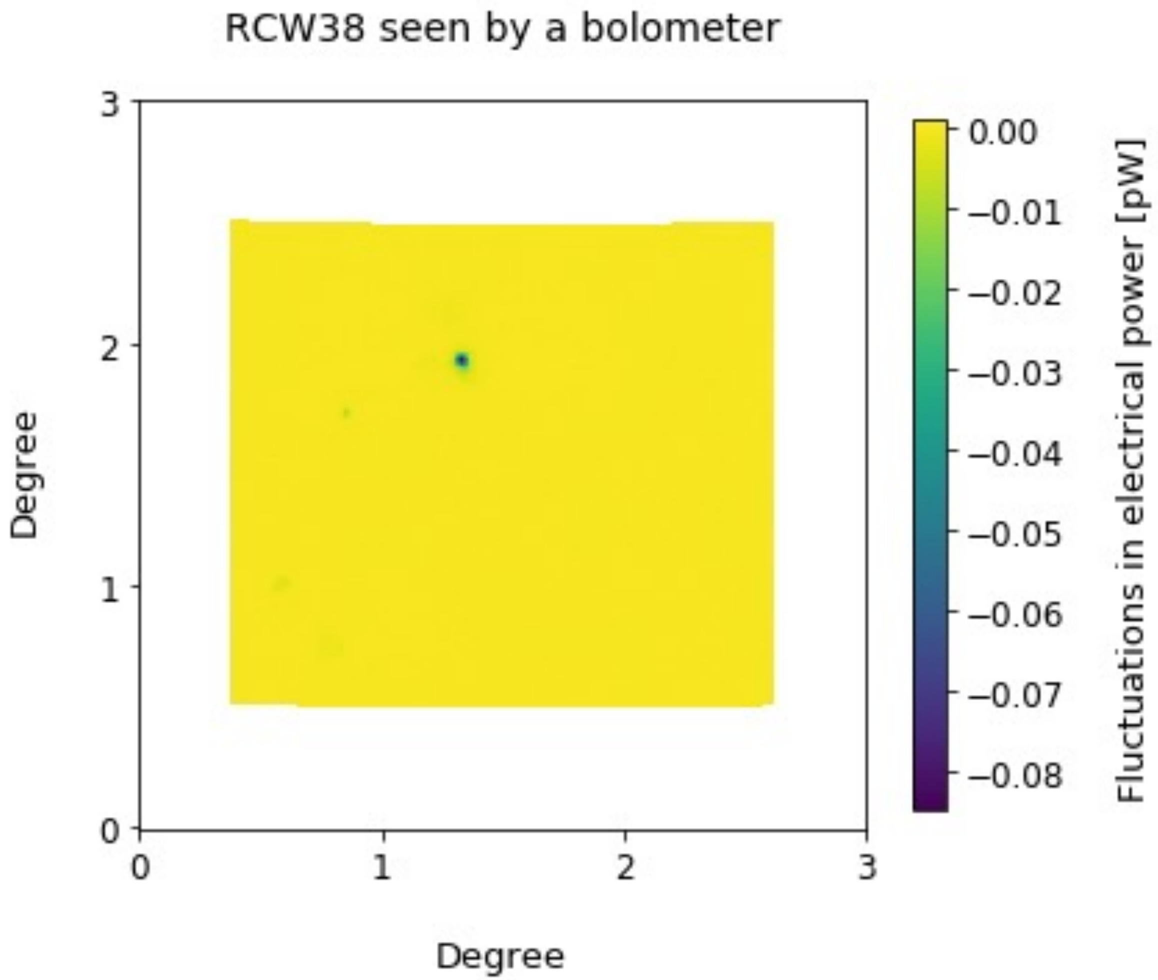


SPT's scanning pattern: one cycle of back and forth in Az followed by a step in El.

Each downward spike in P_{elec} is caused by increased optical power due to the source.

2.1. A thorough observation of an astrophysical source whose flux is known

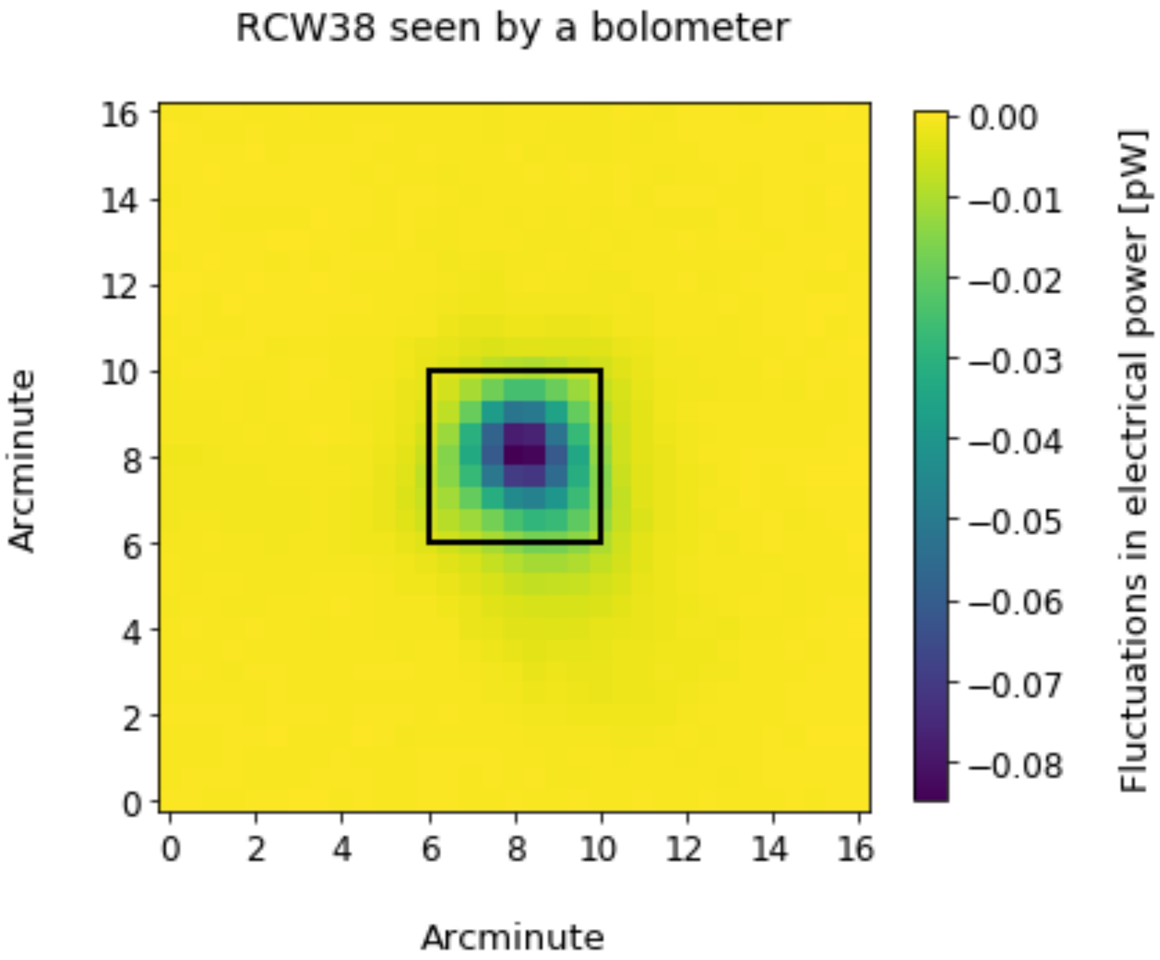
Combining a bolometer's data and the information on where the telescope was pointed at at each moment, we can make a single-bolometer map of RCW38.



No gradient in the vertical direction is seen in this map because we remove the long time-scale drift in a timestream since what we mainly care about is the change in the electrical power caused by the source.

2.1. A thorough observation of an astrophysical source whose flux is known

Then, we can integrate a small region of the map around the source and compare that with the known flux to get a conversion factor from ΔP_{elec} to ΔT_{CMB}.



The integral (just the sum of all the pixel values within the box multiplied by the area of one pixel) for this 95 GHz bolometer is $-0.50\ [\Lambda pW \cdot arcmin^2]$.

The known flux of RCW38 (based on past experiments) near that frequency within this region is $4.79\ [\Delta K_{CMB} \cdot arcmin^2]$.

So, the conversion factor becomes

$$\frac{-0.50\ [\Delta pW \cdot arcmin^2]}{4.79\ [\Delta K \cdot arcmin^2]} = -0.10\ [\Delta pW / \Delta K]$$

2.1. A thorough observation of an astrophysical source whose flux is known

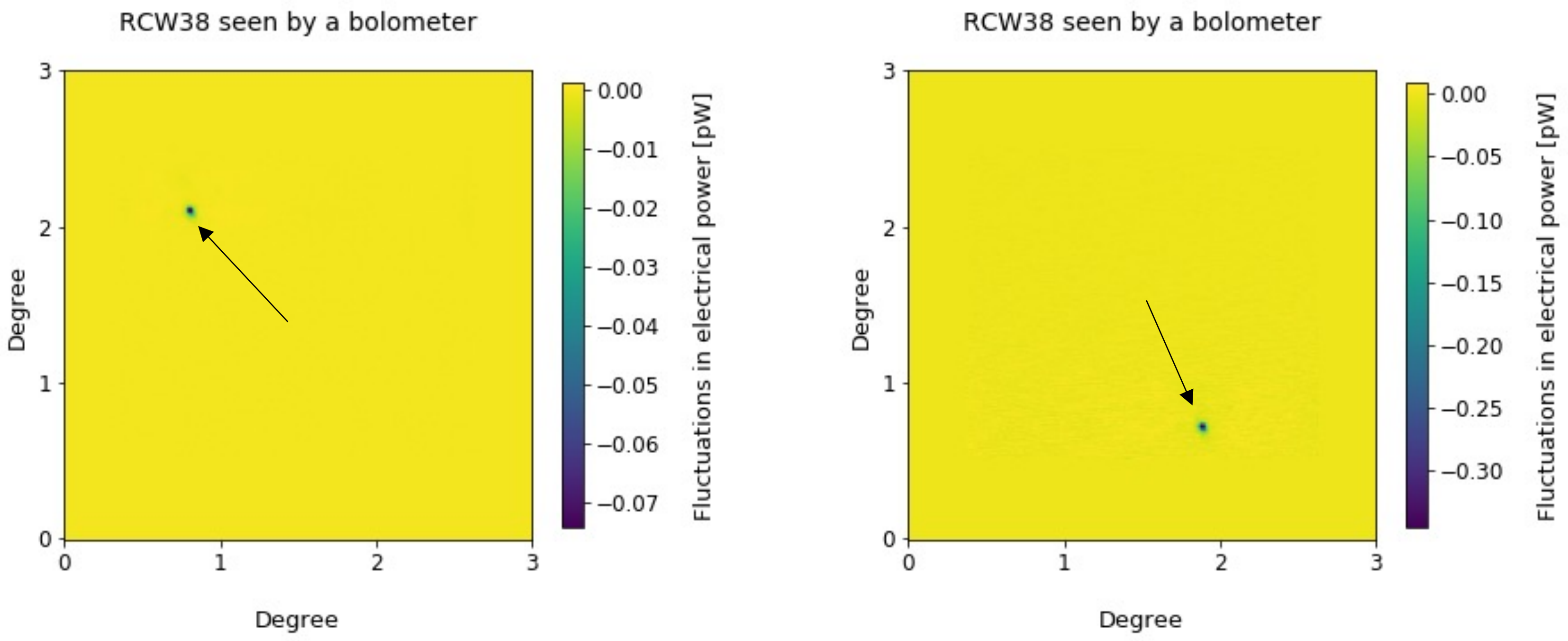
That conversion factor is basically what we need to calibrate that bolometer’s timestream (divide the timestream by this factor) when making CMB maps.

However, that is not quite the end of the story because there are a few corrections we want to make to that conversion factor, which we will get from the other types of calibration observations!

2.1. A thorough observation of an astrophysical source whose flux is known

Incidentally, the coordinates of this map are set up so that the source appears at the center only if the bolometer in question is located at the center of the focal plane.

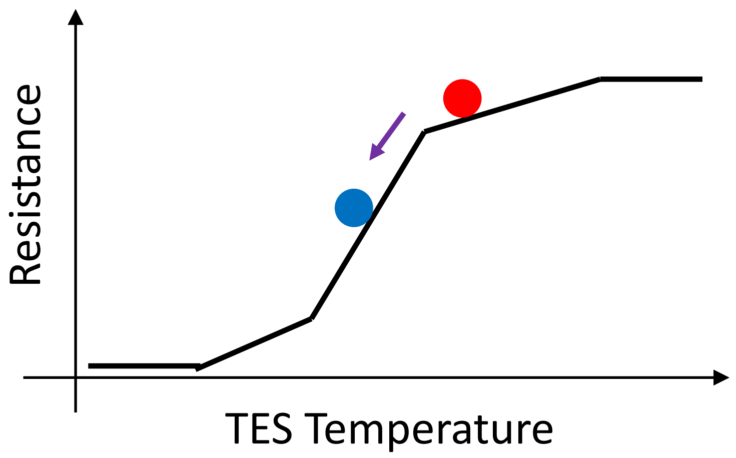
Then, by measuring the offset of the location of the source from the center of the map, we can measure the pointing offset of this bolometer with respect to the center of the focal plane, which is an important piece of information needed to combine many bolometers' data to make CMB maps.



2.2. An observation of an internal calibrator

The $\Delta P/\Delta T$ conversion factor obtained previously actually depends on what elevation angle a detector is pointed at because the detector's responsivity can depend on the elevation.

For example, we can imagine the following scenario:



1. When the telescope is pointed at a certain elevation angle, we tune a bolometer's operating point in its superconducting transition and obtain a $\Delta P/\Delta T$ conversion factor.
2. We then increase the telescope elevation. Since the bolometer now sees less atmospheric emission, it gets less optical power. The electrical power increases but cannot completely make up for the decrease in optical power.
3. The bolometer is now slightly deeper in the transition because it receives less total power. At this new place in the transition, the slope of the $R(T)$ curve is different, so its responsivity is different. So is the $\Delta P/\Delta T$ conversion factor.

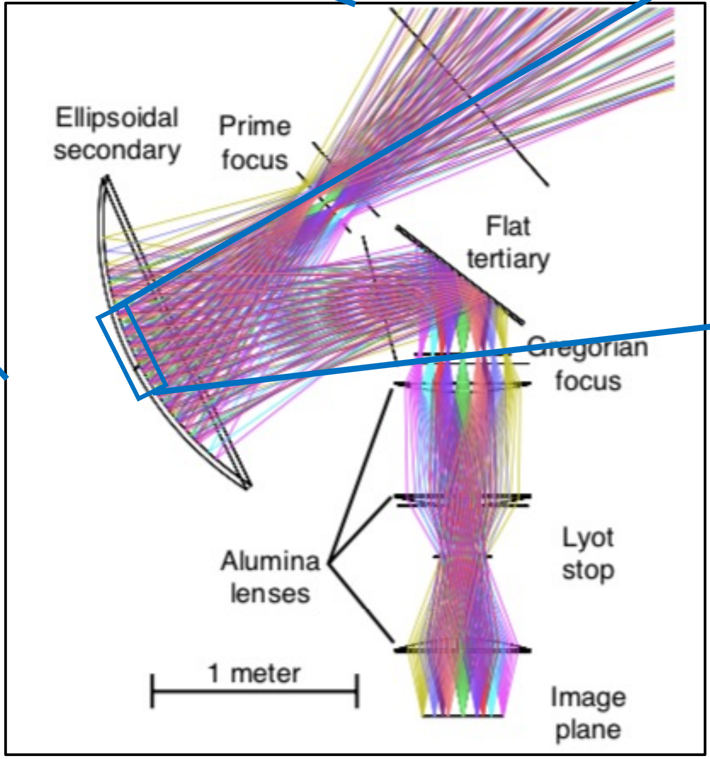
2.2. An observation of an internal calibrator

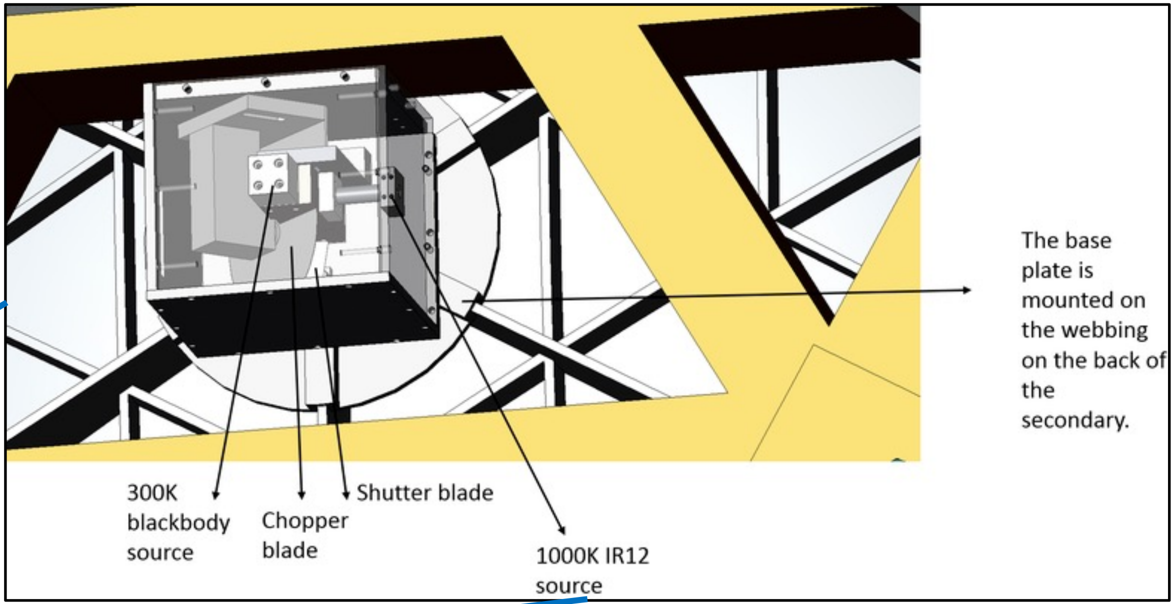
To measure the elevation-dependent responsivity, it might be great if there were many copies of RCW38s scattered all over across the sky at different elevation angles…

Actually, we can make something like that happen by installing a stable radiation source somewhere in the optical path of the bolometers that moves together with the telescope. That way, the bolometers effectively have a source of constant radiation to look at at different elevation angles, and we can measure how a bolometer's response to this calibrator changes as a function of El and use that information to modify the $\Delta P/\Delta T$ obtained at one El value for other values.

For SPT, the comoving calibrator is a chopped blackbody source mounted to the back of the center of the secondary mirror. See the diagrams on the next slide.

2.2. An observation of an internal calibrator



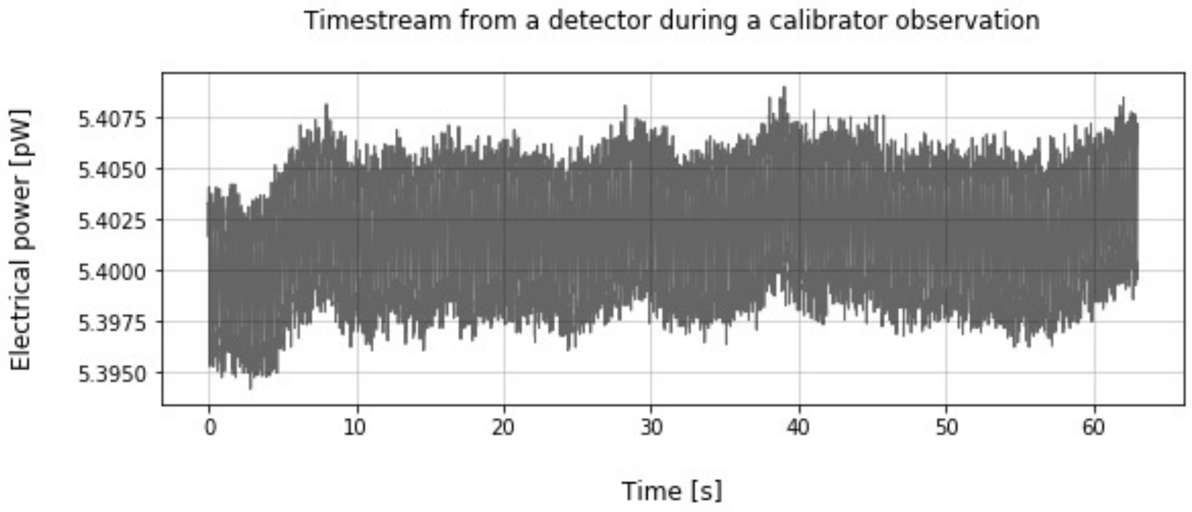


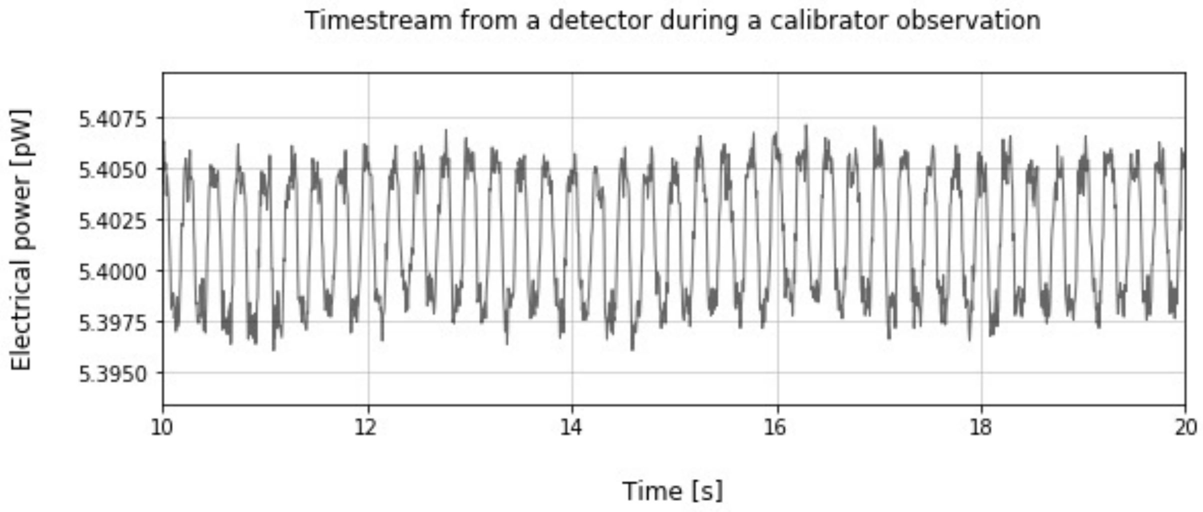
Benson et al., SPT-3G: A Next-Generation Cosmic Microwave Background Polarization Experiment on the South Pole Telescope, Arxiv 1407.2973

2.2. An observation of an internal calibrator

During a calibrator observation, the telescope stays stationary (no change in Az/El). The shutter opens for about one minute exposing the calibrator, and the chopper spins so that bolometers see the $300\ [K]$ source and the $1000\ [K]$ source alternately and periodically.

The figures below show what a timestream looks like during a calibrator observation.



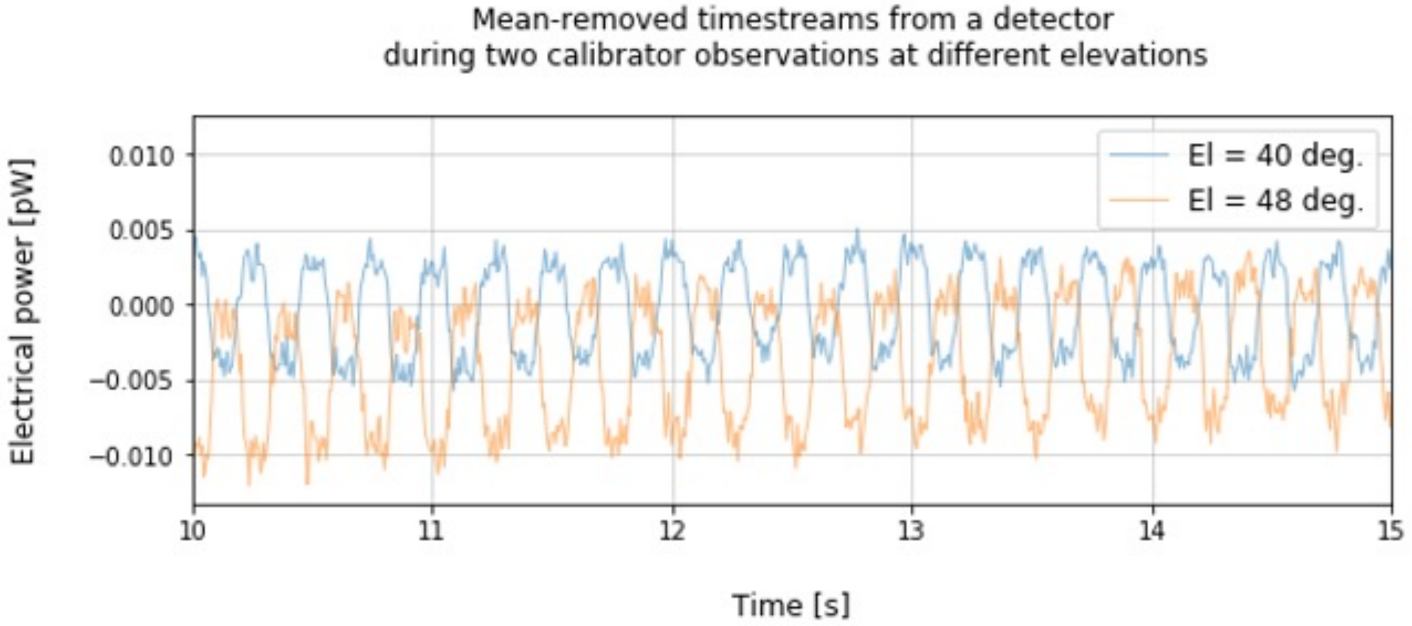


Peaks (troughs) correspond to seeing the colder (hotter) source.

We define a bolometer’s response to the calibrator as the average peak-to-trough amplitude over many cycles.

2.2. An observation of an internal calibrator

For a particular detector, its timestreams from two calibrator observations taken at different El are shown below.



Calibrator response (CR) @ $El = 40\ \mathrm{deg.}:\ 5.4\ [fW]$

Calibrator response (CR) @ $El = 48\ \mathrm{deg.}:\ 7.1\ [fW]$

2.2. An observation of an internal calibrator

Putting everything together, we can write down the following expression:

$$\frac{\Delta P}{\Delta T}(El) = \left[\frac{\Delta P}{\Delta T}(El) \Big/ \frac{\Delta P}{\Delta T}(El_{RCW38})\right] \times \frac{\Delta P}{\Delta T}(El_{RCW38}) = \frac{CR(El)}{CR(El_{RCW38})} \times \frac{\Delta P}{\Delta T}(El_{RCW38})$$

A bolometer's responsivity can change due to other factors than the elevation angle, and calibrator observations can be used to take those factors into account as well. So, we can imagine a more generalized version of the expression above where there are more variables in addition to El.

One factor that does not affect the responsivity, though, is how bright RCW38 looks, which depends on weather conditions. The source looks a little dimmer if the weather is a little cloudier. To correct for this effect, we want to do something more, which brings us to the third type of calibration observation.

2.3. A quick observation of the same astrophysical source

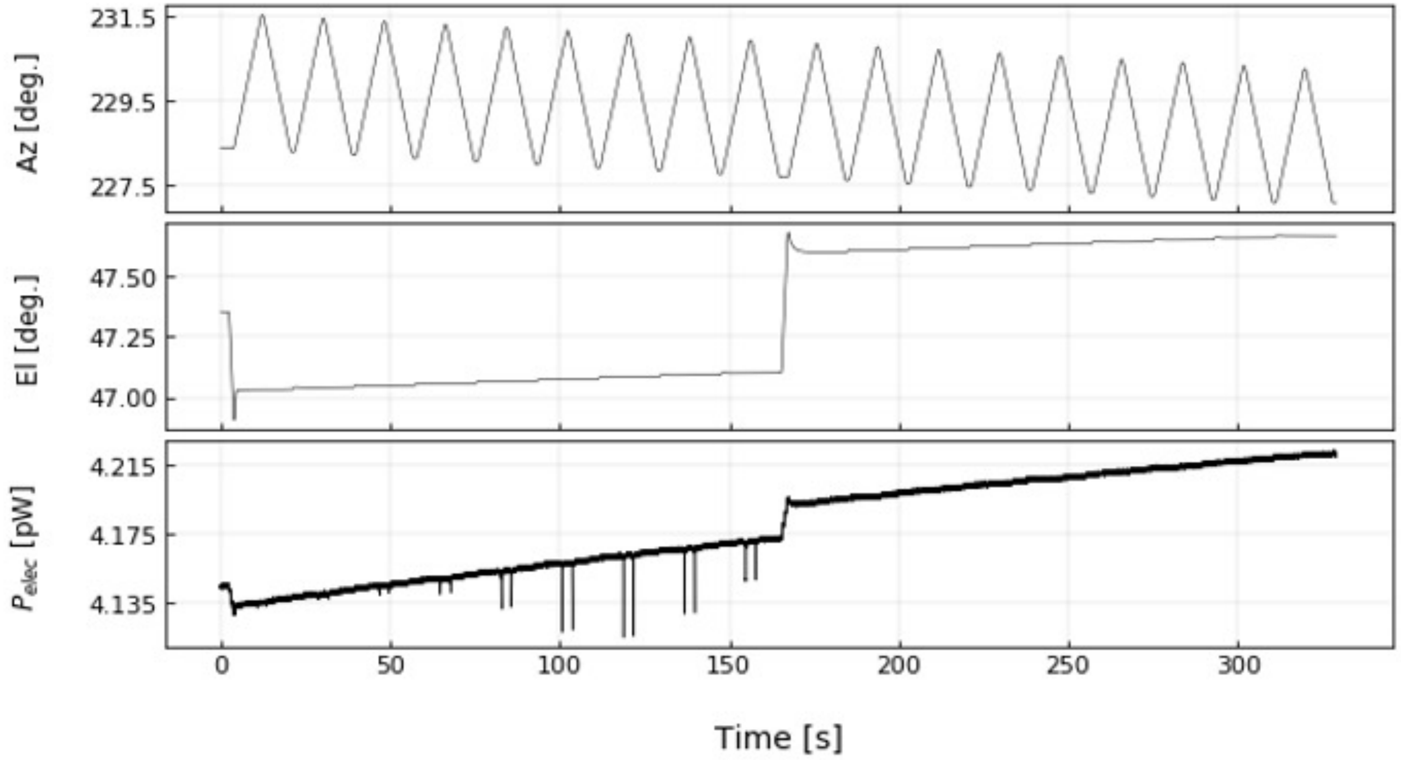
The basic ingredient of the temperature calibration is a thorough observation of RCW38 (or MAT5A) in which every detector sees the source, but this is done only about once in a week because it is time consuming (an hour and a half or so).

So, for a CMB field observation that happens more than a day or so later, the weather conditions may have changed somewhat. To correct for the $\Delta P/\Delta T$ conversion factors obtained earlier so that they can be used for the data from a later field observation, we take a quick observation of the source again right before the field observation.

By comparing how bright the source looks during the quick observation to how bright it looked during the thorough observation, we can measure the effect of changing weather conditions and take that effect into account when obtaining the $\Delta P/\Delta T$ conversion factors for the field observation.

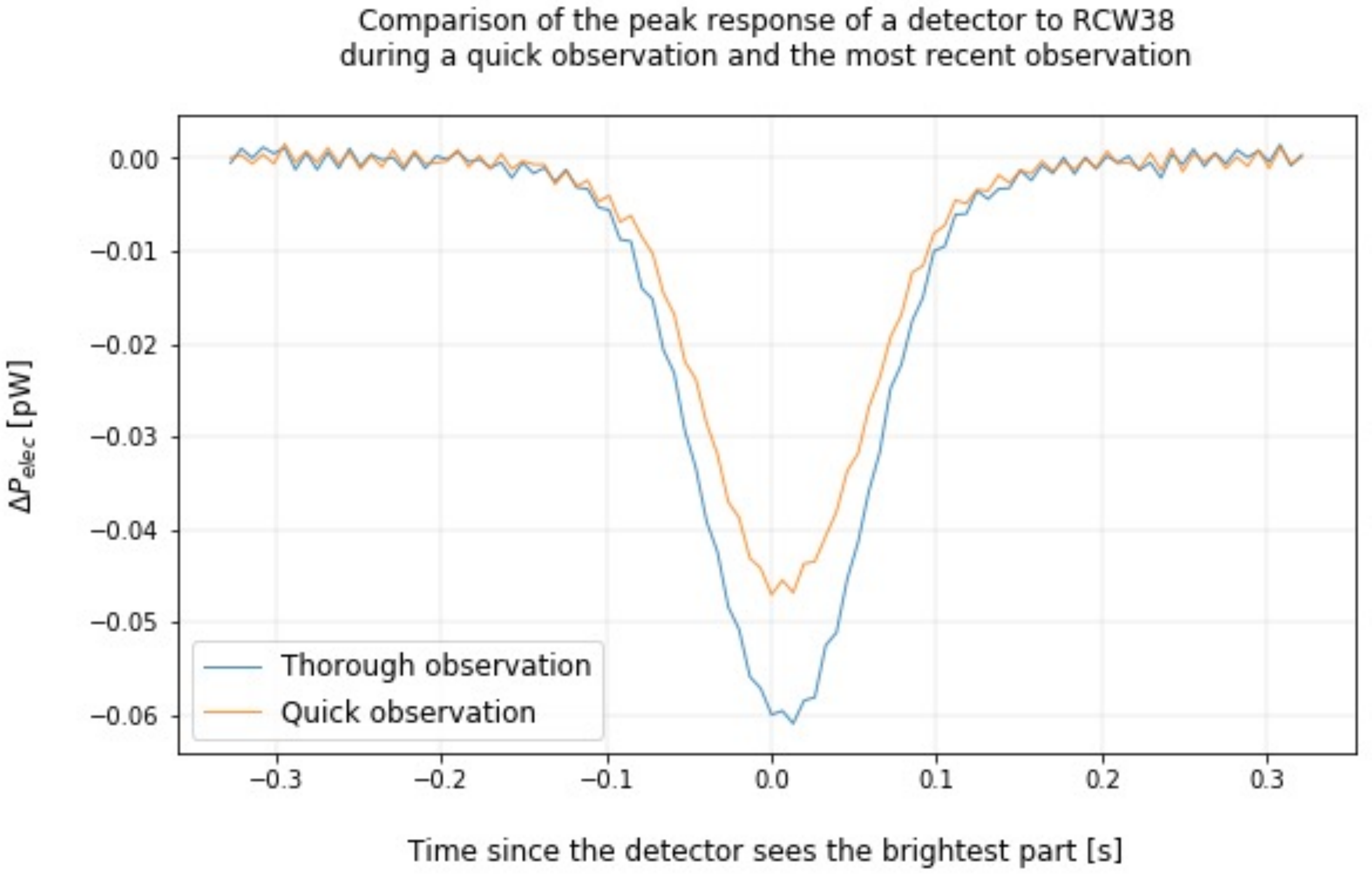
2.3. A quick observation of the same astrophysical source

Since changing weather conditions affect the whole focal plane (the field of view is only two square degrees), we need to have only a small fraction of representative bolometers for each observing band see the source and look at their collective response, so this observation can be quicker. Here are example timestreams from a quick observation.



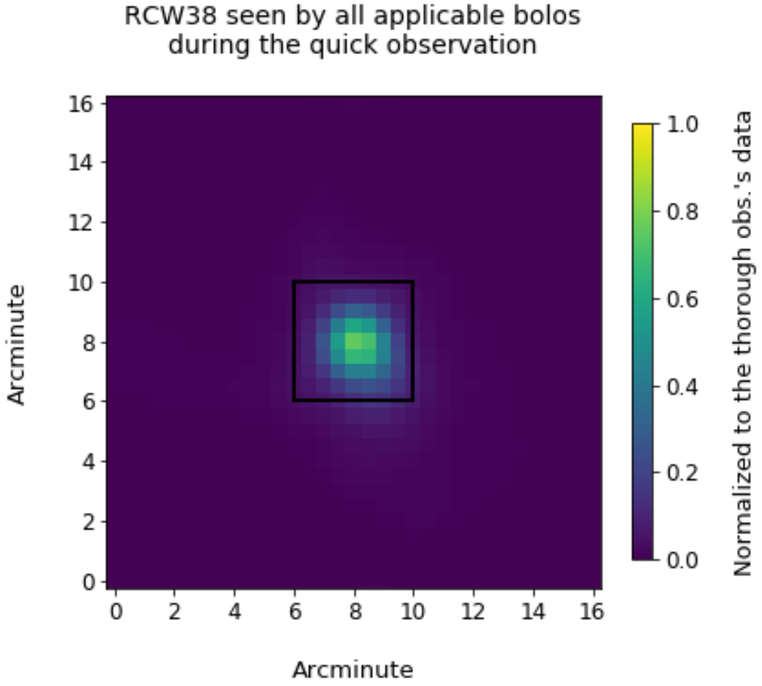
2.3. A quick observation of the same astrophysical source

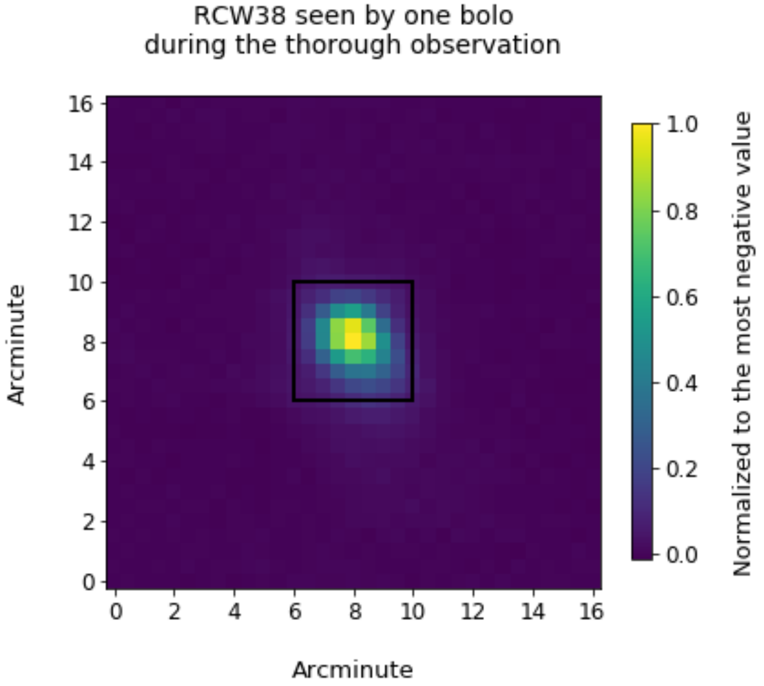
If the weather is cloudier during this quick observation than it was during an earlier thorough observation, the downward spikes in a bolometer's timestream should be smaller than they were. Here is an example from a 150 GHz bolometer.



2.3. A quick observation of the same astrophysical source

To quantify how the flux of the source changed, we can normalize each relevant bolometer's timestream from this quick observation to the peak response it had during the thorough observation and make a normalized coadd. We also make a normalized coadd from the thorough observation.





The left normalized coadd peaks below (above) 1.0 if it is cloudier (clearer) later.

The right normalized single-bolometer map peaks at 1.0 by construction. We can average these from many bolometers to make a coadd.

2.3. A quick observation of the same astrophysical source

Finally, comparing the two coadds gives us a number we can use to correct for the different weather conditions.

$$Normalized\ Integral\ (NI)\ of\ the\ left\ coadd = 3.75\ [arcmin^2]$$

$$Normalized\ Integral\ (NI)\ of\ the\ right\ coadd = 4.60\ [arcmin^2]$$

We can now write down another expression for the $\Delta P/\Delta T$ factor.

$$\frac{\Delta P}{\Delta T}(w) = \left[\frac{\Delta P}{\Delta T}(w) \middle/ \frac{\Delta P}{\Delta T}(w_0)\right] \times \frac{\Delta P}{\Delta T}(w_0) = \frac{NI(w)}{NI(w_0)} \times \frac{\Delta P}{\Delta T}(w_0)$$

$$w, w_0: weather\ conditions\ at\ different\ times$$

Combining this expression with the other one derived from calibrator observations allows us to more accurately use the $\Delta P/\Delta T$ factors obtained from a thorough observation for a different condition (different El, weather, and so on).

2.4. An elevation nod

In addition to a thorough observation of an HII region, a calibrator observation, and a quick observation of the HII region, there is one more type of calibration observation, which is used to calibrate timestreams at a more basic level.

The simplistic circuit diagram I showed earlier has a DC battery, but a slightly better representation of what SPT does is to replace that with an AC voltage source. In other words, we apply a high-frequency (a few MHz) sinusoidal voltage signal to a TES, in which case the current running through the TES is also a sinusoid, but the amplitude of this sine wave is modulated by the slowly-changing resistance of the TES. Then, we can later demodulate this to recover the current timestream. There is a lot of similarities between this and the AM radio.

2.4. An elevation nod

Let's say the voltage has the form $V(t) = V_0 \sin \omega t$. Ideally, the current running through the TES is in phase with the voltage, so $I(t) = [V_0/R(t)] \sin \omega t$. In practice, there is some phase difference between the two, so the current looks more like

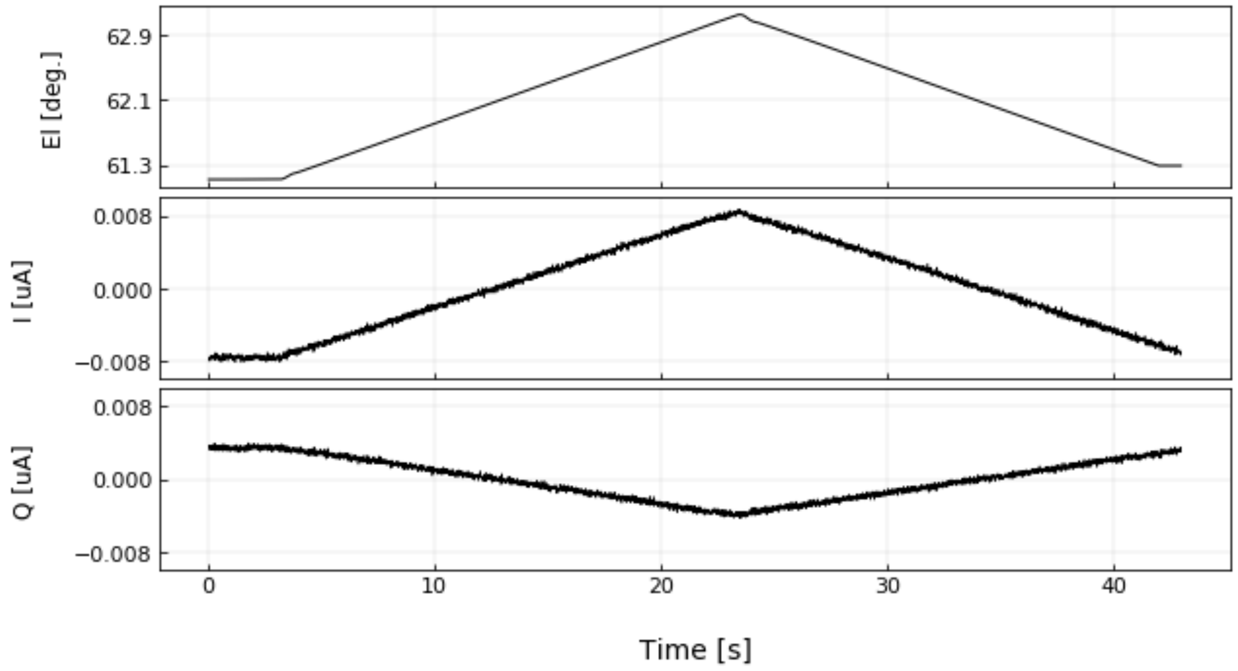
$$I(t) = I_0(t) \sin(\omega t + \varphi) = I_0\,(t) \cos \varphi \sin \omega t + I_0(t) \sin \varphi \cos \omega t$$

The coefficient in front of $\sin \omega t$ ($\cos \omega t$) is called the I (Q) timestream. I for in phase, and Q for quadrature. When we take data, we record both timestreams. Then, we want to combine the two before doing any processing so that we are fully using our data. Using only the I timestream would mean that we are throwing away the $\sin \varphi$ component.

That is where a calibration observation called elevation nod, or elnod, comes in, which is one way to get the phase angle.

2.4. An elevation nod

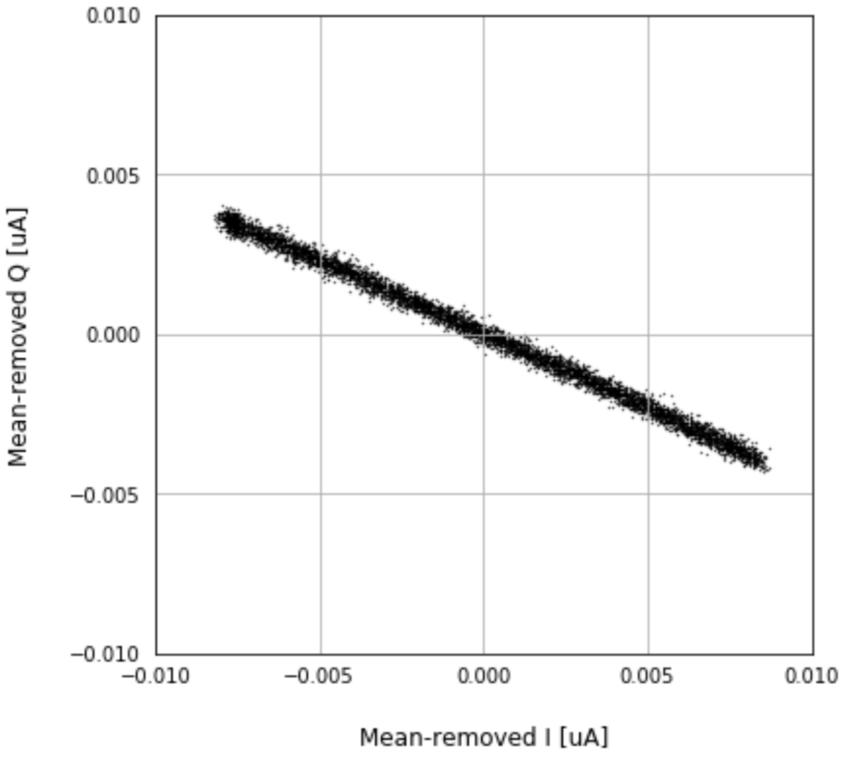
During an elnod, the telescope's elevation undergoes a motion that looks like nodding. The figure below shows the elevation timestream and the I and Q timestreams from a bolometer in some units of current.

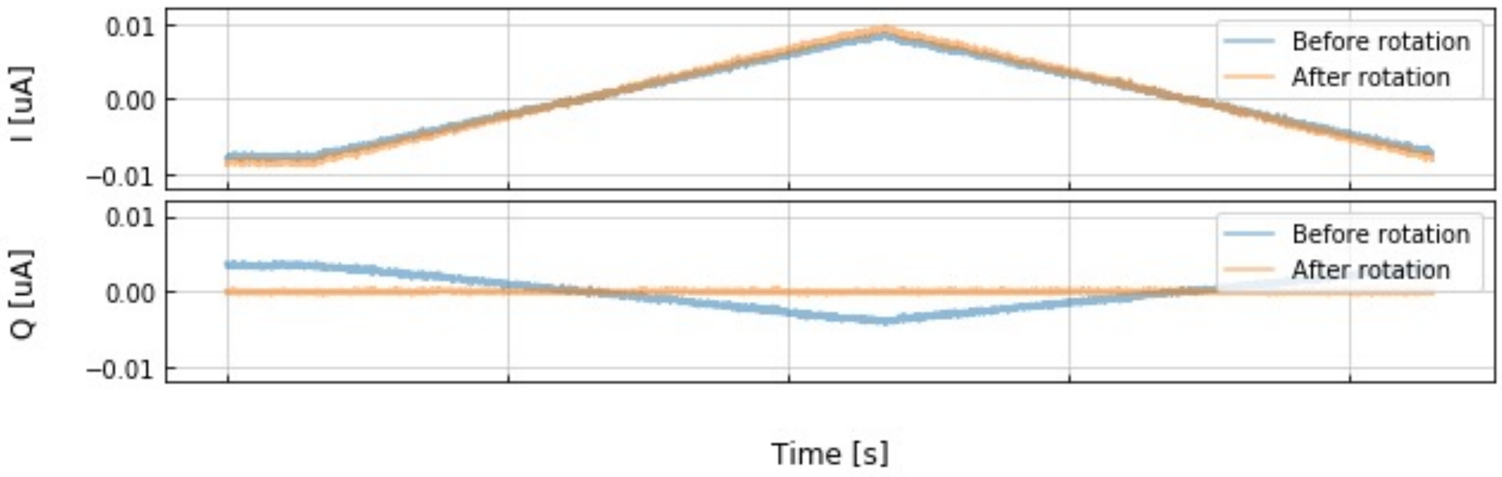


As the elevation increases (decreases), a bolometer receives less (more) total power due to less (more) atmospheric emission, so the current increases (decreases). Also, the Q timestream looks like a smaller, inverted copy of the I timestream for this particular bolometer.

2.4. An elevation nod

In the I-Q plane, the timestream samples more or less lie on a straight line. The phase angle φ is the angle this line makes with the horizontal axis. One way to get this angle is [to calculate the eigenvectors of the covariance matrix]() of the two sets of data points (I and Q). Once we have the angle, we can then rotate the timestreams so that all the signal goes to the rotated I timestream.





After rotating the IQ timestreams from a calibration observation, we can then make maps of RCW38, calculate the calibrator response, and so on.

3. A typical SPT observing schedule

Now that we have covered all types of calibration observations, let's take a look at how all these observations are combined with CMB field observations to form a regular schedule executed by the telescope.

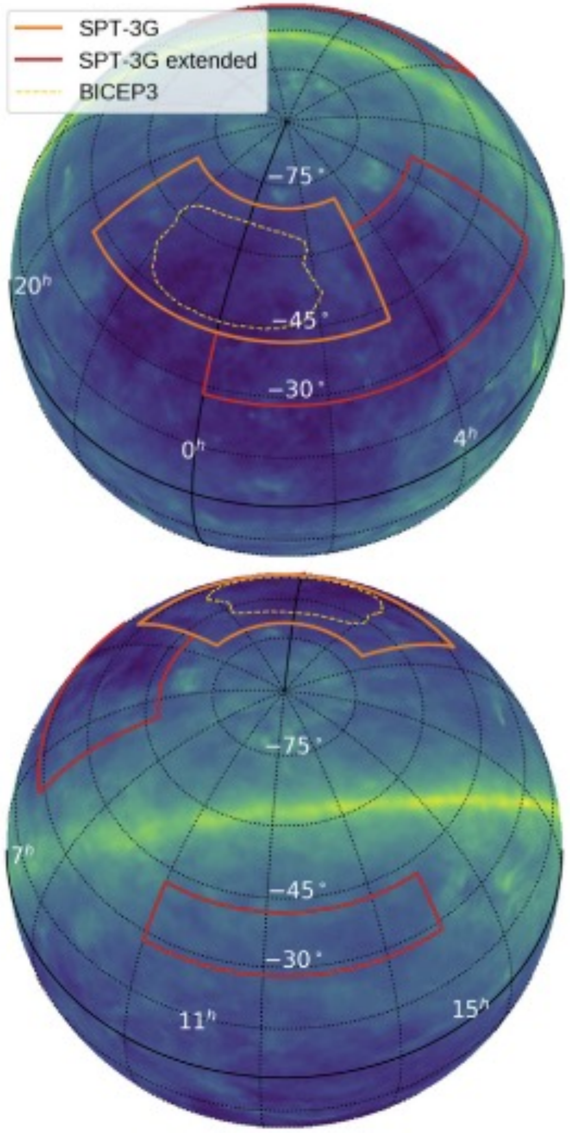
SPT observes certain field of the sky, and each field 's elevation range ($El = -Dec$ at Pole) is too wide for bolometers to cover all of it. The change in the atmospheric loading associated with the elevation range would drive TES out of their superconducting transition. As a result, we split each field into several smaller subfields and observe one subfield at a time (see the images on the next slide).

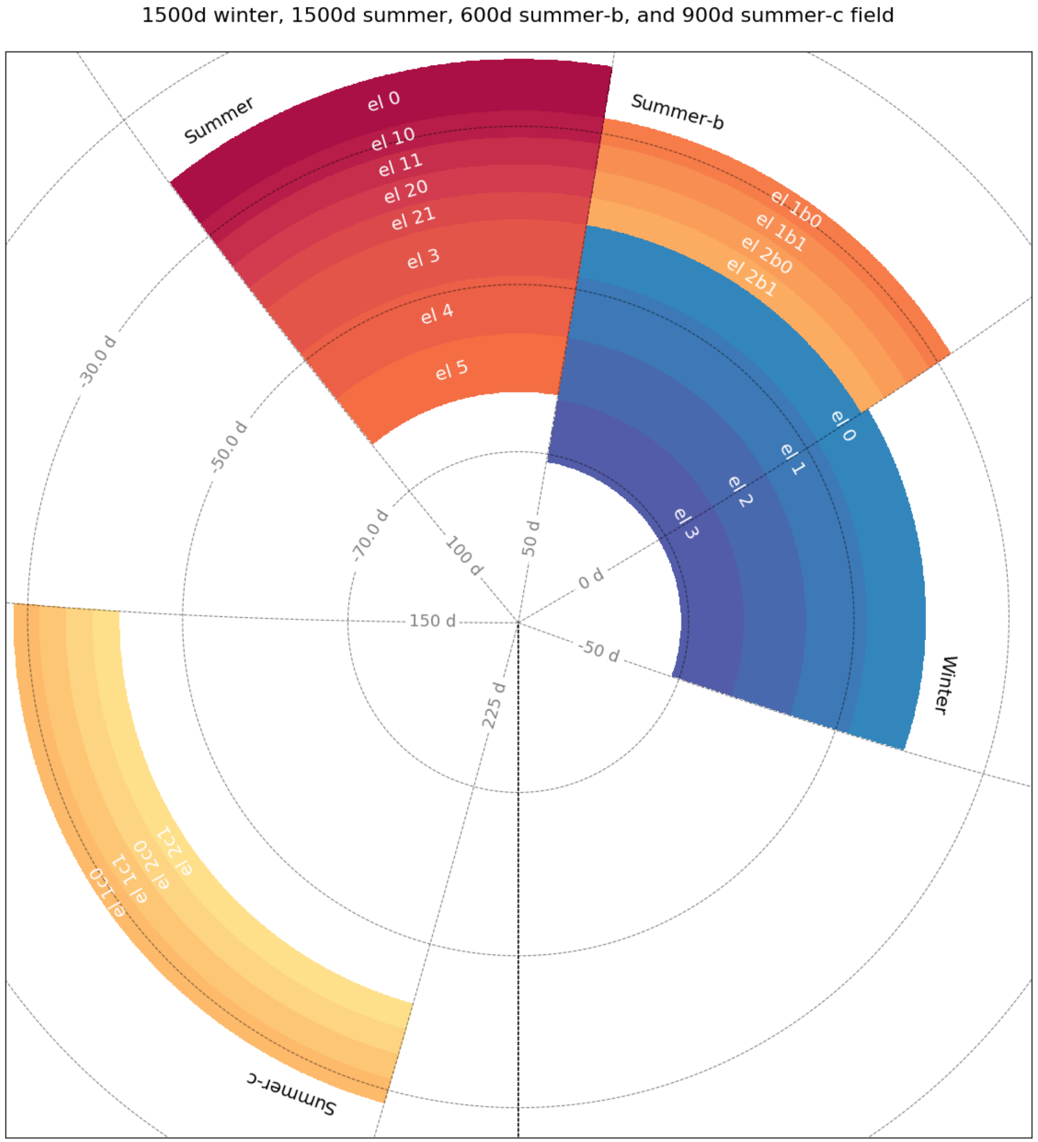
In order to properly calibrate the data from each subfield observation, we need to take a series of calibration observations for each subfield observation.

Also, given that we use a He sorption fridge to cool our detectors through the evaporative cooling of He3, once all He3 evaporates, we need to condense the gas again, which leads to some downtime. Typically, we spend about four hours recycling the fridge, and that allows us to observe for about seventeen hours. During each observing period, we try to take several two-hour subfield observations.

3. A typical SPT observing schedule

As for the subfields, we split our winter field into four subfield, for example.

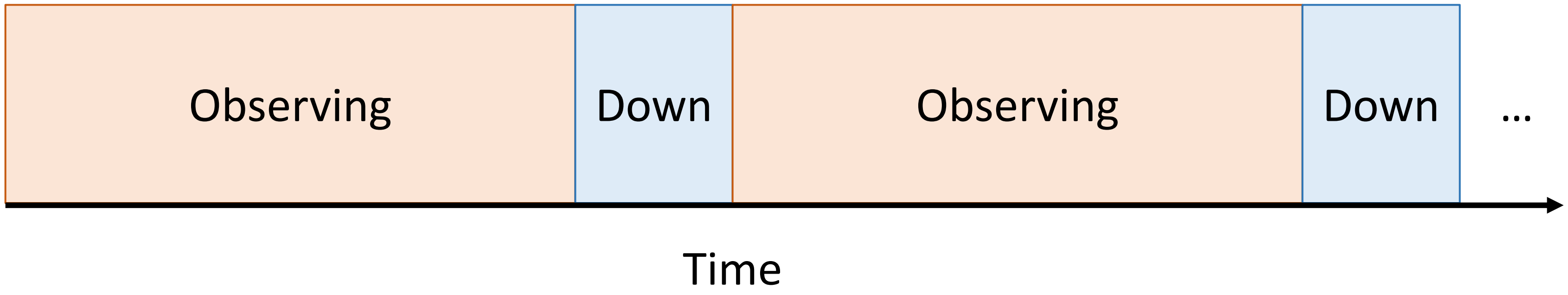


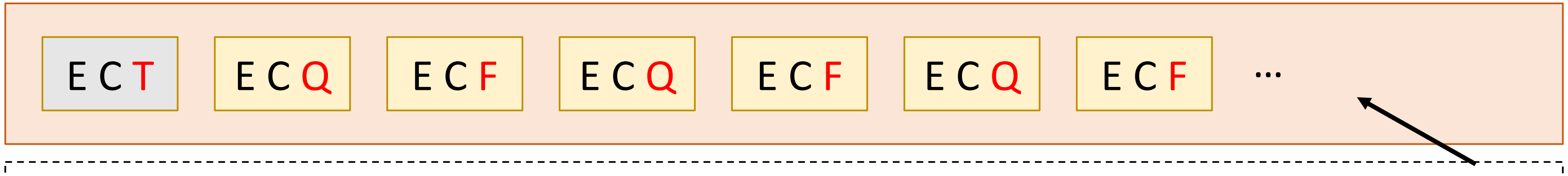


Sobrin et al., The Design and Integrated Performance of SPT-3G, ApJS 258 (2022) 42

3. A typical SPT observing schedule

Then, based on what is described two slides ago, here is a schematic of the telescope schedule.



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E : elnod observation                C : calibrator observation
T : thorough RCW38 observation       Q : quick RCW38 observation
F : subfield observation
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Each observing period contains several subfield observations, each of which is preceded by a quick RCW38 observation. Both subfield and RCW38 observations are preceded by their own elnod and calibrator observations.

The end

That is the end of this presentation!

Hopefully those concrete real-world examples of timestreams from various calibration observations were useful for in enforcing what you learned earlier in the week during lectures about TES bolometers and what you did in the TES labs. Hopefully you also found it useful to hear how one of the CMB experiments is operated.

Thank you for your attention!