SPIRE-JPL-NOT-000623

Temperature Stability Requirements for SPIRE

1. Background

The SPIRE bolometers impose a requirement on the noise stability of the overall instrument. The bolometer sub-system specification document (BDA-PER-10) tabulates 100 mHz as the minimum performance value and 30 mHz as the design value for the 1/f knee frequency of the detector sub-system. For example, in order to extract point sources from drift-scanned SPIRE maps with negligible additional noise, we require that the 1/f noise of the bolometers be < 100 mHz. The 1/f knee frequency is defined as where excess 1/f noise equals the white noise level from photon and bolometer noise. For some observations (spectroscopy, photometer chopping and jiggling), the requirement will be much less demanding because the audio frequencies of interest are at higher frequency. For specific drift-scanned observations, for example large maps to measure fluctuations in the far-infrared background, the requirement may be more severe. Thermal drifts at various temperature stages introduce 1/f noise to the detectors, either by modulating their operating temperature or by varying the sub-millimeter emission arising from warm surfaces that is received by the detectors. We quantify the requirements for temperature stability on the ^{3}He cooler, 4 K stage, and telescope temperature.

2. Requirement

2.1 Thermal drifts at 0.3 K

Thermal drifts in the 3He stage temperature act to produce a false signal at the bolometer. The equation for thermal equilibrium in a bolometer is given as

$$P_e + Q = (\kappa/1+\beta)\,[T^{1+\beta} - T_0^{1+\beta}], \qquad (1)$$

where P_e is the electrical power dissipation, Q is the optical power, and the thermal conductivity at the base temperature is $G_0 = \kappa T_0^{\beta}$. Differentiating both sides gives

$$\mathrm{NEP} = \kappa T_0^{\beta}\, T_{0,n} = G_0\, T_{0,n}, \qquad (2)$$

where NEP is the detector NEP in W/√Hz, and $T_{0,n}$ is the temperature PSD of the cold plate temperature in K/√Hz. I have neglected the heat capacity of the detector, which is not an issue for frequencies much slower than the thermal time constant of the detector. Since the parameters of the detectors are well-defined, it is possible to determine the requirement on $T_{0,n}$. Note that generally $\mathrm{NEP}_{\mathrm{bol}} \propto \sqrt{G_0}$, so in the absence of photon noise, insensitive detectors (high G_0) are actually more sensitive to temperature fluctuations. We tabulate the sensitivity of the bolometers on SPIRE assuming the current design values. If the entire focal plane is co-added, the ultimate sensitivity limit is $T_{0,n}/\sqrt{N}$, where N is the number of pixels in each focal plane unit.

Table 1. Sensitivity to temperature fluctuations at 300 mK

	P/LW	P/MW	P/SW	S/LW	S/SW
NEP [e-17 W/√Hz]	6.0	7.9	10.0	14.0	13.4
G_0 [pW/K]	50	64	80	208	144
$T_{0,n}$ [nK/√Hz]	1200	1230	1250	670	930
$T_{0,n}/\sqrt{N}$ [nK/√Hz]	180	130	100	150	150

2.2 Thermal drifts at higher stages

The power spectral density Q_n characterizes drifts in the optical loading, where Q_n refers to power absorbed at the detector. The criteria for stability is that Q_n = NEP as before. This absorbed power is a related to the temperature of the emitting stage by

$$Q = \varepsilon \, \nu B_\nu(T), \qquad (3)$$

Where ε is a coupling factor depending on the instrument and emissivity, and $\nu B_\nu(T)$ is the blackbody function. Differentiating, we obtain

$$\mathrm{NEP} = \varepsilon \, [d\nu B_\nu(T)/dT] \, T_n. \qquad (4)$$

The requirement for stability assumes 20 % emissivity from 2 K, large due to the pupil stop at this temperature stage. We further assume 10 % coupling from 4 K, probably too conservative. The emissivity of the 80 K telescope is taken as 4 %. We find that there is no difficulty meeting the required stability at 2 K (see below), and that the photometers set the most stringent requirements on the stability of the 4 K and 80 K stages.

Table 2. Sensitivity to temperature fluctuations at 2 K, 4 K and 80 K

			P/LW	P/MW	P/SW	S/LW	S/SW
$T_{0,n}$	1.8 K	K/√Hz	9.1	-	-	-	-
$T_{0,n}/\sqrt{N}$			1.4	-	-	-	-
$T_{0,n}$	4.8 K	mK/√Hz	5.0	25	-	45	-
$T_{0,n}/\sqrt{N}$			0.8	2.7	-	10	-
$T_{0,n}$	80 K	mK/√Hz	1.1	1.1	1.0	1.9	1.3
$T_{0,n}/\sqrt{N}$			0.2	0.12	0.08	0.44	0.22

3. *Case of Linear Temperature Drift*

We consider the impact of a linear temperature drift in time on three observation strategies: chopped photometry, high resolution spectroscopy, and drift scanning. The effect of a linear drift can be completely removed by the choice of observation strategy, but higher order terms will certainly be present and become more difficult to subtract. This calculation serves as a guide for when thermal drifts start to become an issue, and when they are completely negligible.

I make the following (worst case) assumptions about observing modes. For chopping, I assume an integration time of 500 s. This integration time suffices to achieve the confusion limit. The signal is modulated at 2 Hz, but we make the requirement 1 Hz so that the overall noise is increased by 10 %. For spectroscopy, the requirement is to have negligible noise in the lowest frequency bin after in one high-resolution scan of the FTS in taking the spectrum of a point source, requiring 35 s of observation time. Once again, we make the required 1/f frequency half the minimum modulation frequency, $\nu_c = 6/2 = 3$ Hz. For drift scanning, the requirement is to be immune to noise for extracting point sources (calculation done by Matt Griffin and Seb Oliver), $\nu > 0.1$ Hz. For some drift-scanned observations, it is possible that the observer will want information on all angular scales (e.g. detecting correlated structure in the far-infrared background). In this case, we take minimum frequency to be 0.01 Hz (100 arcminutes) over a 1000 s scan (1000 arcminutes), and the requirement is given by co-adding all the pixels in the focal plane. Finally, I assume that the BDA acts as a thermal low-pass filter with $\tau = 100$ s for damping temperature drifts from the ^{3}He refrigerator.

Table 3. Parameters for observing modes

Mode	T_{obs} (s)	ν_c (Hz)
Chopping	500	1
Spectroscopy	35	3
DS / point sources	1000	0.1
DS / extended emission	1000	0.01

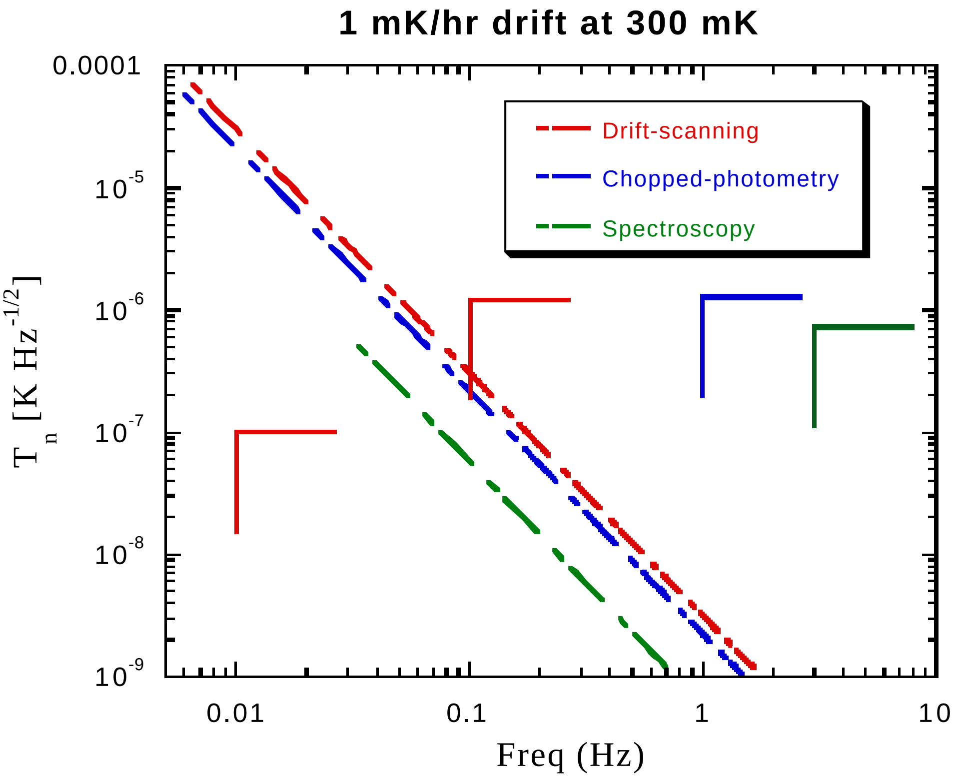

Figure 1. Calculated power spectral densities for a linear temperature drift of 1 mK/hr for the various observing modes. The low-pass filtering effect of the BDA ($\tau = 100$ s) has been assumed, although values are listed in Table 4 which do not include this filtering effect. Two joined lines denote the requirements.

Table 4. Required stability at 300 mK

Mode	$dT(^3He)/dt$ (mK/hr)	dT(BDA)/dt (mK/hr)	$T_{n,req}$ (nK/√Hz)	ν_c (Hz)
Chopping	50	0.9	1200	1
Spectroscopy	9000	4.8	670	3
DS / point sources	3.9	0.06	1200	0.1
DS / extended emission	3e-3	5e-4	100	0.01

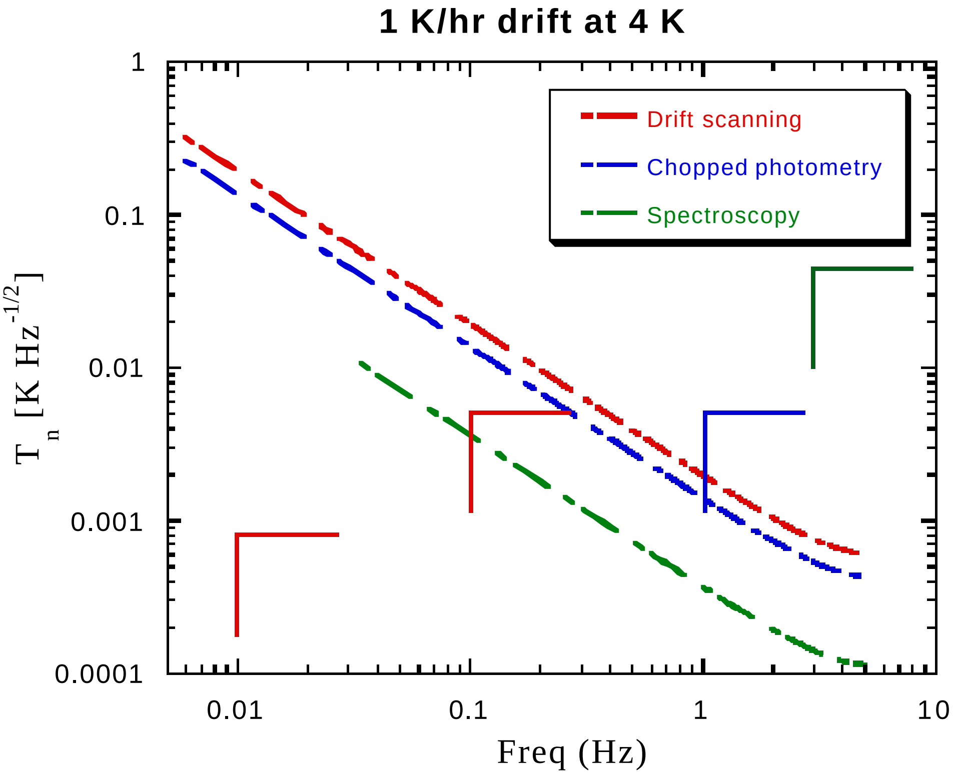

Figure 2. Calculated power spectral densities for a linear temperature drift of 1 K/hr for the various observing modes.

Table 5. Required stability at 4 K

Mode	dT_{max}/dt (K/hr)	$T_{n,req}$ (mK/√Hz)	ν_c (Hz)
Chopping	3.6	5	1
Spectroscopy	320	45	3
DS / point sources	0.26	5	0.1
DS / extended emission	4e-3	0.8	0.01

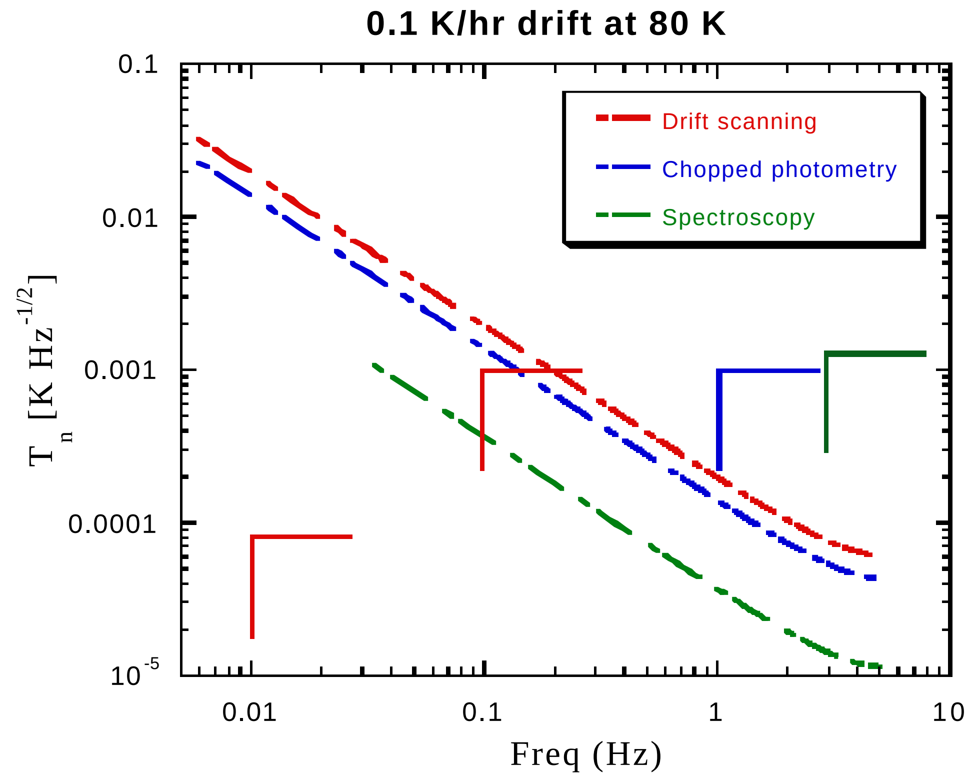

Figure 2. Calculated power spectral densities for a linear temperature drift of 0.1 K/hr for the various observing modes.

Table 6. Required stability at 80 K

Mode	dT_{max}/dt (mK/hr)	$T_{n,req}$ (mK/$\sqrt{Hz}$)	ν_c (Hz)
Chopping	720	1.0	1
Spectroscopy	9200	1.3	3
DS / point sources	50	1.0	0.1
DS / extended emission	0.4	0.08	0.01

Chopped photometry: should be usable even in cases where the instrument is unstable. The following should further reduce the effect of drifts:

1. Use chop-nodding or bin chopped data to cancel a linear drift.
2. Use off source pixels to subtract all drifts. How well this works depends on the mis-matching of pixels for 300 mK drifts (~ 10 %), and the beam mismatch on the 4 K optics (~ 50 %?) and beam mismatch on the telescope (~10 %?).
3. Use thermometry channels to correlate out drifts. Depends how well the thermal responsivity of optical pixels is calibrated.

Spectroscopy: is nearly completely immune to the drifts we might expect, but the following may help further reduce their effect even further:

1. Use return scans of the FTS to prevent a linear drift from being coherently coadded in adjacent scans. Return-scanning also increases the observing efficiency. The effect of not return-scanning over 3600 s is to reduce the drift requirement by $(35/3600)^{1/2}$; still less demanding than photometry.
2. Use off-source pixels to subtract drifts as in CP-1.
3. Use thermometry channels as in CP-3.

Drift-scanned photometry: requires maximum stability of the instrument. Point source photometry should be achievable when the instrument has stabilized. Mapping of extended emission is significantly more demanding, but would be used only in specialized cases requiring careful study. Some benefit could be obtained by the following:

1. Drift scan over the same region on the return path. This allows the drifts to be recorded by taking differences, and some filtering can occur. For example, a linear drift can be easily cancelled. Requires accurate on-the-fly pointing, which may not be possible. Alternately, a fiducial patch could be observed between raster scans.
2. Use thermometry channels as in CP-3. This is unlikely to be of significant benefit for mapping extended emission since the temperature sensitivity of the co-added focal plane exceeds that of the thermometers.

4. *Conclusions*

Even under worse-case assumptions, very large thermal drifts are needed to disturb chopped-photometry mode (50 mK/hr at 0.3 K, 3.6 K/hr at 4 K, 0.7 K/hr at 80 K). Spectroscopy is even less sensitive. Both modes should be usable almost all of the time. Even in the case of a very large transient, simple observation and data reduction strategies can probably reduce susceptibility by an order of magnitude or more.

Drift-scanned modes require good temperature stability. The requirement for extracting point sources should be achievable by the instrument after transients have decayed, but we need to understand the transient profile to determine the loss of observation efficiency. The requirement for mapping extended emission with drift scanning is orders of magnitude more severe, especially for the stability of the ^{3}He cooler. It is not clear that the instrument can achieve the required thermal stability for this mode. However, return-scanning or use of a fiducial patch should relax the requirement. If such a mode can be implemented, further analysis will be necessary to determine the new requirement on system stability.

The following actions would greatly aid in alleviating concerns about thermal stability:

1. Measure temperature stability of 3He fridge with Benoit-style temperature readout at component level as early as possible.
2. Model transient response of thermal system after 3He cycle, JFET turn-on.
3. Investigate use observation modes using fiducial patch, return drift-scanning, and return-scanning FTS.
4. ESA must understand issue regarding thermal stability of the telescope.