SPIRE Spectrometer Pipeline Description

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Blue Sky Spectroscopy Inc.

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Chapter 1. Introduction

1.1. Acronyms

Table 1.1. Acronyms

Short Form	Full Name
ILS	Instrument Line Shape
LHS	Left Hand Side
NHKT	Nominal HouseKeeping Timeline Product
OPD	Optical Path Difference
RHS	Right Hand Side
RMS	Root Mean Square
RSRF	Relative Spectral Response Function
SMEC	SPIRE Spectrometer Mechanism
SMECT	Spectrometer Mechanism Timeline Product
SDI	Spectrometer Detector Interferogram Product
SDS	Spectrometer Detector Spectrum Product
SDT	Spectrometer Detector Timeline Product
SPIRE	Spectral and Photometric Imaging REceiver
TBD	To Be Determined
TBW	To Be Written
ZPD	Zero Path Difference

1.2. Scope of Document

This purpose of thie document is to present for discussion an outline of the modules in the SPIRE spectrometer data processing pipeline. This document will describe the current implementation of the algorithms for the processing modules. Note that this document focuses primarily on those processing modules for which the Lethbridge group and the LAM group are responsible. For an outline of the entire SPIRE spectrometer data processing pipeline, please refer to [RD01].

1.3. Documents

1.3.1. Applicable Documents

AD01   K. J. King, SPIRE Data Product Definition

1.3.2. Reference Documents

RD01   T. L. Lim, SPIRE Pipeline Description, SPIRE-RAL-DOC-002437

1.4. Document History

Table 1.2. Version and Date

Issue	Date
Draft 0.1	27 March 2007
Draft 0.2	02 May 2007
Version 1.0	09 May 2007

Chapter 2. SPIRE Spectrometer Pipeline Overview

2.1. Basic Pipeline Overview

The purpose of the SPIRE Spectrometer pipeline is to transform the spectrometer dectector samples acquired during a single observation into a set of spectra. The pipeline modules collectively perform four basic operations listed below:

1. **Modify Timelines**

   The processing modules in this group perform time domain operations on the spectrometer dectector samples.

2. **Create Interferograms**

   The processing modules in this group merge the timelines of the spectrometer detectors and spectrometer mechanism into interferograms. In addition, the spectrometer detector samples are split into different sets, with each set defined by a single scan of the spectrometer mechanism.

3. **Modify Interferograms**

   The processing modules in this group perform operations on the spectrometer dectector interferograms. These operations differ from those in the "Modify Timelines" group in that they are designed to act on spatial domain data rather than time domain data.

4. **Transform Interferograms**

   The processing modules in this group transform the interferograms into a set of spectra.

The manner in which the basic operations relate to one another is shown in Figure 2.1.

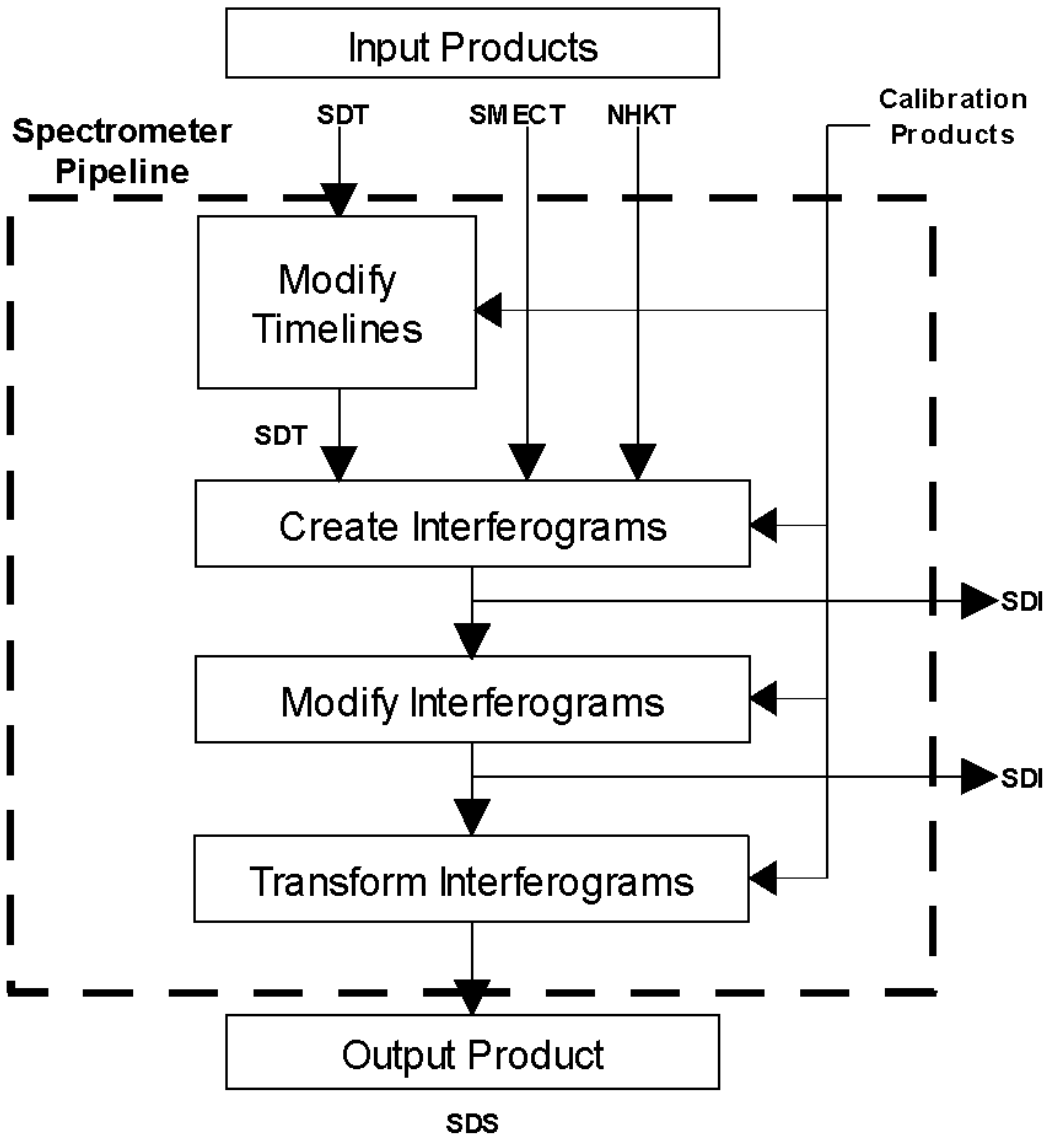**Figure 2.1. Basic Processing Groups of the SPIRE Spectrometer Pipeline**

2.2. Detailed Pipeline Overview

The individual processing modules in the SPIRE spectrometer pipeline and their connection with one another are shown in Figure 2.2. Descriptions of the current implemetation of these processing modules are presented in Section 3.1 - Section 3.4.
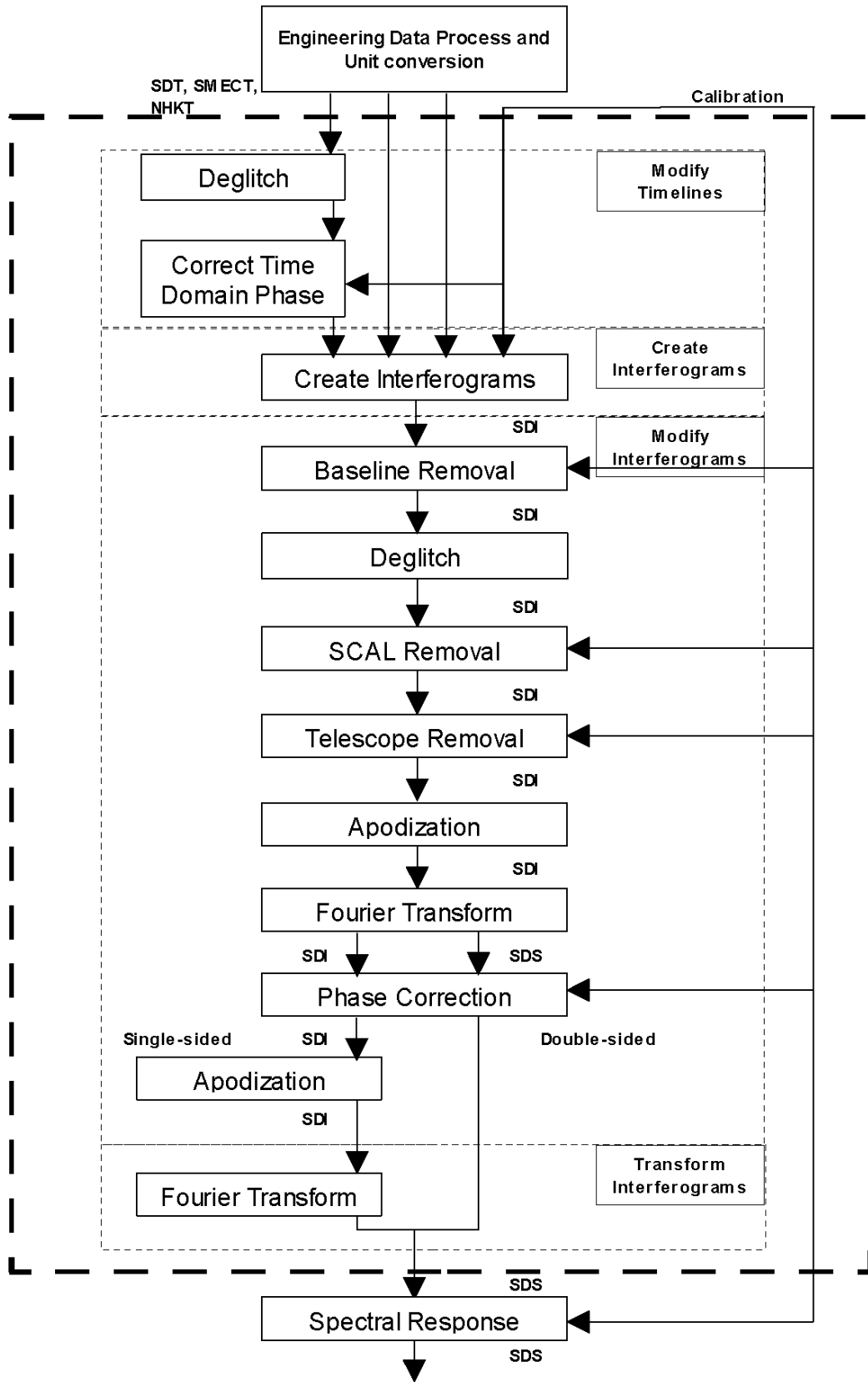
Figure 2.2. Detailed functionality of the SPIRE Spectrometer pipeline.

Chapter 3. Module Description

3.1. Modify Timelines

3.1.1. Time Domain Deglitching

3.1.1.1. Purpose

This module identifies and removes glitches from the spectrometer detector timelines (Level0 Deglitching) or from the spectrometer detector interferograms (Level1 Deglitching). The method employed merges a local regularity analysis with a wavelet analysis.

3.1.1.2. Description

The deglitching task is composed of two steps: the first step detects the glitch signatures over the time domain signal; the second step locally reconstructs the signal by removing the glitch signatures.

1. **Glitch Identification.** Glitch signatures are detected by performing a local regularity analysis (Holderian analysis) over the wavelet transform modulus maxima lines (WTMML) of the signal [1]. On each maxima line, the regularity degree of the signal is estimated by computing the slope of the linear regression over the set of points $(\log_2(|W|), \log_2(s))$, s being the successive scales of the wavelet decomposition, W the corresponding wavelet coefficient. Glitches are detected as they are similar to dirac-like signatures and show a Holder exponent (i.e. regularity degree) close to -1.

2. **Glitch Removal.** From the previous step, each detected glitch is characterized by a Holder exponent H and by a wavelet coefficients variation law $|W| \sim s^H$. From the signal wavelet coefficients, each glitch contribution is subtracted by using the variation law and the signal is locally reconstructed by performing a wavelet transform over the corrected wavelet coefficients.

3.1.2. Time Domain Phase Correction

3.1.2.1. Purpose

The purpose of this module is to adjust the spectrometer detector samples to account for the time delay induced by the detector read-out electronics and the thermal response of the detectors.

3.1.2.2. Description

The time domain phase adjustment is accomplished by convolution of the detector timelines with an inverse delay function. The overall delay funnction is the combination of the frequency response of the SPIRE spectrometer read-out electronics and the thermal response of the spectrometer detectors. While the response of the read-out electronics is the same for all spectrometer detectors, the thermal response is different for each detector. As such, the delay function is computed on a detector-by-detector basis.

3.2. Create Interferograms

3.2.1. Create Interferograms

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[1] C.Ordenovic, C. Surace, B. Torresani, A. Llebaria, JP. Baluteau, "Use of a local regularity analysis by a wavelet analysis for glitches detection", Proc. SPIE Vol. 5909 (2005), 556-567.

3.2.1.1. Purpose

A typical SPIRE spectrometer observation consists of a series of scans of the spectrometer mechanism while the instrument is pointed at a given target. In the SPIRE spectrometer, the sampling of spectrometer detectors and the spectrometer mechanism is decoupled; the two subsystems are sampled at different rates and at different times. The purpose of this module is to combine the spectrometer detector timelines and spectrometer mechanism timeline into a set of interferograms whose samples are equidistant for a given SPIRE spectrometer observation.

3.2.1.2. Description

The process by which interferograms are created involves two steps, each of which is described below.

1. **Interpolation of the SMEC timeline.** This step converts the spectrometer mechanism timeline from one that is non-uniform in position to one that is uniform in position.

    a. **Create a regular SMEC position vector.** This step creates a common vector of SMEC positions that will be the basis for the interferograms for all of the spectrometer detector pixels and for all of the scans in the observation. This common position vector will contain samples that are uniformly-spaced in terms of SMEC position. A common set of SMEC positions is desired as it will allow for easier scan-to-scan and detector-to-detector comparisons of the interferograms of the particular SPIRE spectrometer observation.

    b. **Parse the SMEC timeline into discrete scans.** This step splits the original SMEC timeline into a series of discrete timelines, each of which represents one scan. The delineation of the original SMEC timeline is done by comparing consecutive samples in the SMEC timeline and determining those samples where the motion of mirror mechanism chaned direction.

    c. **Create the new uniform SMEC timelines.** The next step is to determine, on a scan-by-scan basis, the times when the spectrometer mechanism reached the sample positions in the common regularly-spaced SMEC position vector. The original SMEC timeline is used as the basis function and the sample times that correspond to the regularly-spaced SMEC positions are found by interpolation.

2. **Merge the spectrometer detector and the new SMEC timelines.** This step combines the signal samples from the spectrometer detector timelines with the newly-created regularly-spaced spectrometer mechanism timeline.

    a. **Interpolation of the spectrometer detector timelines.** The spectrometer detector signal samples are mapped onto the the times corresponding to the common regularly-spaced SMEC positions by way of interpolation. Since there is a 1:1 relationship between the regularly-spaced SMEC positions and its sample times, this interpolation effectively maps the spectrometer detector signal sampled to the regularly-spaced SMEC positions.

    b. **Convert from mechanical path difference to optical path difference.** This step shifts and scales the position samples of the newly created spectrometer detector interferograms in such a way as to convert these samples from mechanical path difference (MPD) to optical path difference (OPD). In order to perform this step, both the position of zero path difference in units of MPD and the factor that converts a step in MPD to a step in OPD must be known for each spectrometer detector.

Note

The data from the SPIRE PFM test campaigns indicates that for each spectrometer detector, there is different position of zero path difference for each emitting element (Telescope, SCAL2, SCAL4). As such it may be appropriate to remove the step that converts from MPD to OPD from the interferogram creation module and implement it only after the effects of SCAL and the Telescope have been removed from the spectrometer detector interferograms. This option is worthy of further discussion.

3.2.1.3. Future development

An alternate method of interferogram creation will be required for the step and integrate mode of the spectrometer. The algorithm for this method is still TBD.

3.3. Modify Interferograms

3.3.1. Baseline Removal

3.3.1.1. Purpose

The purpose of this module is to remove the baseline from the interferograms of a spectrometer observation.

3.3.1.2. Description

On a detector-by-detector and scan-by-scan basis, a polynomial is fitted to and then subtracted from the baseline of the measured interferogram.

Note

A more appropriate algorithm for baseline removal may be to rely on calibrated curve rather than a fitted polynomial. In addition, it may be useful to divide this process into two modules: the first module would remove any time-dependent baseline (e.g. drift due to changes in the detector temperature) from the spectrometer detector timelines; the second module would then remove any position-dependent baseline (e.g. vignetting) from the spectrometer detector interferograms.

Warning

There are some questions as to whether this modules is necessary in the standard SPIRE FTS processing pipeline. It may be that any baseline present in the measured interferograms will only add low, out-of-band frequencies to the final spectra and will therefore not adversely affect the source spectra. In addition, application of this correction in a less than optimal manner may in fact introduce anomolous features to the measured spectra, in which case this module will do more harm than good. This is an issue that warrants further discussion.

3.3.2. Interferogram Deglitching

3.3.2.1. Purpose

The ipurpose of this processing module is to eliminate glitches in the spectrometer detector interferograms.

3.3.2.2. Description

The interferogram deglitching module is composed of two steps. The first step identifies the anomolous samples in the spectrometer detector interferograms; the second step removes these samples and repairs the interferograms.

1. **Glitch Identification.** Anomolus samples, or glitches, are identified for each spectrometer detector by comparing, on a position-by-position basis, the samples from one scan to those from all other scans in the same observation. The samples that deviate more than a prescibed amount from the median are flagged as glitches.

2. **Glitch Removal.** The second phase of the deglitching module removes and replaces the samples that were identified as glitches in step 1. For a glitch at a given position for a given spectrometer detector, the value of the replacement sample is determined by the average of the

samples from the other other interferograms at that position.

> **Note**
>
> The two steps of the interferogram deglitching module rely on a statistical analysis of the measured interferograms. As such, a minimum number of interferograms will be required so that these statistics will be meaningful. If this module is kept as part of the standard processing pipeline for the SPIRE spectrometer, an analysis should be performed to determine the minimum number of scans required per observation so that this number can be added to the proposal handling system.

3.3.3. SCAL Correction

3.3.3.1. Purpose

This module subtracts the contribution of the SCAL calibrator from the measured spectrometer detector interferograms.

3.3.3.2. Description

The SCAL module is divided into two tasks: the first task creates a spectrometer detector interferogram product from the telemetry and a model of the SCAL sources (ScalTask); the second task subtracts the modeled interferograms from the measured interferograms (ScalCorrectionTask).

1. **ScalTask.** This task performs the following subtasks in succession:

   a. Check for temperature fluctuations of the SCAL sources and bath temperatures (TemperatureConditionTask). If the temperatures fluctuations are too large during a given scan, the task is stopped and an exception is thrown.

   b. Compute the gray-body function of the SCAL sources (GrayBodyTask). The gray-body function for SCAL is the sum total of the products of the Planck functions of each SCAL source and their corrsponding emissivity functions.

   c. Generate the modeled SDS product (SDSGenerator). For each SPIRE spectrometer channel, the modeled SCAL spectrum is computed as the product of the SCAL gray-body function and the geometric solid angle as seen by that channel.

   d. RSRF correction (RsrfFilteringTask). Each modeled spectrum in the SCAL SDS product is multiplied by the inverse RSRF function for the corresponding channel.

   e. Correct for Optical Phase (OpticalPhaseCorrectionTask). Each modeled spectrum in the SCAL SDS product is multiplied by an inverse optical phase function (i.e. by the complex exponential of the phase function).

   f. Generate the modeled SDI product (SDIGeneratorTask). An inverse Fourier transform is applied to each spectrum in the SCAL SDS product in order to obtain a set of modeled SCAL interferograms. These interferograms are symmetric, gridded in terms of OPD, and are centred on the position of ZPD particular to each spectrometer detector channel.

2. **ScalCorrectionTask.** The final step in the SCAL correction task involves subtraction of the modeled SCAL interferograms from the measured interferograms. If necessary, the modeled interferograms are interpolated to the same OPD positions as the measured interferograms.

3.3.4. Telescope Correction

3.3.4.1. Purpose

This module subtracts the contribution of the Herschel Telescope from the measured spectrometer

detector interferograms.

3.3.4.2. Description

The Telescope correction module is divided into two tasks: the first task creates a spectrometer detector interferogram product from the telemetry and a model of the Telescope (TelescopeTask); the second task subtracts the modeled interferograms from the measured interferograms (TelescopeCorrectionTask).

1. **TelescopeTask.** This task performs the following subtasks in succession:

   a. Check for temperature fluctuations of the telescope and bath temperatures (TemperatureConditionTask). If the temperatures fluctuations are too large during a given scan, the task is stopped and an exception is thrown.

   b. Compute the ray-body function for the Telescope (GrayBodyTask). The gray-body function for the Telescope is the sum total of the products of the Planck functions for the Telescope and the bath and their corrsponding emissivity functions.

   c. Generate the modeled SDS product (SDSGenerator). For each SPIRE spectrometer channel, the modeled Telescope spectrum is computed as the product of the Telescope gray-body function and the geometric solid angle as seen by that channel.

   d. RSRF correction (RsrfFilteringTask). Each modeled spectrum in the Telescope SDS product is multiplied by the inverse RSRF function for the corresponding detector.

   e. Correct for Optical Phase (OpticalPhaseCorrectionTask). Each modeled spectrum in the Telescope SDS product is multiplied by an inverse optical phase function (i.e. by the complex exponential of the phase function).

   f. Generate the modeled SDI product (SDIGeneratorTask). An inverse Fourier transform is applied to each spectrum in the Telescope SDS in order to obtain a set of modeled Telescope interferograms. These interferograms are symmetric, gridded in terms of OPD, and are centred on the position of ZPD particular to each spectrometer detector channel.

2. **TelescopeCorrectionTask.** The final step in the Telescope correction task involves subtraction of the modeled Telescope interferograms from the measured interferograms. If necessary, the modeled interferograms are interpolated to the same OPD positions as the measured interferograms.

3.3.5. Apodization

3.3.5.1. Purpose

The natural instrument line shape (ILS) for a Fourier Transform spectrometer is a cardinal sine or Sinc function. For interferograms that contain features that are at or near the resolution of the spectrometer, the Sinc line shape can introduce secondary maxima in the calculated spectra. The apodization functions available within this module may be used by astronomers that wish to minimize these secondary maxima.

3.3.5.2. Description

Apodization is performed by multiplying the spectrometer detector interferogram by a tapering or apodizing function prior to transformation. A consequence of apodization is that it leads to a reduction in the resolution of the resultant spectrum. To minimize the effect on spectral resolution, the apodization module in the SPIRE spectrometer data processing pipeline provides a number of functions that optimize the trade-off between reduction in the secondary maxima and reduced resolution.

Note

In addition to the reduced spectral resolution mentioned above, application of an apodization function to the measured interferograms can make removal of the ILS more difficult. If the final spectral product to be delivered is to be free of the ILS, then it may be prudent to remove the Apodization module from the standard spectrometer data processing pipeline.

3.3.6. Phase Correction

3.3.6.1. Purpose

The purpose of this module is to remove any asymmetries in the spectrometer detector interferogram *signal* samples.

3.3.6.2. Description

The phase correction module performs two types of correction to the spectrometer detector interferograms depending on whether they are double-sided or single-sided (see Appendix A for the definitions of double-sided and single-sided interferograms).

Double-sided Phase Correction. The spectra derived from double-sided interferograms contain phase information for each spectral element. As such, phase correction can be performed in the spectral domain. First, a function is fit to the weighted, in-band portion of the measured phase. A phase function is then computed by taking the complex exponential of the negative of the fitted phase. Phase correction is performed by multiplying the measured spectrum with the phase function. The use of a fit to the measured phase rather than the actual phase has the effect of reducing noise in the resultant spectrum.

Finally, if desired, the phase-corrected spectrum is transformed back to the spatial domain, the result of which is an interferogram whose sample *signals* are symmetric about the position of zero path difference.

Single-sided Phase Correction. Phase correction of single-sided interferograms is a two step process. In the first step, the double-sided portion of the spectrometer detector interfergram is extracted and transformed. As with double-sided phase correction, a weighted function is fit to the in-band phase. Unlike the double-sided case though, this phase function derived from the fit is not multiplied with the measured spectrum. Rather, the phase function is itself transformed to the spatial domain. A convolution operation is then performed between the phase function and the original single-sided spectrometer detector interferogram. In this manner, the phase function can be applied to the high-resolution portion of the measured interferograms.

Note

The major drawback of the current phase correction algorithm is that the observed data is used to correct itself. This aspect poses a potential problem for the case where the measured data is of poor quality (i.e. the signal-to-noise ratio is low). A phase function derived from data of poor quality may not be reliable and its usage could result in further degradation of the data.

Future development of this module will involve using the observations from the ground test campaigns and those from the verification stage to quantify the systematic sources of phase for the SPIRE iFTS. The phase function will then be computed from these known sources of phase. Performing phase correction in this manner will remove the need to employ a fitting function to compute the phase function and remove the dependence of the phase function on the quality of the data.

3.4. Transform Interferograms

3.4.1. Fourier Transform

3.4.1.1. Purpose

The purpose of this module is to transform a set of interferograms from a SPIRE spectrometer observation into a set of spectra. In its current form, this processing module is capable of transforming both double-sided and single-sided interferograms (see Appendix A for the definition of double-sided and single-sided interferograms).

3.4.1.2. Description

Double-sided Transform. For the double-sided transform, each spectrometer detector interferogram is examined and the double-sided portion of the interferogram is used to compute the resultant spectrum. The resultant spectra will contain both real and imaginary components.

Single-sided Transform. In the case of the single-sided transform, only those interferogram samples to one side of the position of zero path difference are considered. The spectra that result from the single-sided transform therefore contain only real components.

Appendix A. Definitions

A.1. Double-sided and Single-sided Interferograms

The terms double-sided and single-sided as used in this document describe the two types of interferograms that can be measured with a Fourier Transform Spectrometer.

A.1.1. Double-sided Interferograms

Double-sided interferograms are defined as those interferograms or that portion of measured interferogram where the sample *positions* are symmetric about the position of zero path difference (ZPD). That is, a double-sided interferogram is one that contains an equal number of samples before and after the ZPD sample [1]. An envelope of a double-sided interferogram is shown in Figure A.1.
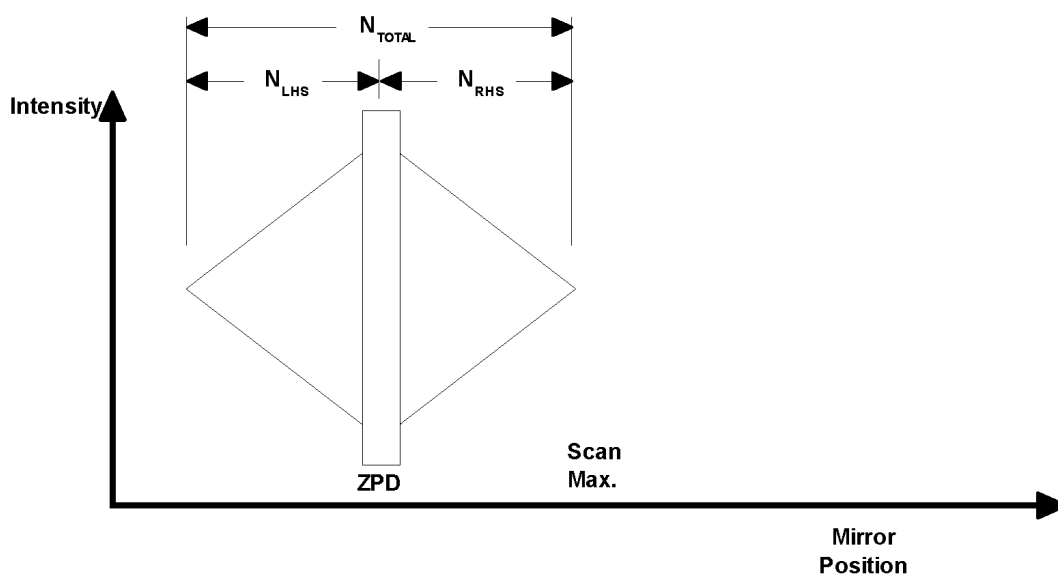

Figure A.1. Envelope of a double-sided interferogram

A.1.2. Single-sided Interferograms

Single-sided interferograms are defined as those interferograms that contain more samples on one side of ZPD than the other. An envelope of a single-sided interferogram is shown in Figure A.2.

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[1] Some implementations of the Fourier Transform may require an even number of points (N_{TOTAL} even). In this case, the RHS of the double-sided interferogram will contains an extra point to render the total number of points even.
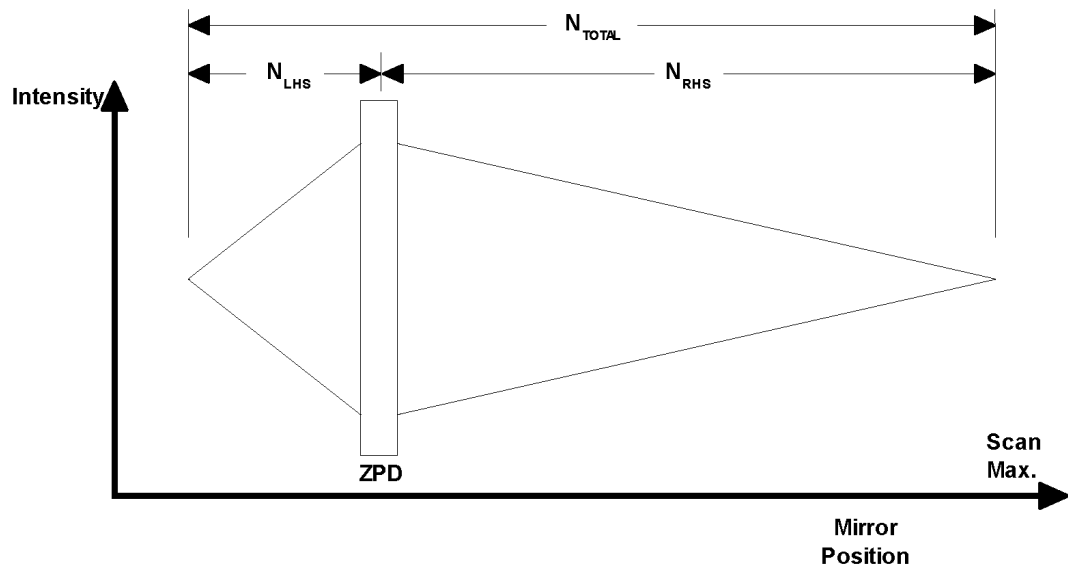
Figure A.2. Envelope of a single-sided interferogram