Atmospheric Emission Noise at Pico Veleta

Dominic Benford 2009-04-08 through 2009-05-28

This document is intended to detail the calculations made for GISMO to determine the atmospheric emission optical loading and resultant photon noise in the 2mm band at Pico Veleta.

Using an atmospheric model (**AT**, from the Harvard-Smithsonian CfA), we estimated the emissivity of the atmosphere from Pico Veleta, shown in Figure 1. The model was used to produce calculated antenna temperatures at each frequency from 30 GHz to 300 GHz, then converted into an emissivity.

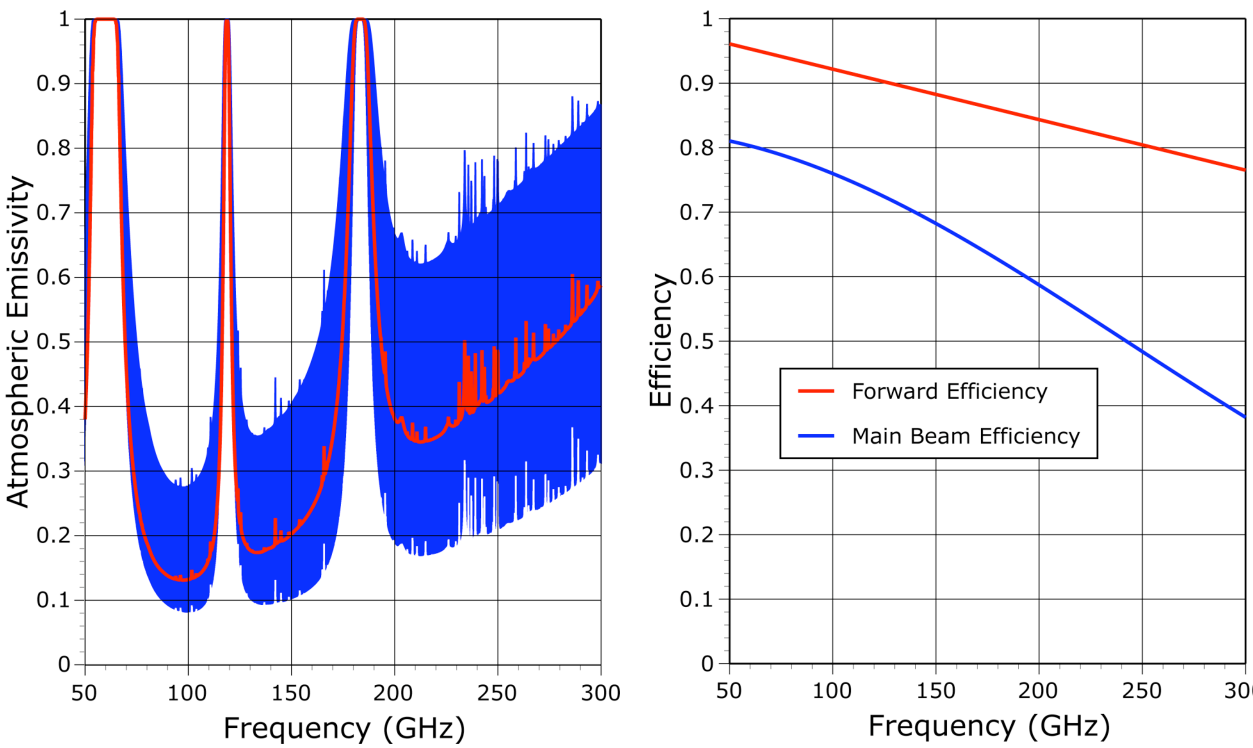

Figure 1. (Left) Atmospheric emissivity estimate for Pico Veleta, as produced by the **AT** model. The solid region is bounded at the bottom by a line-of-sight emissivity of 10%, which corresponds to high elevation in fairly good weather, and at the top by a line-of-sight emissivity of 40%, which corresponds to 2.5 airmasses in poor weather. The solid red line shows a more typical emissivity for observations with GISMO, which are predicated on intending to use it only in less-than-ideal conditions. (Right) Calculated main beam and forward efficiencies for the 30m telescope, using values found online in IRAM literature.

Optical power and noise can be calculated using the photon occupation number n at an emissivity ε at frequency ν:

$$n(\varepsilon,\nu) = \eta_{sys}\left[1-\xi+\xi\varepsilon\right]\cdot\left(\frac{1}{e^{h\nu/kT}-1}\right),$$

where η is the total optical efficiency from the atmosphere to the detector, T is the atmosphere physical temperature, and ξ is the forward efficiency of the telescope (Figure 1). The efficiency factors at the front reduce the photon occupation number of a blackbody by the effective emissivity of the atmosphere and transmission of the system. We assume fiducial values of ξ=0.88 for the 30m at 150 GHz, and T=275 K. Optical efficiencies for GISMO are calculated both for the present case with a 40% neutral density filter installed in the instrument, in which case η_{sys}=0.14, and for a future observation conducted without this filter, in which case η_{sys}=0.35. The resultant effective photon occupation number is shown in Figure 2. It is immediately apparent that the photon number is everywhere greater than unity, and therefore the photon noise will have a significant contribution from photon correlation noise.

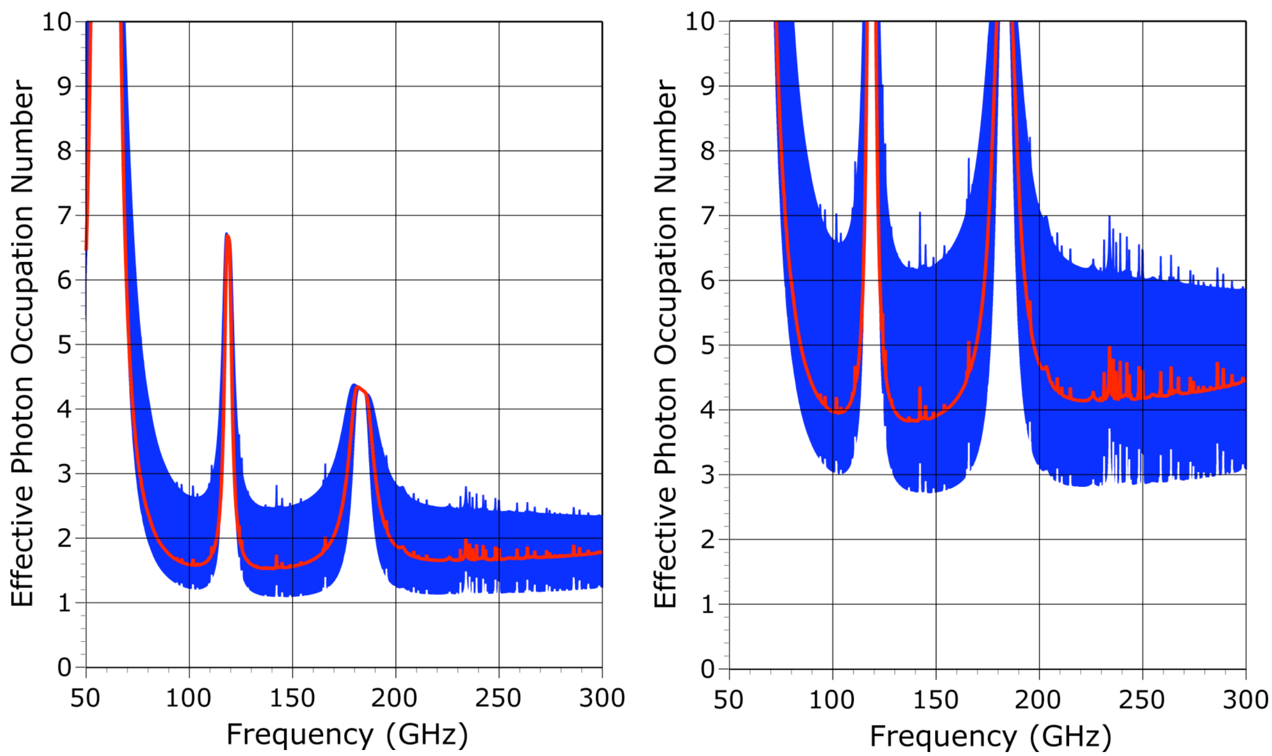

Figure 2. Effective photon occupation number calculated as described in the text. The panel at left is for the current GISMO implementation with the 40% neutral density filter, whereas the panel on the right is for a future observation conducted without the neutral density filter.

We can calculate the photon NEP, power, and NEFD for this occupation number using:

$$NEP_{occ} = h\nu\sqrt{2\cdot\Delta\nu\cdot n(n+1)},$$

$$P_{occ} = \frac{2h\nu^3}{c^2} n\cdot A\Omega\cdot\Delta\nu,$$

and $$NEFD_{occ} = \sqrt{2}\cdot\sqrt{2}\cdot\frac{NEP}{A\Delta\nu}\cdot\frac{\gamma}{\eta_{sys}(1-\varepsilon)\eta_{MB}},$$

where the factor of 2 in the NEP is for two polarizations (number of modes); for the power it is the same (as per the Planck function); and for NEFD the two factors represent differencing between two (Gaussian) noise signals and the conversion in bandwidth to time (1 s corresponds to 0.5 Hz). The other parameters are taken as A=500 m^2 for the effective area, $A\Omega$=3.93·10^{-6} m^2 for the GISMO throughput, and $\Delta\nu/\nu$=0.15 (22 GHz @ 150 GHz) for GISMO's bandpass filter. The main beam efficiency η_{MB} is calculated for the 30m, and produces a 68% efficiency at 2 mm (Figure 1). Finally, the factor γ represents the effective increase in NEFD due to spreading of the instrumental response to a point source onto multiple pixels; this arises from the signal of a point source being spread out in an observing technique-dependent way onto the noise of multiple pixels (noise including not just the instrumental noise, but the atmospheric noise that is present in all pixels), and can be calculated via convolution integral using a specific observing pattern. In an arbitrary-position scan such as a 2D Lissajous map, the factor is γ=4.07. For a simple time-domain data series (corresponding to a linear scan across a source), the factor is γ=2.06.

The power is shown in Figure 3, where an additional 5 pW is included for an estimated maximal loading from the internal emission of the GISMO cryostat. Figure 4 shows the NEP estimates.

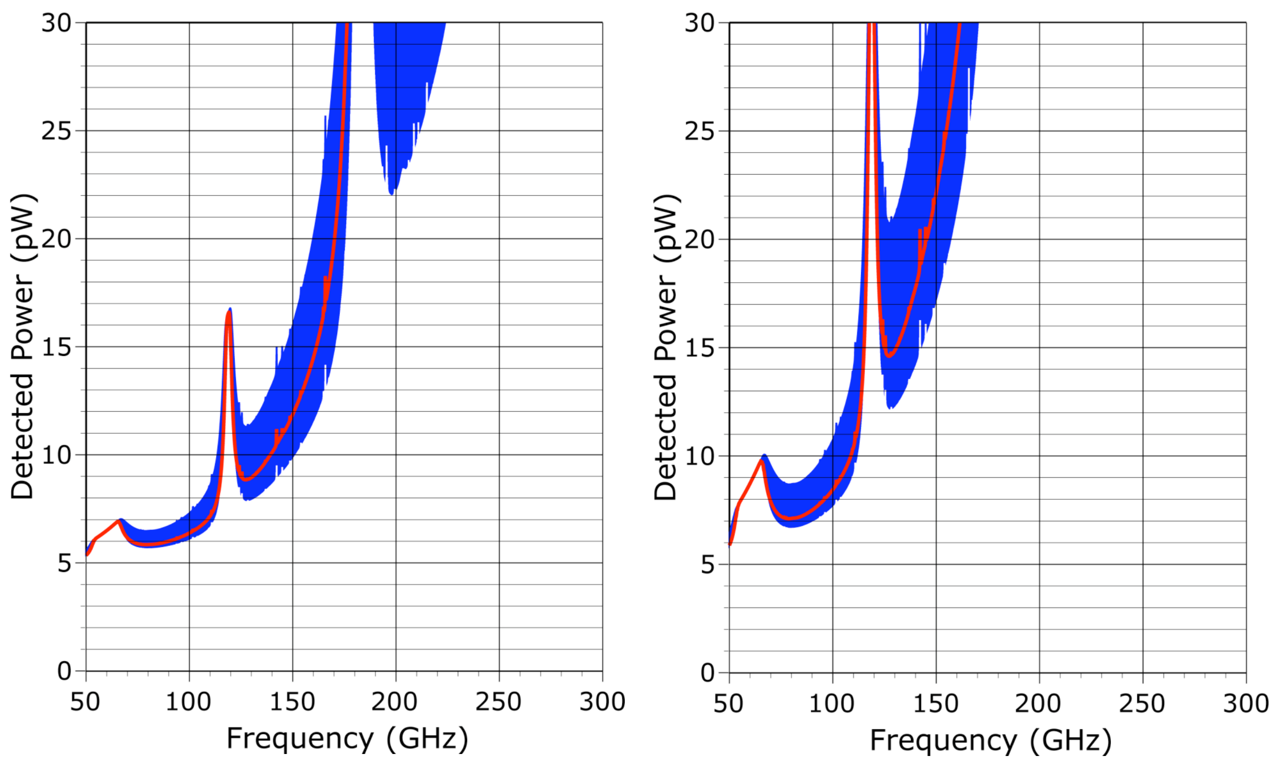

Figure 3. Effective power in the photon occupation number and cryostat load calculated as described in the text. The power at 2mm is 7 pW from the sky in the current configuration. Calculations predict that an additional load of up to ~5 pW comes from the instrument (roughly 3 pW at 4K, 1 pW at 77 K, and 1 pW at 300 K). The panel at left is for the current GISMO implementation with the 40% neutral density filter, whereas the panel on the right is for a future observation conducted without the neutral density filter. The detector saturation power is approximately 30pW, and so there should be no possibility of saturation under practically all observing conditions with the neutral density filter, whereas without it, the detectors will satuarate under poor conditions.

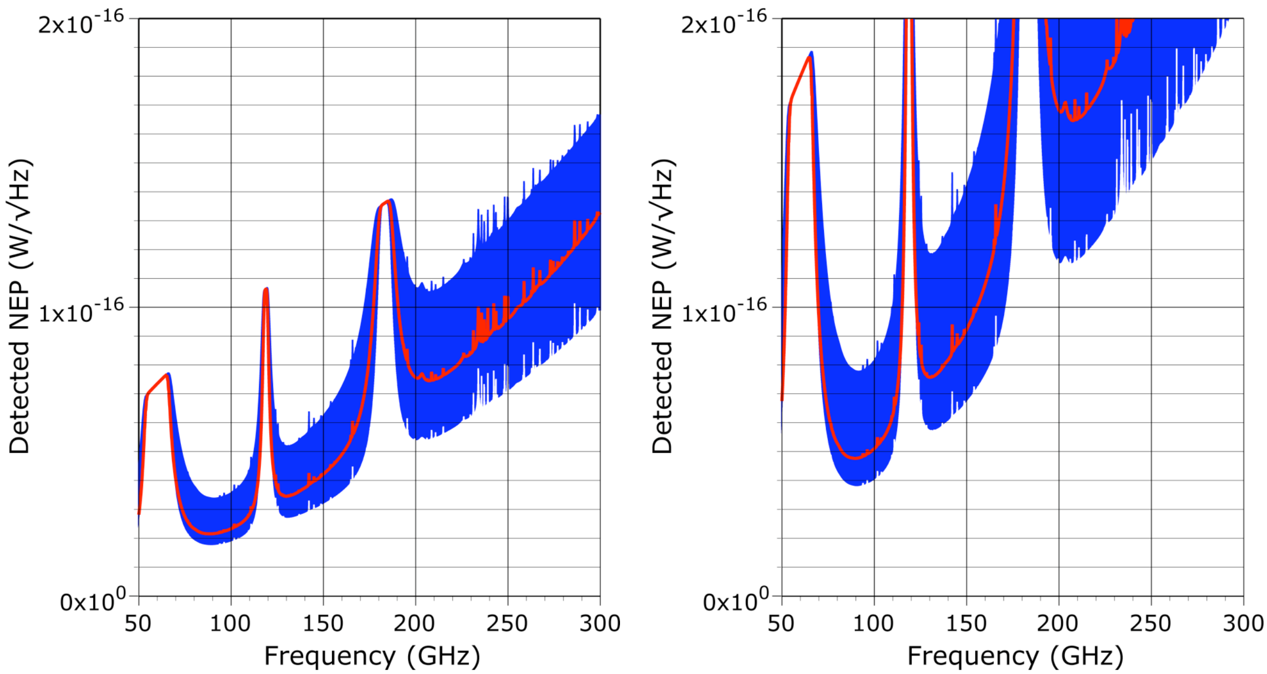

Figure 4. Detected Noise Equivalent Power (NEP) from the atmospheric photon occupation number, calculated as described in the text. This calculation also has been done in the GISMO filter model, which uses only shot noise but approximately validates this model. The panel at left is for the current GISMO implementation with the 40% neutral density filter, whereas the panel on the right is for a future observation conducted without the neutral density filter.

The *NEFD* is calculated using the total system NEP, which includes contributions from detector NEP, in-band photon noise from the instrument, and out-of-band photon noise. The relative magnitude of these contributions is calculated to be $4{\cdot}10^{-17}$ W/√Hz, $3{\cdot}10^{-17}$ W/√Hz, and $3{\cdot}10^{-18}$ W/√Hz, respectively. (Note that the instrument NEP is currently approximately equal to the atmospheric NEP, and with the removal of the neutral density filter the instrument NEP becomes much smaller.) Because the point-source S/N correction factor γ is 4.07 for maps and 2.06 for time-domain linear scans, there are two different values for the NEFD for comparison with GISMO measurements.

An approximate value for the current map NEFD (Figure 5) in typical weather is 34 mJy in one second, with a range between 28 mJy and 56 mJy in good and bad conditions, respectively. This is in good agreement with the measured value of ~45 mJy determined from the estimated flux of J1148+5251 in relatively poor weather. Of the 34 mJy expected NEFD, we can determine an approximate breakdown into the contribution from atmosphere photon noise, instrument photon noise, and detector noise; these values are 22, 16, and 22 mJy in one second. In this regard, GISMO is on the cusp of being photon-noise-limited. Removing the neutral density filter from GISMO should bring these contributions down to approximately 20, 6, and 8 mJy in one second, which is clearly photon noise dominated. The total system NEFD would drop to around 22 mJy, an improvement in effective observing speed of a factor of 2.4.

As a further check, we can estimate that for MAMBO, the photon NEP should be around $2 \cdot 10^{-16}$ W/√Hz, and that the NEFD would be around 35 mJy in a second in good weather. (This is calculated using the MAMBO solid angle and assuming a 20% emissive atmosphere at 250 GHz, equivalent to the best conditions presented for GISMO). To the best of our knowledge, these values are appropriate as compared to IRAM documentation found online.

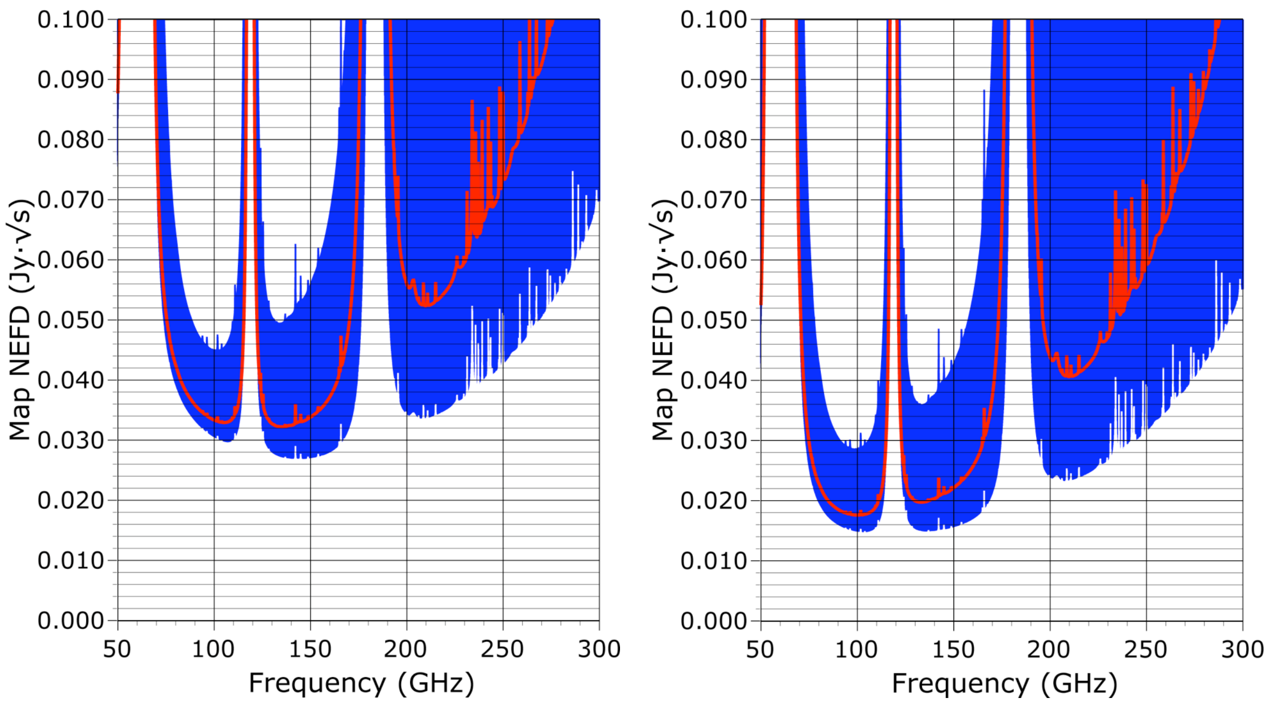

Figure 5. Total GISMO and IRAM 30m Noise Equivalent Flux Density (NEFD) in typical weather ranges, appropriate for maps of point sources of unknown position. At 150 GHz, an NEFD of around 34 mJy in one second should be achieved, slightly lower than typical values measured during run #2 (between 40 and 50 mJy in one second), during most of which the weather was mediocre. The panel at left is for the current GISMO implementation with the 40% neutral density filter, whereas the panel on the right is for a future observation conducted without the neutral density filter. After removal of the neutral density filter, the typical NEFD should drop to 22 mJy in a second, and should be as good as 16 mJy per second in excellent weather.

For the case of time-ordered data, the NEFD is extracted by fitting not to the S/N in a map, but in a single crossing of a source over a pixel. The predicted NEFD is 24 mJy in 1 s (Figure 6), which has been confirmed by a measurement of 30 mJy in 1 s on 3C545 in moderately poor weather. This NEFD can be realized when trying to detect point sources of known position, whereas the map NEFD is appropriate when trying to detect point sources of unknown position. When the neutral density filter is removed, the NEFD should drop to around 16 mJy (11 mJy in excellent conditions), an improvement in effective observing speed of a factor of 2.3.

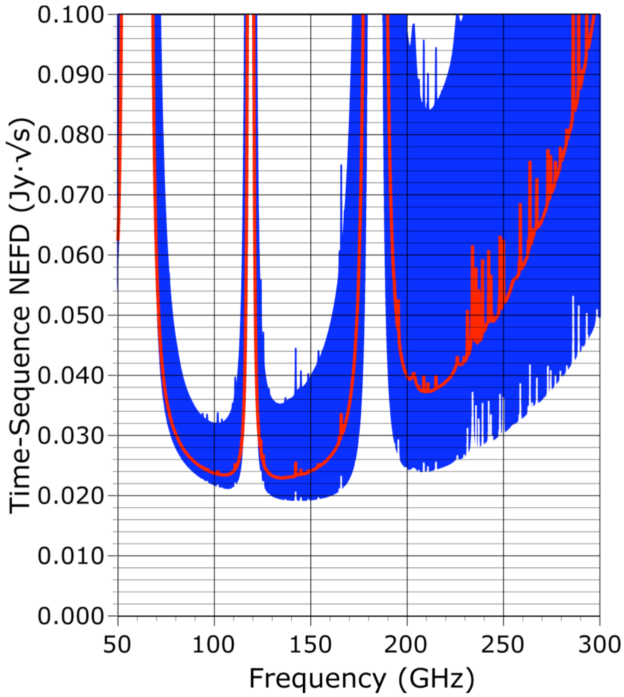

Figure 6. Total GISMO and IRAM 30m Noise Equivalent Flux Density (NEFD) in typical weather ranges, appropriate to observations of point sources of known position. At 150 GHz, an NEFD of around 24 mJy in one second should be achieved, similar to the measured value on 3C545. The panel at left is for the current GISMO implementation with the 40% neutral density filter, whereas the panel on the right is for a future observation conducted without the neutral density filter. After removal of the neutral density filter, the NEFD should drop to 16 mJy.