Removing the baseline of interferograms from the SPIRE imaging FTS

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1. Scope

This note describes and evaluates techniques to remove the baseline of the interferograms measured by the SPIRE imaging Fourier transform spectrometer (iFTS). The two main techniques considered here differ in how the interferogram baseline is characterized: either by its Fourier components or a polynomial function. The goodness-of-fit to the interferograms, the introduced spectral artifacts in the optical passband, unintended side effects on the interferograms, and the performance in the case of clipped interferograms serve to evaluate the performance of the techniques. In addition, this note proposes a technique to remove a constant baseline. Recommendations are made for appropriate use and parameter selection for SPIRE based on applying the algorithms on data from a test observation.

2. Motivation

The interferogram of an ideal FTS can be separated into a constant offset and a modulated portion. Real interferograms display not only a constant offset but a baseline which is a function of optical path difference (OPD) and/or time.

In the case of the SPIRE iFTS the OPD-dependent baseline is due to efficiency losses when light traverses the interferometer module not strictly perpendicularly (see Kjetil Dohlen: Herschel – SPIRE: Optical Error Budgets, January 17, 2002, LOOM.KD.SPIRE.2000.002-4). From the PFM test campaigns it is known that these efficiency losses occur approximately symmetrically about a stage position close to ZPD and decrease the power incident on the detectors with increasing distance from that point of symmetry (see David Naylor, Trevor Fulton, Peter Davis: Vignetting in PFM1 High Resolution Interferograms, version 1.1, April 29, 2005, SPIRE-UOL-REP-002410 and the SDAG presentation by Marc Ferlet: SPIRE PFM1 & CQM2 – Optical performances, May 23, 2005). This 'vignetting' (aka smile or frown) is strictly a function of incident radiation and OPD and should remain stable as long as the integrity of the optical chain is maintained.

Changes that occur as a function of time and not OPD, e.g. drifts of the SCal temperature or the operating temperature of the bolometers, may also add to a non-constant interferogram baseline and will vary from scan to scan.

Determining the shape of the baseline and removing it serves two purposes:

1. Enhance or enable subsequent processing steps:
   a. 2nd level deglitching (relies on interferograms with a highly repeatable baseline)
   b. Channel fringe removal (TBD)
   c. Fourier transform of the zero-padded interferograms
2. Sudden changes in the baseline or a slow deterioration of the baseline can be flagged in the quality control pipeline or the long term trend analysis.

3. Removal Algorithms

Baseline removal consists of two parts: First a fit to the baseline and then the subtraction of the fitted baseline from the measured signal. The fitting procedure used in the first step is the crucial element which is considered in the following. Selecting parameters for an optimal baseline fitting involves a trade-off between goodness of fit, robustness, and introduction of spectral artifacts in the optical and other artifacts. Sections 3.1 to 3.3 discuss polynomial baseline removal, FT baseline removal, and offset removal respectively.

3.1 Polynomial fitting

A polynomial function can be used to approximate the interferogram baseline. Polynomials of even order are used because of the known instrumental symmetries of the SPIRE iFTS. The respective algorithm is as follows:

1. Fit a polynomial of even order to the full range of the interferogram
2. Subtract the polynomial from the interferogram signal

3.1.1 Free parameters

The order of the polynomial baseline may be varied to optimize the goodness and stability of the fit while minimizing the spectral artifacts introduced within the optical passband.

Goodness of fit

The goodness of the polynomial fit to the baseline is measured by χ^2 which is determined as follows:

$$\chi^2 = \Sigma(interferogram_i - baseline_i)^2$$

$interferogram_i$ is the i[th] element of the interferogram array; $baseline_i$ is the i^{th} element of the baseline array. Lower values of χ^2 indicate closer fits. The results of the goodness of fit of polynomial fits are reported in Table 1 and illustrated in Illustration 1. The absolute values of the reported χ^2 values are very large because the slowly varying polynomials cannot describe the rapid modulation of the interferograms well. These results indicate that

- 2^{nd} order polynomials do not fit the interferograms very well and produce a typical over- and under-shoot (see the left-hand-side of Illustration 1).
- polynomial functions of order 4 or higher can indeed fit the interferogram baseline well but do not eliminate higher frequency oscillations (see the right-hand-side of Illustration 1).
- higher order polynomials produce a better fit than lower order polynomials up to an order of about 10, (see Table 1).
- Polynomials of degree 10 or more often have very poor fits to interferograms (data not shown here).

Pixel	χ2 of the polynomial fit to the interferogram [ADU²]			
	Order 2	Order 4	Order 6	Order 8
SLWA1	2.93E+07	9.94E+05	8.35E+05	7.97E+05
SLWA2	2.30E+07	1.44E+06	1.49E+06	1.24E+06
SLWB1	1.68E+07	1.82E+06	1.85E+06	1.62E+06
SLWC1	1.25E+07	7.51E+05	7.52E+05	6.90E+05
SLWC4	2.02E+06	1.70E+06	2.09E+06	1.62E+06
SLWC5	1.39E+07	1.30E+06	1.33E+06	1.25E+06
SLWD1	5.38E+06	1.23E+06	1.42E+06	1.17E+06
SLWE1	1.57E+06	1.16E+06	1.19E+06	1.14E+06
SLWE2	4.37E+06	1.57E+06	1.74E+06	1.51E+06
χ2 evaluated on interferogram sub-interval MPD = [14,32] mm				

Table 1: fit of polynomial baselines to a selection of strongly vignetted interferograms. χ2 decreases with increasing order (from observation 3001172B).

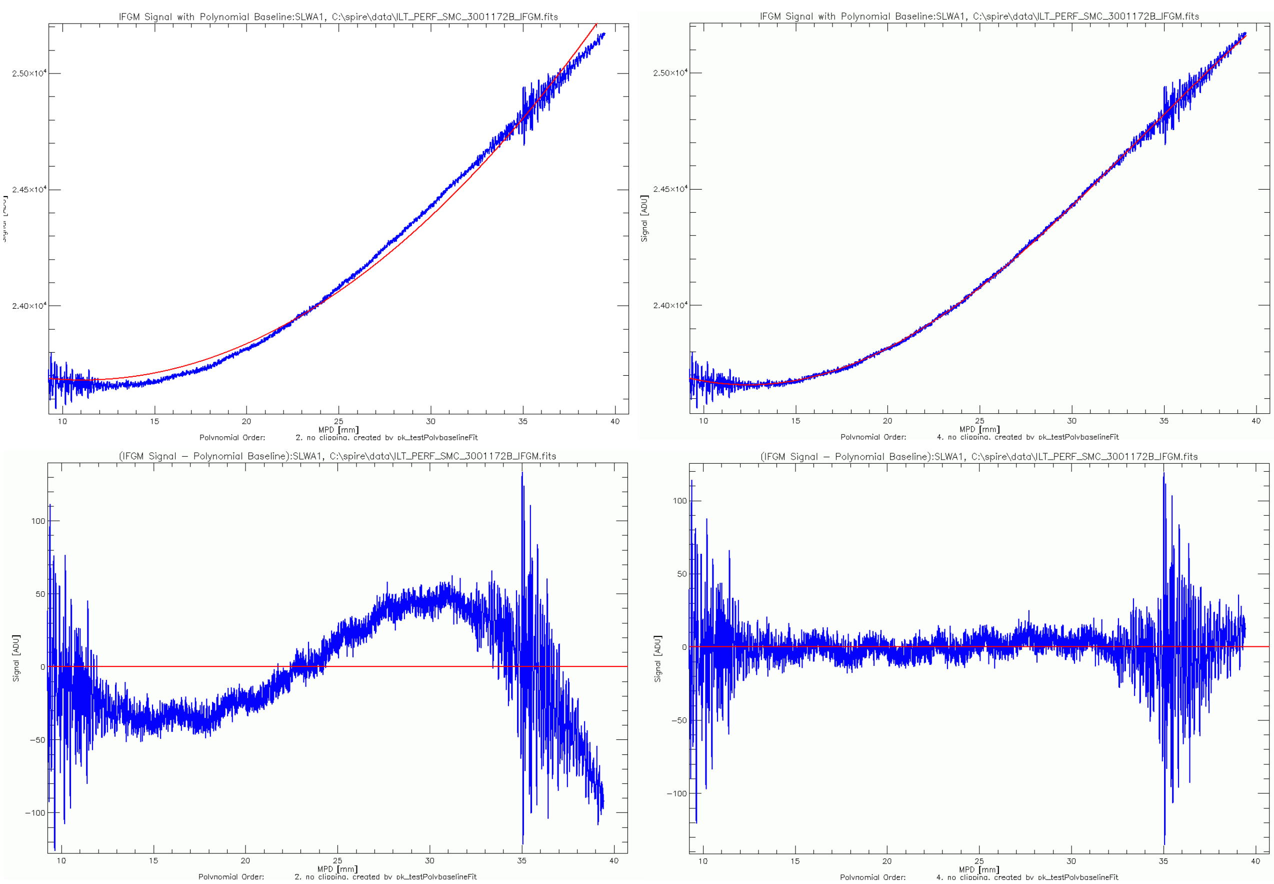

Illustration 1: 2nd and 4th order baseline removal for an interferogram that displays a baseline with a time-modulation of unknown origin (ordered from left to right, top to bottom):(a) Detail of a 2nd order fit to the interferogram, (b) 4th order fit to the interferogram, (c) (Interferogram signal - 2nd order polynomial baseline), (d) (Interferogram signal - 4th order polynomial baseline).

Spectral artifacts within the optical passband

Subtracting a polynomial baseline from its interferogram introduces artifacts within the optical passband. The ranges for the optical passband are taken from the SDAG report, November 30, 2006, on a pixel-by-pixel basis. The significance of the in-band error can be assessed by comparing it to the in-band signal. Table 2 reports the minimum signal-to-error ratio in the optical passband as a function of the order of the polynomial function used for the baseline fit.

Pixel	**Minimum in-band signal to error [SNE] (observation 3001172B)**			
	Order 2	Order 4	Order 6	Order 8
SLWA1	2780	3660	3270	3240
SLWA2	3170	3680	3460	3300
SLWB1	2810	3380	3120	2940
SLWC1	2490	2940	2780	2680
SLWC4	12800	14300	14100	12900
SLWC5	3390	4620	4360	4420
SLWD1	4190	4760	4660	4260
SLWE1	2970	3210	3200	3140
SLWE2	4220	4450	4390	4150

Table 2: Minimum in-band signal to error ratio [SNE = min(in-band signal/error)] caused by subtracting polynomial baselines from the interferograms (observation 3001172B)

These results indicate that

- the SNE does not depend strongly on the fitting order and is always higher than the SNR we will be able to achieve. The introduced artifacts are small compared to the noise in the optical band.
- the 4^{th} order fit generally introduces the least amount of error to the optical passband.

In order to check the spectral contamination in the optical passband for all pixels, see Illustration 2, which shows that for observation 3001172B, the in-band SNR is greater than 2000 for all unclipped pixels when the order is 8 or less.

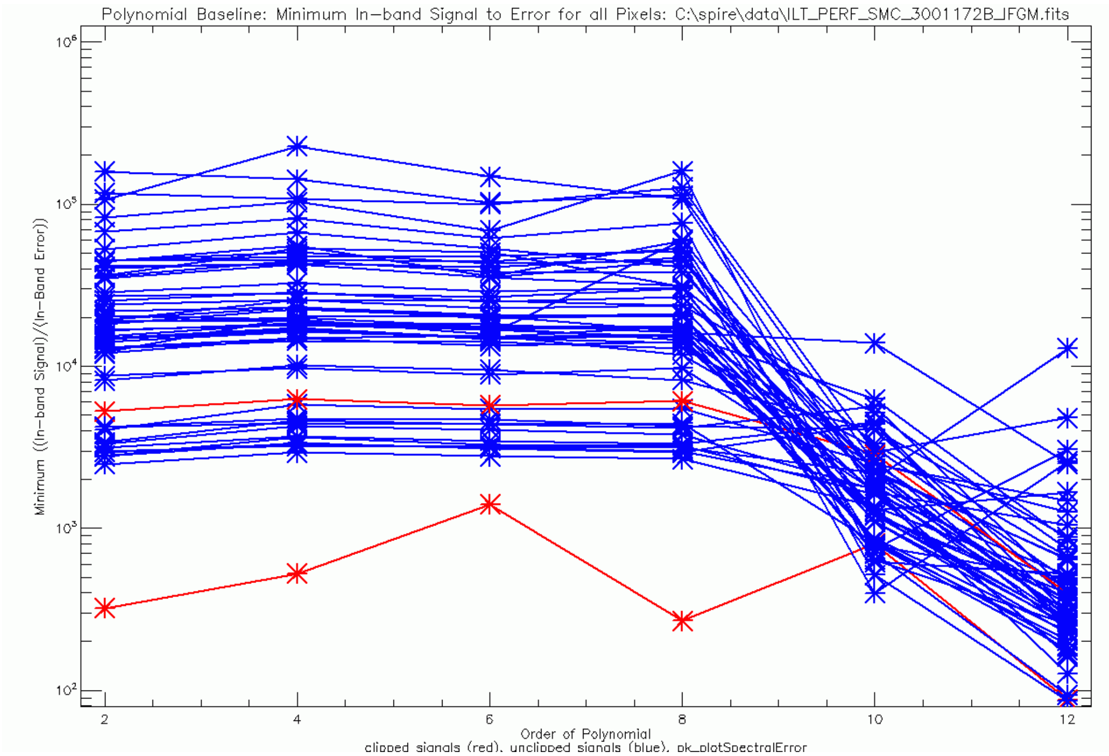

Illustration 2: Minimum in-band signal to error ratio (SNE) introduced by subtracting the polynomial baseline from the interferogram vs. order of polynomial baseline. Data from all pixels are over-plotted. Red data points represent data from clipped interferograms.

Vignetting trends and order

The coefficients of the 2nd order polynomial fit can be used to track the amount of vignetting. Illustration 3 shows that it might be possible to use the second order polynomial baseline to predict the level of vignetting by determining the flux incident from the two input ports. It remains to be studied how baseline fits with polynomials of higher order would be used to that purpose.

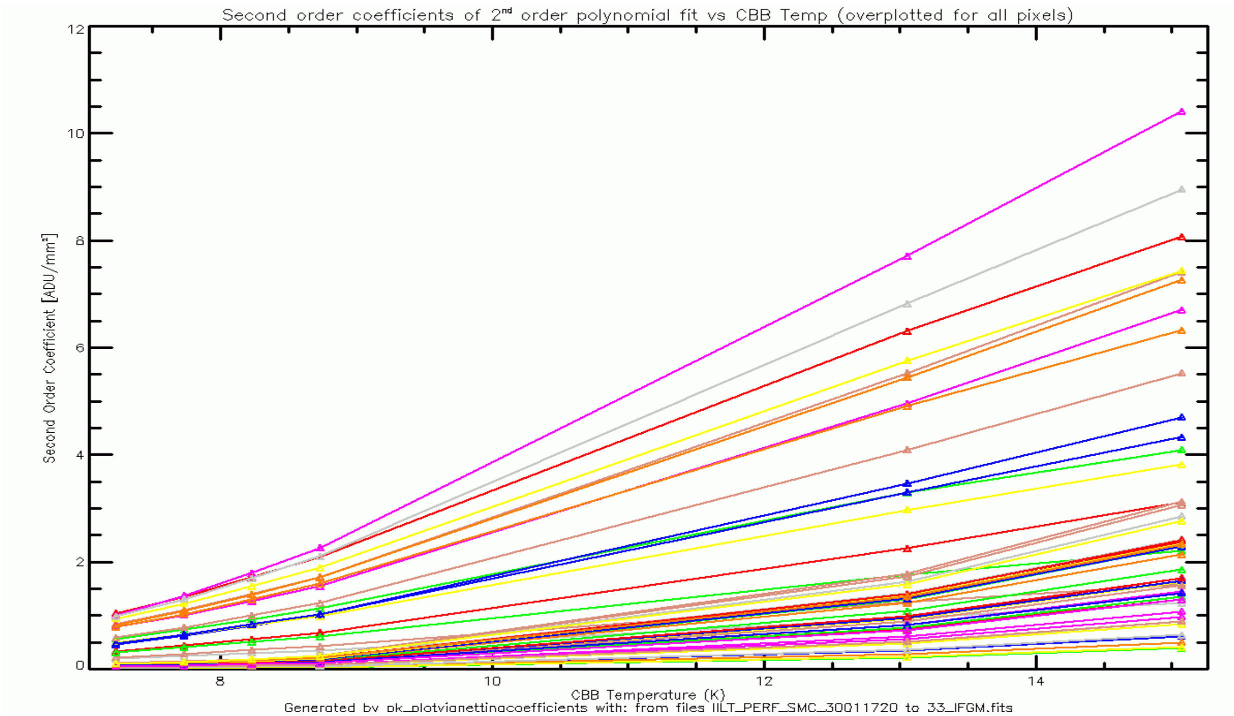

Illustration 3: The 2nd order coefficient of the polynomial fit shows the increasing "curvature" of the interferograms with increasing loading , due to increasing CBB temperature. Each line represents data from one pixel.

3.1.2 The effect of clipping on polynomial baselines

When the ADC of the detector read-out electronics clips an interferogram, the polynomial fit to the baseline is negatively affected (see Illustration 4). The polynomial fit to the baseline is clearly inadequate in the central burst region – for clipped and unclipped interferograms. However, this poor fit in the central region does not affect the quality of the fit as long as the fit is equally inadequate above and below the baseline. In the case of clipping, this assumption does not hold and the baseline fit fails. In response to this failure, the fit should be limited to portions of the curve that do not include signal "near ZPD." This additional free parameter would have to be defined sensibly.

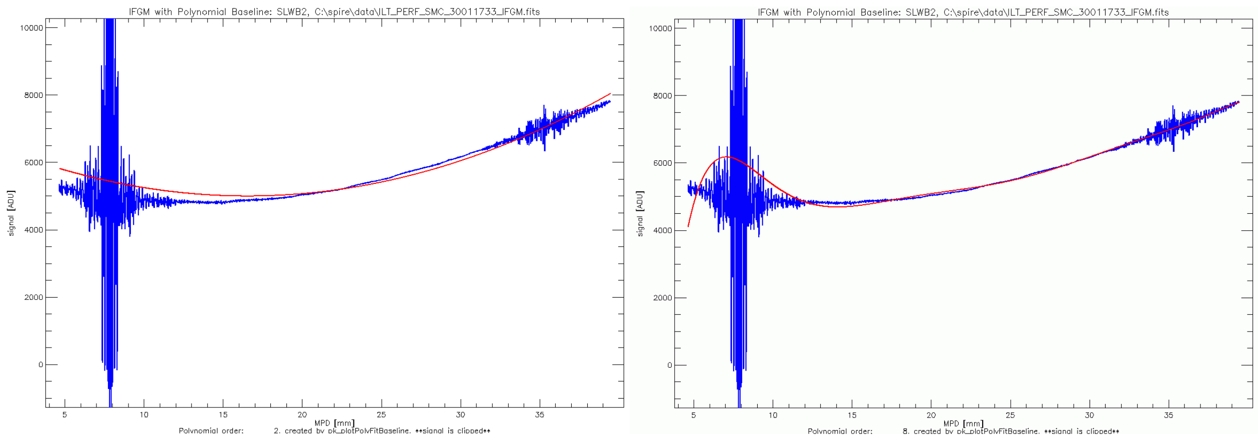

Illustration 4: Effect of clipping on polynomial baselines of different orders: (left) 2nd order polynomial, (right) 8th order polynomial.

3.1.3 Advantages/Disadvantages

Polynomial fitting to the baseline has specific advantages and disadvantages:

Advantages

- Straightforward and robust computation.
- The fitted baseline can be reproduced from a small number of coefficients.
- The spectral artifacts within the optical passband are smaller than the instrumental noise.

Disadvantages

- Cannot fit time-dependent oscillations of the baseline.
- A 2nd order polynomial will systematically mis-fit the baseline (too low/high).
- A suitable sub-range of the interferogram has to be defined for fitting when the interferogram is clipped.

3.2 Zero-infilling of Fourier components: FT Baseline

The interferogram baseline can be approximated by the low frequency components of the Fourier transform of the interferogram. The respective algorithm is as follows (see Illustration 5):

1) Butterfly the entire signal (there is no need to find ZPD or discard any part of the signal.)
2) Fourier transform the butterflied signal.
3) Zero out the spectrum above a chosen wavenumber threshold.
4) Inverse Fourier transform the zero'ed spectrum to produce the baseline.
5) Subtract the baseline from the interferogram signal.

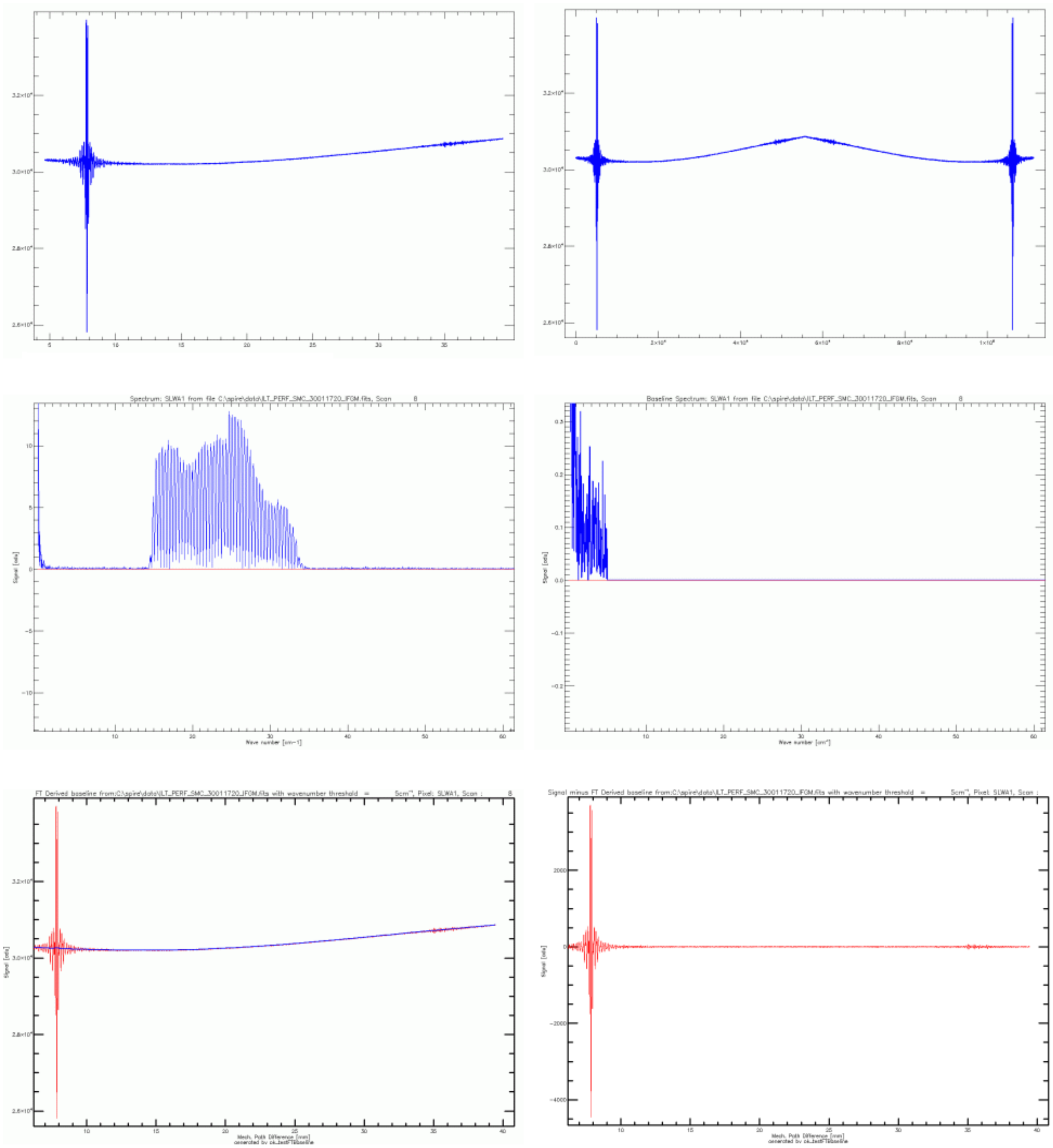

Illustration 5: Computation of the interferogram baseline from the low frequency components of a sample spectrum (ordered from left to right, top to bottom): (a) Signal, (b) butterflied signal, (c) spectrum of butterflied signal (real component -blue, imaginary- red), (d) zeroed spectrum (baseline spectrum), (e) signal (red) with baseline (blue), (f) signal minus baseline.

3.2.1 Free parameters

Varying the threshold determines how much of the low-frequency part of the spectrum is used to compute the baseline. There is a trade-off between how well the baseline fits the interferogram and the artifacts introduced within the optical passband.

Goodness of fit

The results of the goodness of fit of the the FT baseline are reported in Table 3, Illustration 6, and Illustration 7. These results indicate that

- The goodness-of-fit of the FT baseline to its interferogram improves with increasing threshold (Table 3 and Illustration 7).
- If the threshold is very low (~0.3 cm^{-1}) then the baseline does not follow the signal well, particularly at high mechanical path difference where it deviates visibly (see Illustration 6 on the left).
- The FT baseline removal with a sufficiently high threshold removes periodic, low-frequency modulation (see Illustration 6 at the bottom).

	$\chi 2$ of FT baseline fit to interferograms from observation 3001172B [ADU^2]						
Pixel	Threshold = 1 cm^{-1}	Threshold = 2 cm^{-1}	Threshold = 3 cm^{-1}	Threshold = 4 cm^{-1}	Threshold = 6 cm^{-1}	Threshold = 8 cm^{-1}	Threshold = 10 cm^{-1}
SLWA1	6.72E+05	6.38E+05	6.26E+05	6.23E+05	6.01E+05	5.97E+05	5.86E+05
SLWA2	9.53E+05	9.26E+05	8.60E+05	8.67E+05	8.27E+05	8.11E+05	8.02E+05
SLWB1	1.32E+06	1.25E+06	1.20E+06	1.21E+06	1.18E+06	1.16E+06	1.15E+06
SLWC1	5.91E+05	5.58E+05	5.51E+05	5.50E+05	5.41E+05	5.36E+05	5.28E+05
SLWC4	1.20E+06	1.18E+06	1.08E+06	1.06E+06	9.99E+05	9.91E+05	9.93E+05
SLWC5	1.07E+06	1.03E+06	1.01E+06	1.01E+06	9.92E+05	9.85E+05	9.80E+05
SLWD1	8.78E+05	8.18E+05	7.84E+05	7.94E+05	7.48E+05	7.33E+05	7.16E+05
SLWE1	9.91E+05	9.62E+05	9.46E+05	9.26E+05	9.04E+05	8.90E+05	8.65E+05
SLWE2	1.17E+06	1.12E+06	1.08E+06	1.07E+06	1.04E+06	1.02E+06	1.02E+06

Table 3: $\chi 2$ of the FT baseline fit to interferograms in the sub-interval MPD = [14,32] mm at various thresholds for selected pixels.

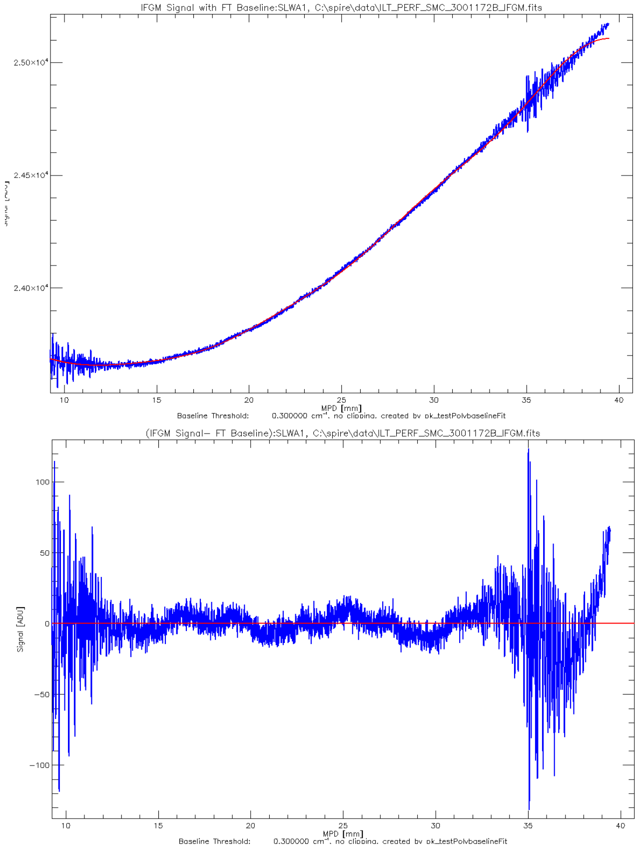

Illustration 6: FT baselines with thresholds of 0.3 cm^{-1} and 4.0 cm^{-1} (ordered from left to right, top to bottom):Baseline fit (red) with threshold = 0.3/4.0 cm^{-1}, in the top row on the left/right. Interferogram signal - FT baseline with threshold = 0.3/4.0 cm^{-1}, in the bottom row on the left/right.

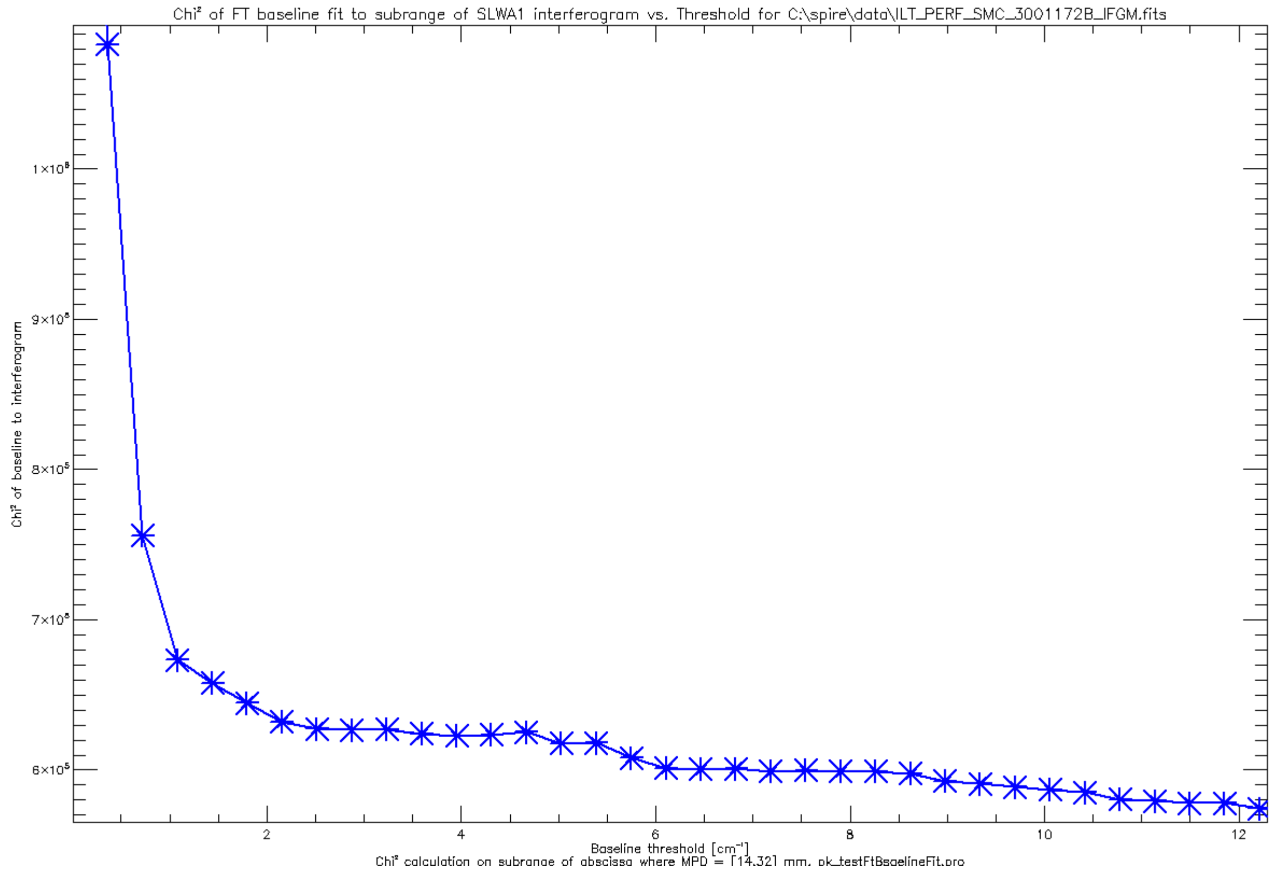

Illustration 7: χ^2 fit of the FT baseline for MPD = [14,32] mm of the SLWA1 3001172B interferogram as a function of the selected baseline.

Spectral artifacts within the optical passband

The FT fitting of the baseline also introduces spectral artifacts. While trying to improve the goodness of fit spectral artifacts should be kept to a minimum. Comparing the amplitude of the introduced spectral artifacts to the signal allows to assess the significance of these errors (see Table 4 and Illustration 8).

	Minimum in-band SNE from observation 3001172B						
Pixel	Threshold = 1 cm^{-1}	Threshold = 2 cm^{-1}	Threshold = 3 cm^{-1}	Threshold = 4 cm^{-1}	Threshold = 6 cm^{-1}	Threshold = 8 cm^{-1}	Threshold = 10 cm^{-1}
SLWA1	14300	22300	9660	11400	6920	3100	2780
SLWA2	25500	141000	19400	44500	15600	8750	5390
SLWB1	12600	26100	8490	11200	5830	3890	5320
SLWC1	9090	12100	8820	9980	6860	5090	2690
SLWC4	45500	11700	43100	175000	7420	5160	8190
SLWC5	13900	10600	13300	14900	17800	22400	12600
SLWD1	27000	78800	37900	159000	20000	9200	7720
SLWE1	49500	84200	251000	40800	152000	58300	65100
SLWE2	216000	31000	188000	65500	15400	6260	6570

Table 4: Minimum in-band signal to error ratio (SNE = min(In-band signal/Introduced error)) caused by subtracting FT baselines from interferograms (from observation 3001172B).

These results indicate that

- the maximum in-band error varies somewhat irregularly at low thresholds (see Table 4).
- the in-band error increases rapidly as the wavenumber threshold increases past 10 cm^{-1} (data not shown).
- the SNE is significantly larger than the SNR we can hope to expect from the SPIRE iFTS for unclipped interferograms. The SNE is above 2,000 for all pixels out to a threshold of 8 cm^{-1} (see Illustration 8).
- the threshold with the highest minimum SNR value is 2 cm^{-1}, at a value of 10,569 (see Table 4). There is, however, no threshold that is optimal for all pixels.

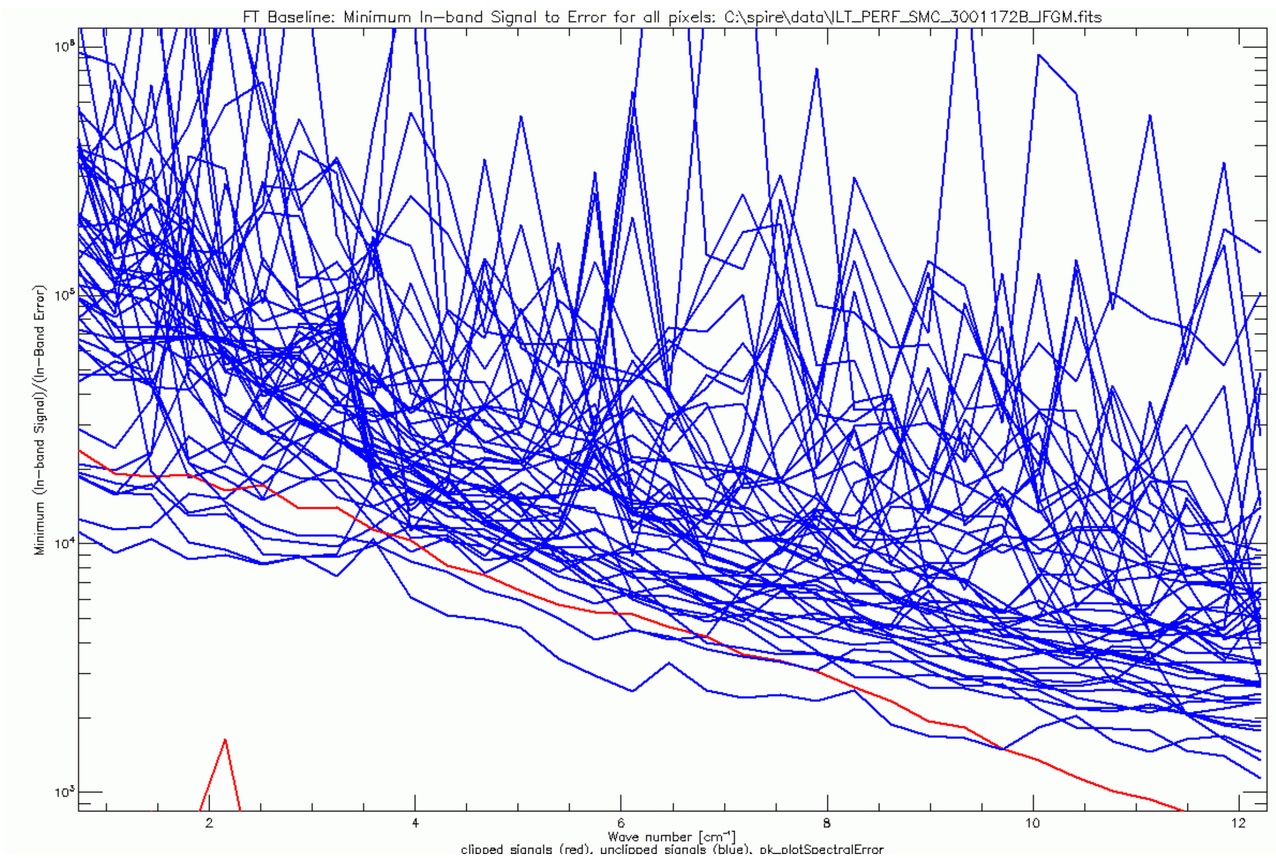

Illustration 8: Minimum in-band signal to error ratio (SNE) introduced by subtracting the FT baseline from its interferogram vs. wavenumber threshold of the FT baseline. All data points are from observation 3001172B where CBB = 8.73 K. All pixels are over-plotted on the same graph. Red data points represent SNE data from clipped interferograms. Blue data points represent SNR data from unclipped interferograms.

Step-following and glitch-following varying with threshold

Fitting the baseline with the low Fourier components of the interferogram introduces additional complications by changing anomalous features of the interferogram. Signal steps, as they have been observed for SSWF4, are smoothed to varying degree depending on the selected threshold (see Illustration 9).

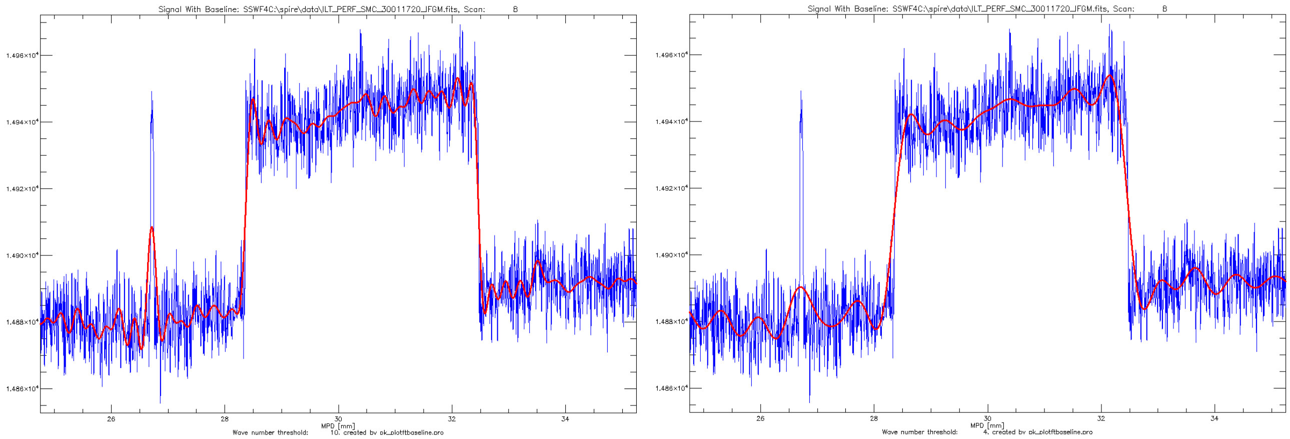

Illustration 9: FT baselines affected by step-glitch: (left) A 10 cm^{-1} baseline follows a wide glitch (MPD= 26.4 mm) and a step-glitch., (right) A 4 cm^{-1} baseline follows a wide glitch less closely .

Glitches are also smoothed out by the removal of the FT baseline (see Illustration 10), which may reduce the likelihood that the glitch is detected by the 2nd level deglitching routine. One of the main purposes for baseline removal is to aid in glitch detection so the effect of this reduction is critical.

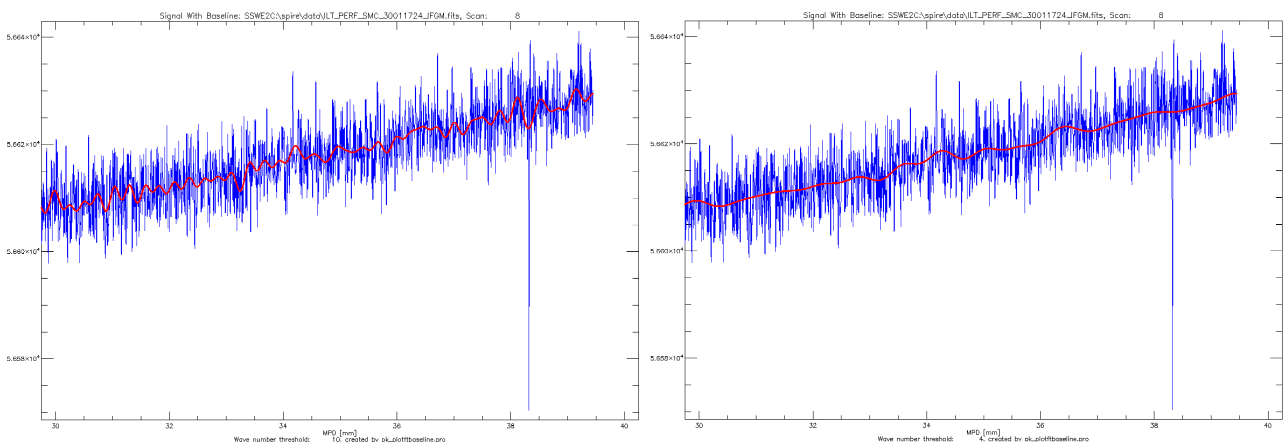

Illustration 10: Baseline following narrow glitches: (left) A 10 cm^{-1} baseline follows a glitch (at MPD = 38.3 mm) without eliminating it. This glitch would be shortened by baseline removal by approximately 1/10 of its height, (right) A 4 cm^{-1} baseline follows a narrow glitch negligibly.

3.2.2.2 Piece-wise FT Baselines

It may be possible to further reduce the error introduced within the optical passband by separating and fitting the interferogram into intervals:

1. [0, ZPD-1]
2. [ZPD, MPD_{max}]

A baseline created from interval of the interferogram from ZPD onward contributes no error to the spectrum. However, joining the $baseline_{[0,ZPD-1]}$ to $baseline_{[ZPD,max]}$ may lead to a discontinuity at ZPD.

3.2.2.3 Finding vignetting trends with baseline spectra

The spectra of FT baselines increase in magnitude with increased optical loading (see Illustration 11). It might be possible to identify vignetting trends by analyzing ratios between consecutive spectra. This could allow for the isolation and analysis of the various effects that contribute to the baseline.

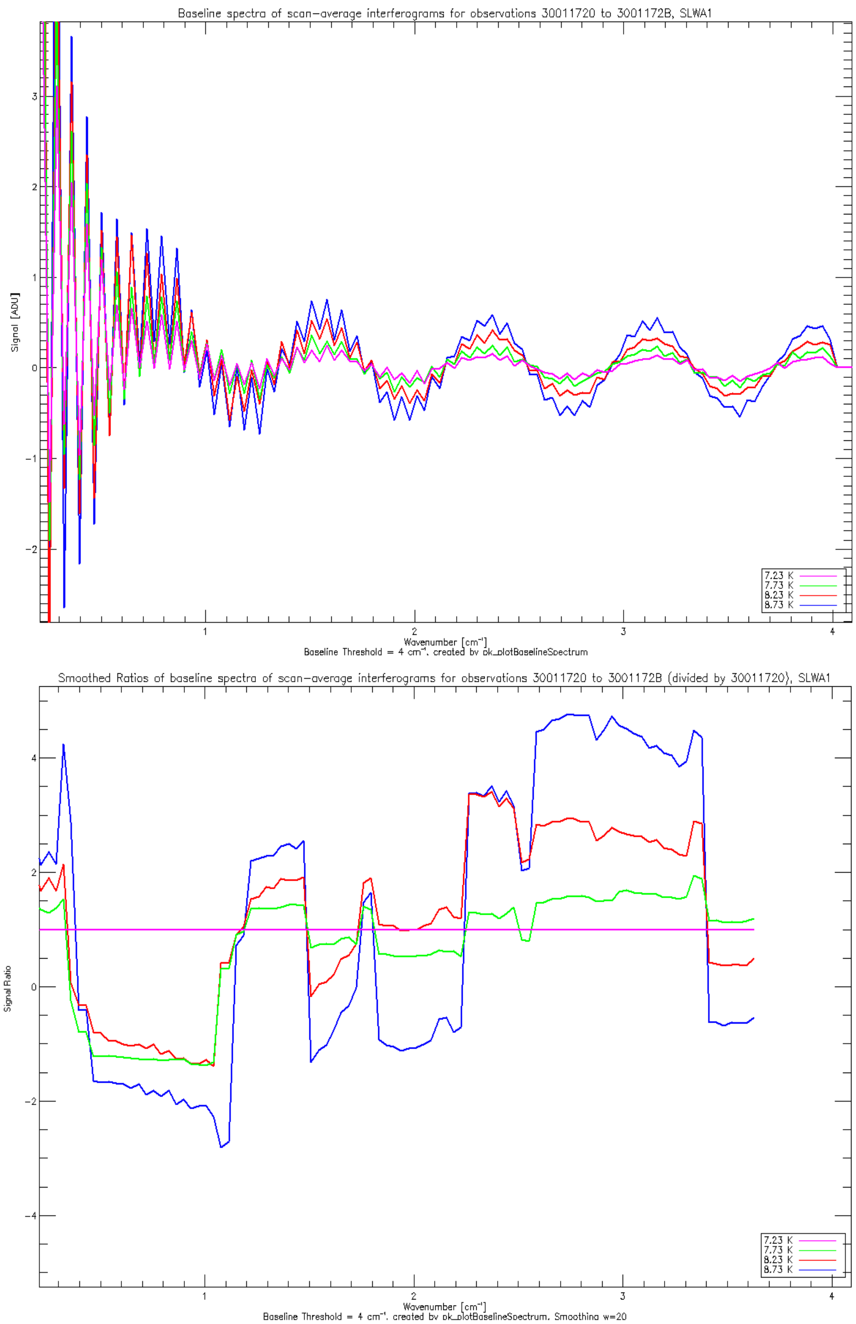

Illustration 11: SLWA1 baseline spectra (ordered top to bottom): (a) Baseline spectra of scan-averaged interferograms with varying CBB temperature. The sinusoidal-like pattern becomes smoother as wavenumbers increase, (b) Smoothed ratios of baseline spectra show similarities between observations.

3.2.2 The effect of clipping on FT baselines

Clipping degrades the goodness of fit and increases the optical passband error (see Illustration 12).

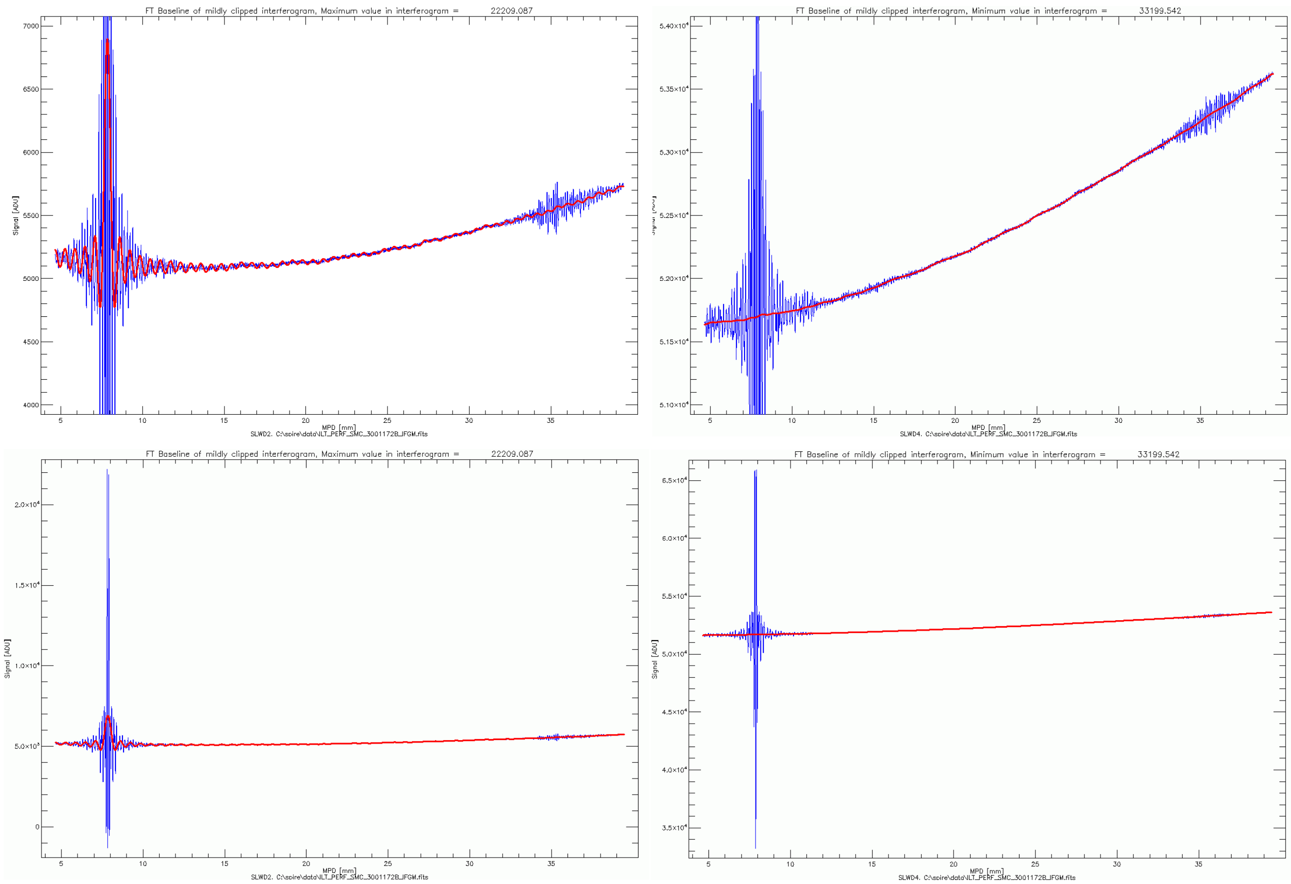

Illustration 12: Effect of clipping on FT Baseline, threshold = 4 cm^{-1} (ordered left to right, top to bottom): (a) A detail of a heavily clipped interferogram that has oscillations in its baseline (SLWD2, 3001172B), (b) A detail of a lightly clipped interferogram with a baseline with less noticeable oscillations (SLWD4, 3001172B), (c) A full view of the heavily clipped interferogram , (d) A full view of the lightly clipped interferogram.

Just as in the case of polynomial fitting of clipped interferograms, it may be possible to resolve this problem by fitting only a suitable sub-section of the interferogram. In the case of the FT fitting it is somewhat more involved to extend the fitted baseline beyond its original (fit) range.

3.2.3 Advantages/Disadvantages

Fitting the baseline with low frequency Fourier components has specific advantages and disadvantages:

Advantages

- Follows the baseline closely at higher thresholds (threshold ≥ 4 cm^{-1}).
- The amplitude of the spectral artifacts within the optical passband is below the instrumental noise.
- Time-dependent oscillations are fitted and removed.

- Further analysis of the baseline's Fourier components may help isolate effects contributing to the baseline (e.g. changes in the SCal temperature, operating temperature of the bolometers)

Disadvantages

- Smoothens glitches and step glitches, especially with increasing thresholds.
- Relatively long time for calculation.
- A suitable fit range has to be selected when clipping occurs.

3.3 Offset removal

Offset removal subtracts a constant offset value from each element of the interferogram signal. It is the simplest way of enabling magnitude comparisons between scans and may be all that is required for comparative deglitching.

The algorithm to remove a constant offset can be implemented either as fitting a polynomial of order 0 or as calculating the baseline as the 0'th Fourier component only. It remains to be studied which one of these choices would be preferable for what purposes.

Advantages

- Simple.
- Does not introduce spectral artifacts.

Disadvantages

- Only the offset is eliminated; any other baseline variation as a function of OPD or time is not reduced.

4. Evaluation of algorithms

Baseline removal should be accurate but, at the same time, leave the spectral frequencies in the optical passband unaffected as much as possible. Unintended side effects such as glitch and step-glitch smoothing should be avoided.

- The FT baseline with a reasonable threshold (2 – 4 cm^{-1}) fits an interferogram better than a polynomial fit, resulting in a better fit to the interferogram. The FT baseline can follow periodic features of the baseline in contrast to the polynomial fitting.
- The FT baseline with a reasonable threshold (2 – 8 cm^{-1}) introduces slightly less spectral contamination than those caused by polynomial baselines for unclipped interferograms. Low threshold FT baselines typically introduce lower error for unclipped SLW pixels than polynomial baselines.
- When verifying the performance of 2^{nd} level deglitching it has become clear that the glitch identification works significantly better with a polynomial fit to the baseline when compared to a FT-based fitting.
- A dedicated channel fringe removal will have to remove more power outside of the optical passband than can be accepted at this stage of the pipeline. It is therefore anticipated that a dedicated channel fringe removal will implement its own baseline removal scheme.

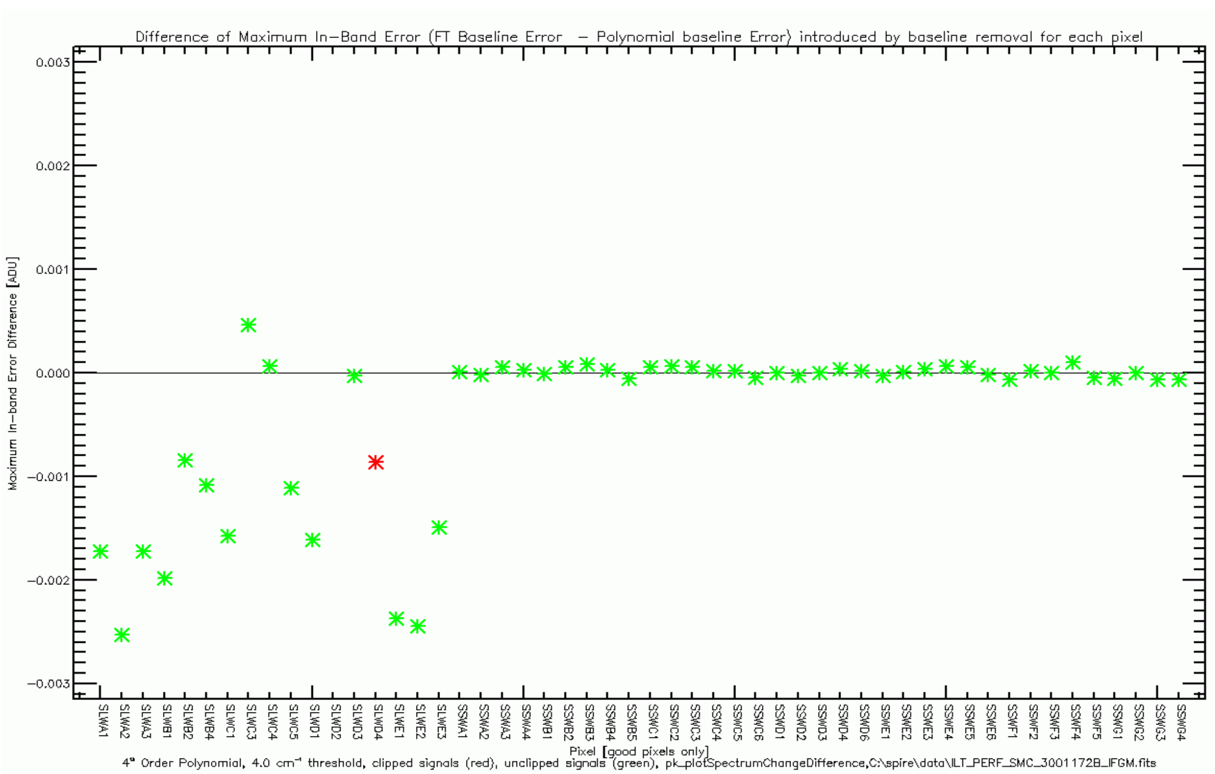

Illustration 13: Difference in maximum passband error between an FT baseline (threshold = 4 cm^{-1}) and a 4^{th} order polynomial baseline for observation 3001172B: The negative data indicate pixels for which the polynomial baseline technique has greater error. The largest differences in error are present in SLW pixels (the FT baseline is superior for SLW pixels). Red symbols indicate data derived from clipped interferograms.

5. Recommendations for SPIRE

The current functionality of the implementation is as follows:

1. The fit of the FT baseline up to a user-selected threshold is subtracted from the interferogram. The FT baseline fitting up to a threshold of 4 cm^{-1} is set as the default process for the baseline removal task.
2. An n'th order polynomial fit to the baseline is subtracted from the interferogram. The default order of the fit is set to 4.

The following functionality should be implemented in the near future:

1. The order of the polynomial fit will be restricted to even numbers.
2. The task will give the user access to the baseline that has been subtracted from the interferogram.
3. Change the default settings to 4^{th} order polynomial fitting in the light of the performance of 2^{nd} level deglitching.

In the more distant future, additional functionality could be added to accurately remove the baseline of clipped interferograms for interactive analysis. It may also be possible to characterize the baseline from precise knowledge of the instrument and known or modeled values of the input power.