Non-linear Behaviour of Bolometric Detectors in Fourier Spectroscopy

David A. Naylor, Brad G. Gom, Scott C. Jones, Locke D. Spencer

Department of Physics, University of Lethbridge, Lethbridge, AB, CA, T1K 3M4

Naylor@uLeth.ca

Abstract: The non-linear behaviour of bolometric detectors can lead to significant radiometric errors in Fourier spectroscopy if left uncorrected. We discuss a preliminary investigation of this effect and its correction.

OCIS codes: (300.6300) Spectroscopy, Fourier transforms; (300.6270) Spectroscopy, far infrared.

1. Introduction

The non-linear behaviour of sensitive bolometric detectors used in conjunction with a Fourier transform spectrometer can lead to significant radiometric errors in the derived spectra if left uncorrected[1]. Several far-infrared space astronomy missions, under study by leading space agencies, require bolometric detectors at least two orders of magnitude more sensitive than those currently in operation. Rapid progress is being made in detector development laboratories around the world and it is anticipated that within the next year the goal of optical NEPs approaching $10^{-19}\ W/\sqrt{Hz}$ will have been reached. With this sensitivity, observations of many galactic sources, when viewed with a telescope and FTS operating at cryogenic temperatures, will produce such large modulation around the zero path difference region of the interferogram that non-linear effects will be present. Our group has started to investigate the non-linear behaviour of different types of far-infrared detectors and to study ways of correcting this non-linearity. We report on progress to date.

2. Theory

The interferogram of a polychromatic source can be expressed as

$$I(z) = \int_{\sigma_{min}}^{\sigma_{max}} B(\sigma) \exp(2\pi i \sigma z) d\sigma \quad [W] \ , \tag{1}$$

where I represents the power falling on the detector as a function of the optical path difference within the interferometer, z, and the source emits over a frequency range σ_{min} to σ_{max}, cm^{-1}. If the detector response is non-linear, the measured detector voltage, V_d, can be expressed as

$$V_d(z) = \alpha\, I(z) + \beta\, I^2(z) + \gamma\, I^3(z) + \ \ldots \quad [V] \ . \tag{2}$$

where the coefficients α, β and γ depend upon the type of detector and its operating point which is usually taken as the unmodulated component of the interferogram. Using the convolution theorem the multiplication in the spatial domain corresponds to convolutions of increasing order in the spectral domain. The derived spectrum $S(\sigma)$ is then determined by the Fourier transform of Eq. 1 and can be expressed as

$$S(\sigma) = \alpha B(\sigma) + \beta[B(\sigma) * B(\sigma)] + \gamma[B(\sigma) * B(\sigma) * B(\sigma)] + \ \ldots \quad [W/cm^{-1}] \ . \tag{3}$$

The α term contains the spectral radiance, $B(\sigma)$, of the source under study centred at σ_o and of width σ_w. The quadratic, β, term represents the autocorrelation of $B(\sigma)$, and results in two spectral features of width $2\sigma_w$. The first spectral feature is centred at 0 cm^{-1}; the second is centred at $2\sigma_o$. The cubic, γ, term in Eq. 3 also contributes two spectral features to the observed spectrum, both of width $3\sigma_w$ and centred at σ_o and $3\sigma_o$, respectively.

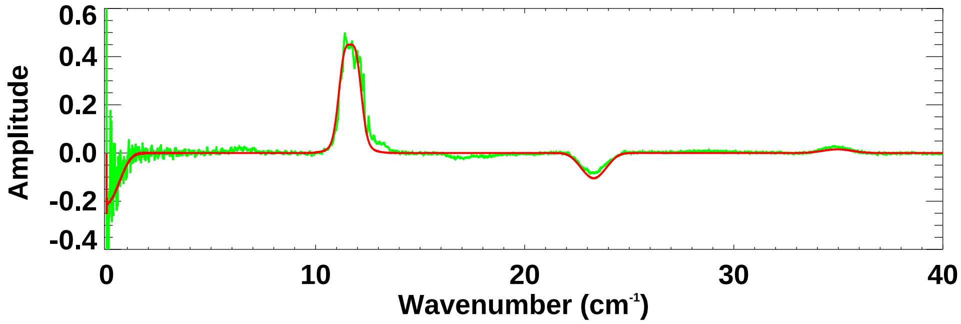

Fig. 1. Comparison of FTS spectra obtained with a TES detector that was intentionally driven nonlinear and a theoretical bolometer model.

3. Results

Fig. 1 illustrates the effects of nonlinearity described by equation 1. The green curve is the measured spectrum derived from a sensitive superconducting transition edge sensor (TES)[2] operating close to the normal state of the metal film where non-linear effects become significant (Note: when a TES is operated at the centre of its transition it is an intrinsically linear device). This spectrum was measured with a narrow band filter centred at 11.6 cm^{-1} and of width 1.1 cm^{-1}. The spectral features arising from the quadratic term, at 0 and 23.2 cm^{-1} can be clearly seen. The cubic term gives two features, one which is centred on the fundamental band, the second is centred at 34.8 cm^{-1}. The red curve in Fig. 1 shows the predicted spectrum derived using a theoretical bolometer model[3]. The model spectrum is in good agreement with the experimental data. Providing that the interferogram is sufficiently oversampled, the harmonic features can be used, not only to assess the level of detector non-linearity, but also to devise methods for its correction.

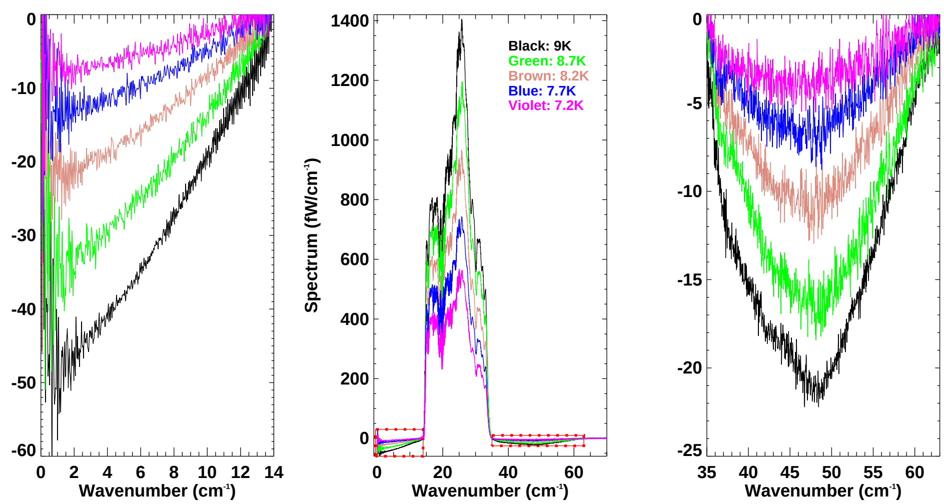

Fig. 2. Spectra obtained using the Herschel/SPIRE FTS, with one input port viewing a blackbody source at 4.6 K, and the other a blackbody between 6.7 and 9 K.

To further illustrate the effects of bolometer non-linearity on FTS spectra, Fig. 2 presents spectra obtained with the Herschel/SPIRE FTS during ground test campaigns[4]. In these measurements one input port of the FTS viewed a calibration source at 4.6 K while the temperature of the blackbody at the second port was varied between 6.7 and 9 K. The spectra are overlaid in the centre plot of Fig. 2. The zoomed regions corresponding to the location of the quadratic nonlinearity term are also shown. No contributions were seen from cubic or higher order terms.

The SPIRE detectors are designed to have extremely good 1/f noise performance[5], and as such allow a direct comparison of the integrated power under the two harmonic features that arise from the quadratic nonlinearity term. Fig. 3 graphs the integrated power in these features as a function of the total in-band power. There is seen to be excellent agrement between the power in each harmonic band, furthermore, the nonlinear behaviour of the detector is clearly evident and increases as expected as a function of loading.

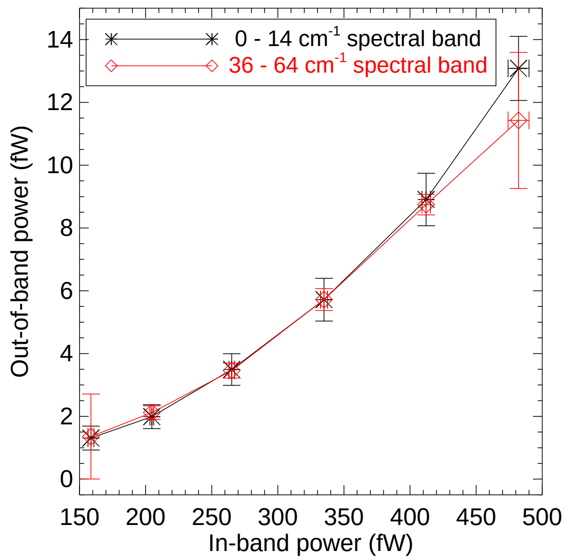

Fig. 3. Integrated out-of-band vs. in-band spectral power measured with a SPIRE detector. The black asterisks and red diamonds correspond to the quadratic non-linear harmonic regions, below and above the fundamental band, respectively. Error bars are $\pm$ 1σ.

4. Conclusion

By Fourier transformation of an over-sampled interferogram it is possible to determine the amount of detector non-linearity from analysis of the harmonic regions of the spectrum, provided that these regions do not overlap significantly with the nominal spectral bandpass. Though not shown for lack of space here, we have successfully inverted the theoretical bolometer model to correct for the non-linearity shown in Fig. 1. A reconstruction algorithm, based on minimizing the residual signal in the harmonic regions, has been developed and results from its application to experimental data will be presented. While detector non-linearity will always be present at some level, armed with a detailed bolometer model, a knowledge of the total power loading on the bolometer (both optical and electrical), a careful selection of nominal spectral band and a suitably (four times) oversampled interferogram, it should be possible to significantly enhance the radiometric accuracy of FTS spectra. This research has been funded by AI, CFI, CSA, NSERC, and STFC.

References

1. A. Kleinert, “Correction of detector nonlinearity for the balloonborne Michelson Interferometer for Passive Atmospheric Sounding,” Applied Optics **45**, 425 – 431 (2006).
2. W. Holland et al., “SCUBA-2: A large format submillimetre camera on the James Clerk Maxwell Telescope,” in *Proc. SPIE* **4855** (2003).
3. R.V. Sudiwala et al., “Thermal Modelling and Characterisation of Semiconductor Bolometers,” J. IRMMW **23** (2002).
4. Locke D. Spencer et al., “Performance Evaluation of the Herschel/SPIRE Instrument Flight Model Imaging Fourier Transform Spectrometer,” in *Proc. SPIE* **7010** (2008).
5. M. Griffin et al. , “Herschel-SPIRE: design, ground test results, and predicted performance,” in *Proc. SPIE* **7010** (2008).