SPIRE Spectrometer Pipelines and Data Products

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on behalf of the SPIRE ICC

Pipeline development & validation

- The development of pipelines is distributed between several institutes. Algorithms and development plans are specified by the ICC
- A SPIRE **Configuration Control Board** supervises the development
- Automatic unit testing is performed every night and pipelines are tested by an ESAC operator every few weeks
- In the Summer, the ICC started a **Scientific Validation** process to review **algorithms**, **documentation** and **implementation** of pipelines

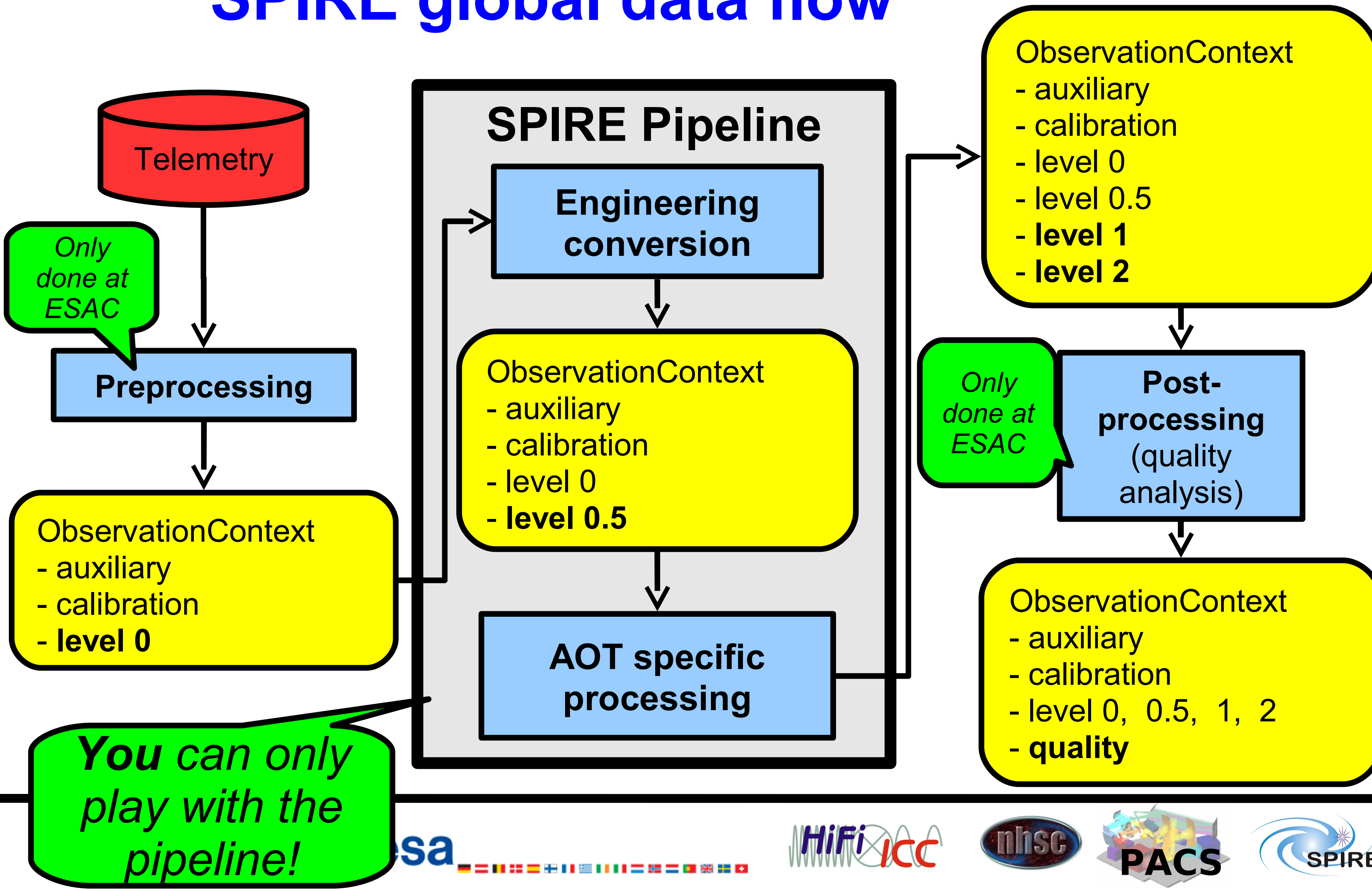
SPIRE Pipeline implementation

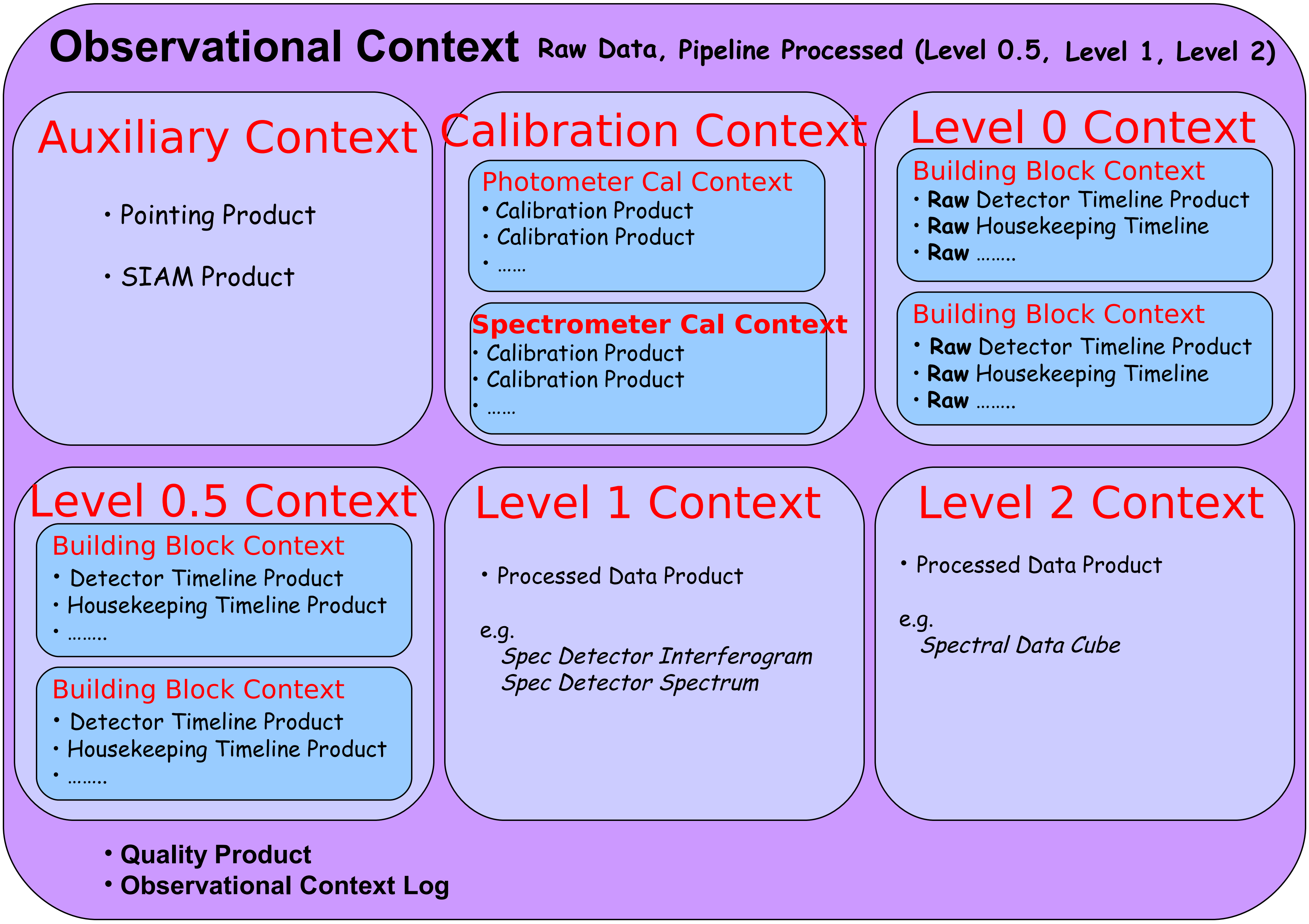
- The pipelines are implemented as a sequence of **Tasks** each performing a specific process/correction on the data
- All Tasks are written in Java (mainly for performance reasons)
  - ⟶ No computation is carried out in the pipeline scripts
- The pipeline is implemented as a **Jython script** that passes data (in the form of Products) between Tasks
- There is one pipeline script for each instrument mode
- Tasks are flexible enough to allow the **Interactive Analysis** user to apply different strategies

Current Pipeline Status

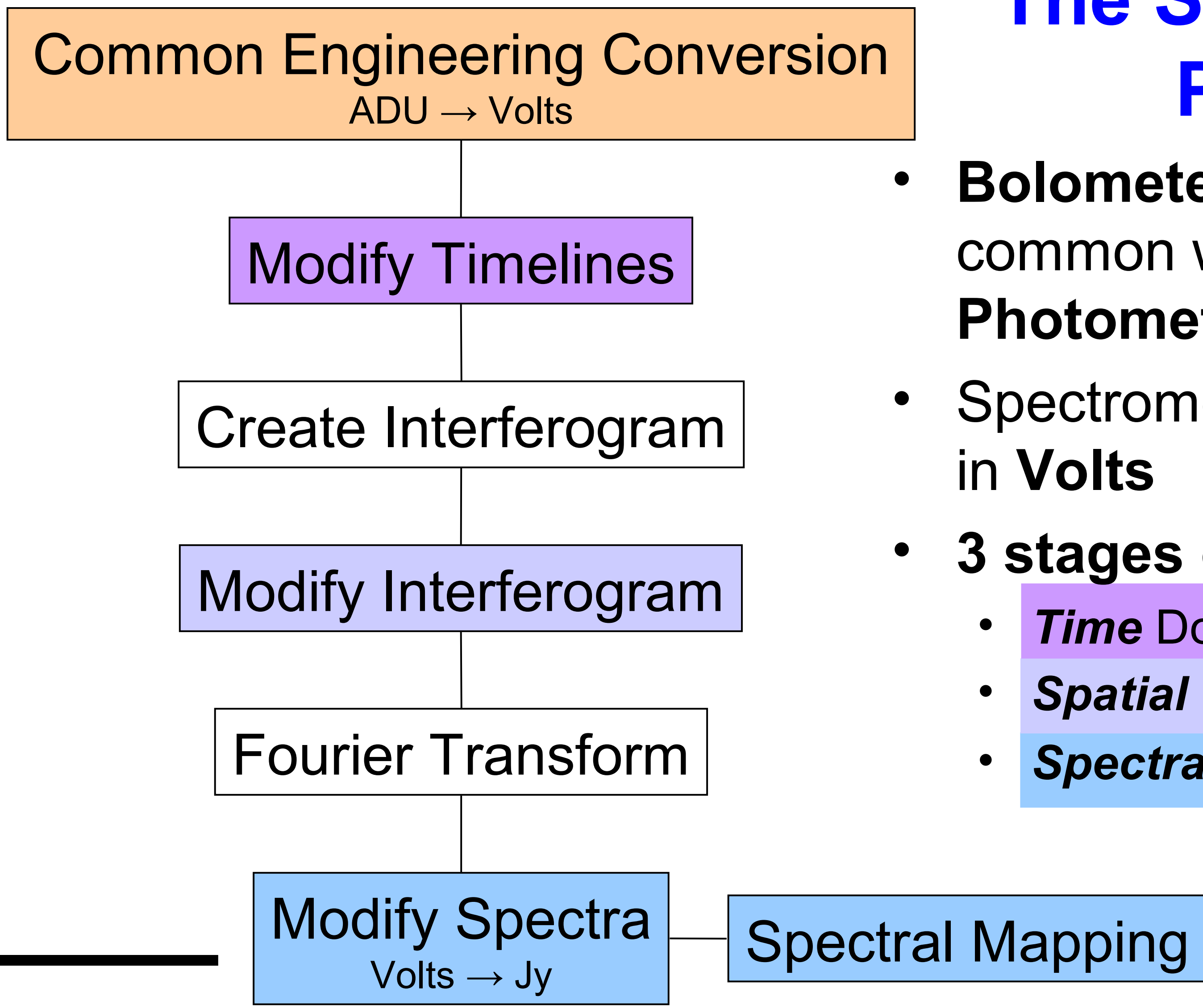
- Almost all tasks **written** and **implemented** in the pipeline
- Issues requiring attention:
  - User friendliness for Interactive Analysis
  - Some modules require optimisation (*Deglitch tasks*)
  - Calibration files to be updated after launch (*PV phase*)
  - *Spectral Mapping* implementation to be completed
  - Moving coordinate frames for targets with large motion
- Functionality & documentation currently being reviewed as part of **Scientific Validation** process
  - Will have good confidence in the flow of modules and algorithms at launch!

SPIRE global data flow




Observational Context Raw Data, Pipeline Processed (Level 0.5, Level 1, Level 2)
Auxiliary Context
• Pointing Product
• SIAM Product
Calibration Context
Photometer Cal Context
• Calibration Product
• Calibration Product
• ……
Spectrometer Cal Context
• Calibration Product
• Calibration Product
• ……
Level 0 Context
Building Block Context
• Raw Detector Timeline Product
• Raw Housekeeping Timeline
• Raw ……..
Building Block Context
• Raw Detector Timeline Product
• Raw Housekeeping Timeline
• Raw ……..
Level 0.5 Context
Building Block Context
• Detector Timeline Product
• Housekeeping Timeline Product
• ……..
Building Block Context
• Detector Timeline Product
• Housekeeping Timeline Product
• ……..
Level 1 Context
• Processed Data Product
e.g.
Spec Detector Interferogram
Spec Detector Spectrum
Level 2 Context
• Processed Data Product
e.g.
Spectral Data Cube
• Quality Product
• Observational Context Log

The Spectrometer Pipeline



- **Bolometer** processing common with **SPIRE Photometer**
- Spectrometer pipeline works in **Volts**
- **3 stages of processing:**
  - ***Time*** Domain
  - ***Spatial*** Domain (*Mirror position*)
  - ***Spectral*** Domain

Data Product Levels

Common Engineering Conversion
ADU → Volts

Level 0 products
Raw instrument timelines in **ADU**

Modify Timelines

Level 0.5 products
Converted timelines in engineering units

Create Interferogram

Interferogram

Modify Interferogram

Fourier Transform

Modify Spectra
Volts → Jy

Spectral Mapping

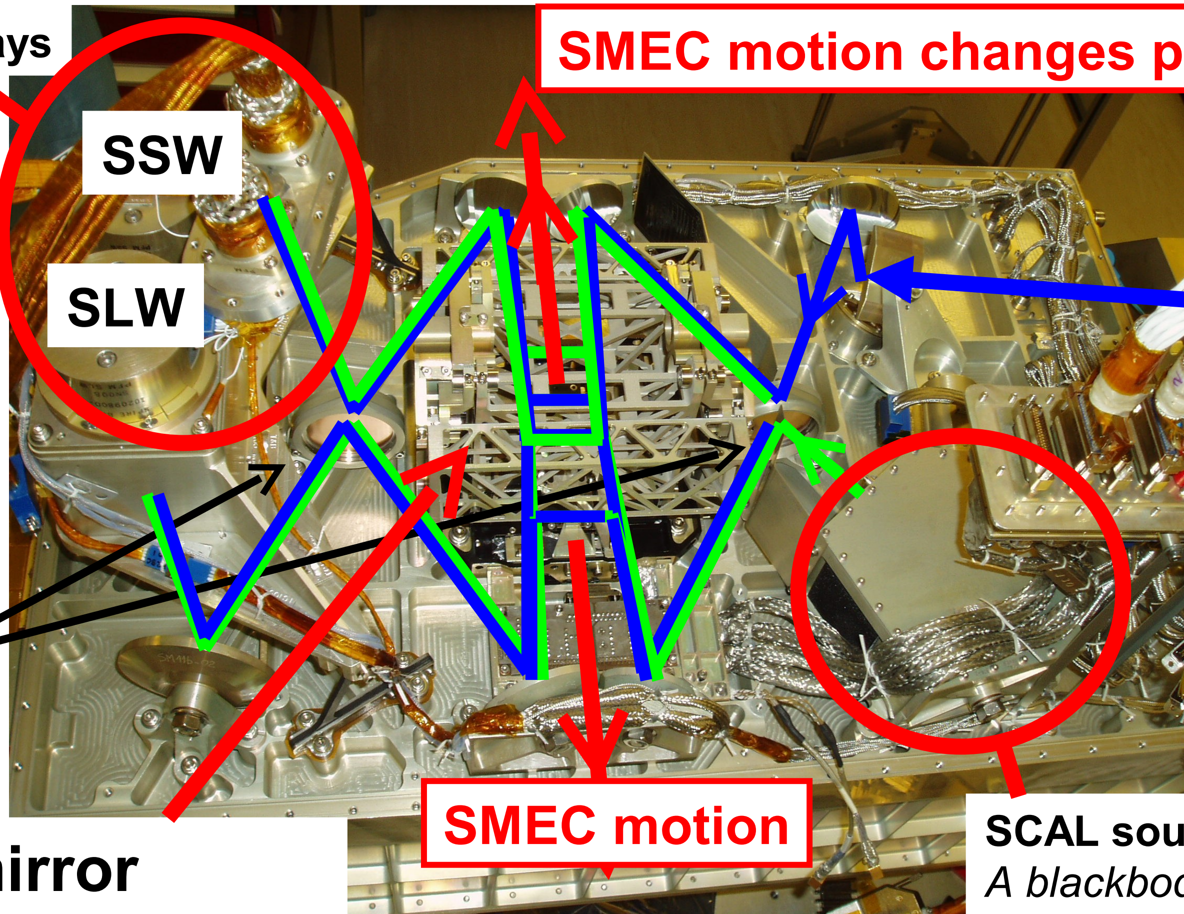
Level 1 products

The ***spectrum*** in units of
Flux Density *vs.* ***Wavenumber***
for ***each detector*** in ***each band***

Level 2 products

Regularly gridded into a 3D spectral cube with axes longitude, latitude and Wavenumber

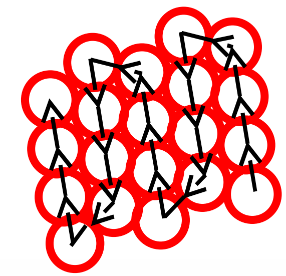
Spectrometer Mechanism Scans

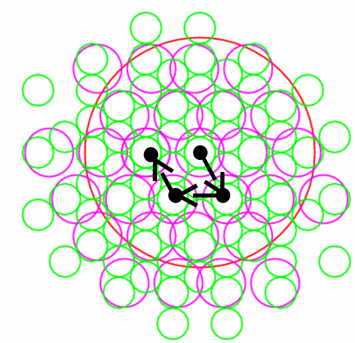


Scanning mirror mechanism = SMEC

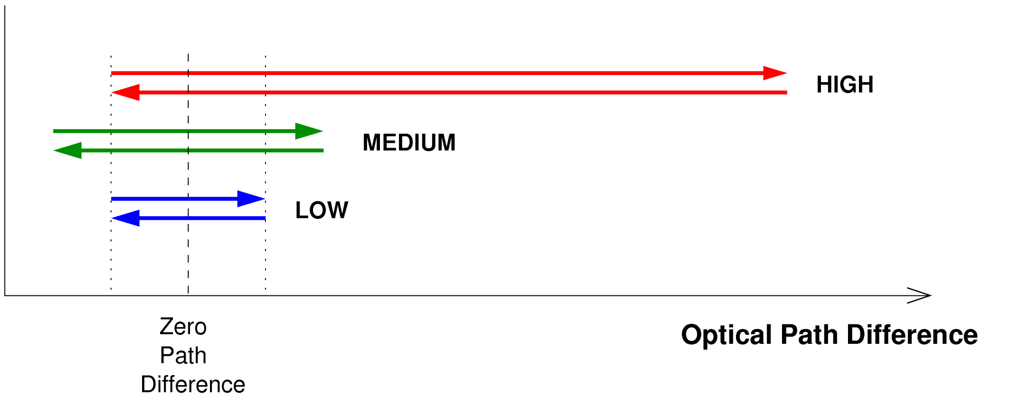
Reminder of Observing Modes

Pointing	•Single •Raster	Move telescope
Spatial Resolution	•Sparse •Intermediate •Full	Move BSM (1, 4 or 16 positions)
Spectral Resolution	•Low •Medium •High	Scan the SMEC different distances



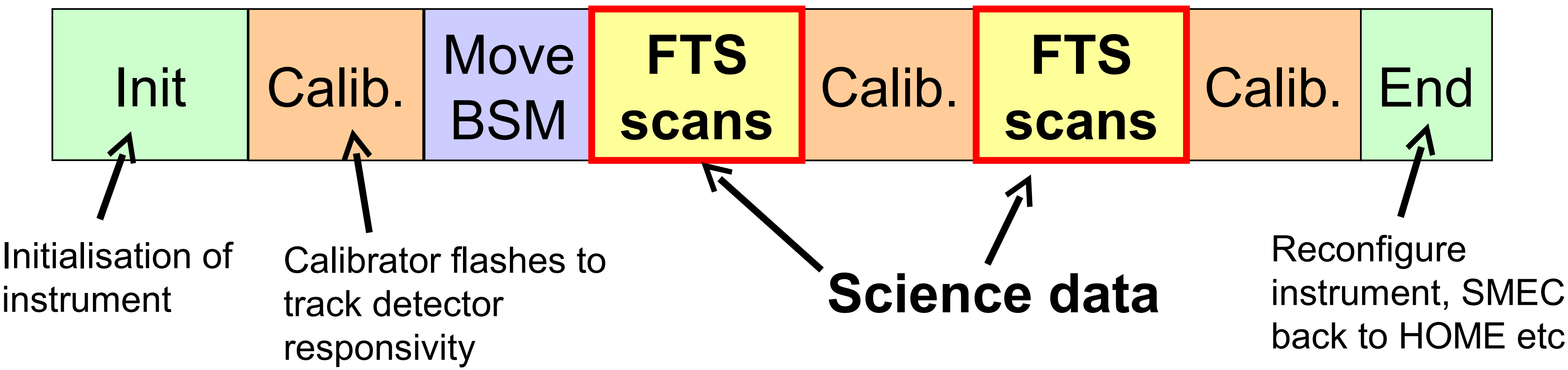


Repetitions = number of scan pairs (forward+reverse)
Minimum of 2



Observation Building Blocks

- SPIRE observations are divided into ***Building Blocks***:



- Each basic instrument operation is contained in a separate building block
- The data that you get are also divided per building block.

Building Block Data

- The data you get reflect the observation structure:

Observation Context

Level-0.5 Context

*converted **timelines**, grouped per Building Block*

Building Block Context

Detector timeline: SDT (~80 Hz)
Housekeeping timeline: NHKT (1 Hz)
SMEC position timeline: SMECT (~240 Hz)

Building Block Context

Detector data timeline: SDT (~80 Hz)
Housekeeping timeline: NHKT (1 Hz)
SMEC position timeline: SMECT (~240 Hz)

Data structure summary

- ***Product***: the basic Herschel data container

  metadata + tables ⟶ *can be saved to FITS*

- ***Context***: a "wrapper" containing a collection of Products

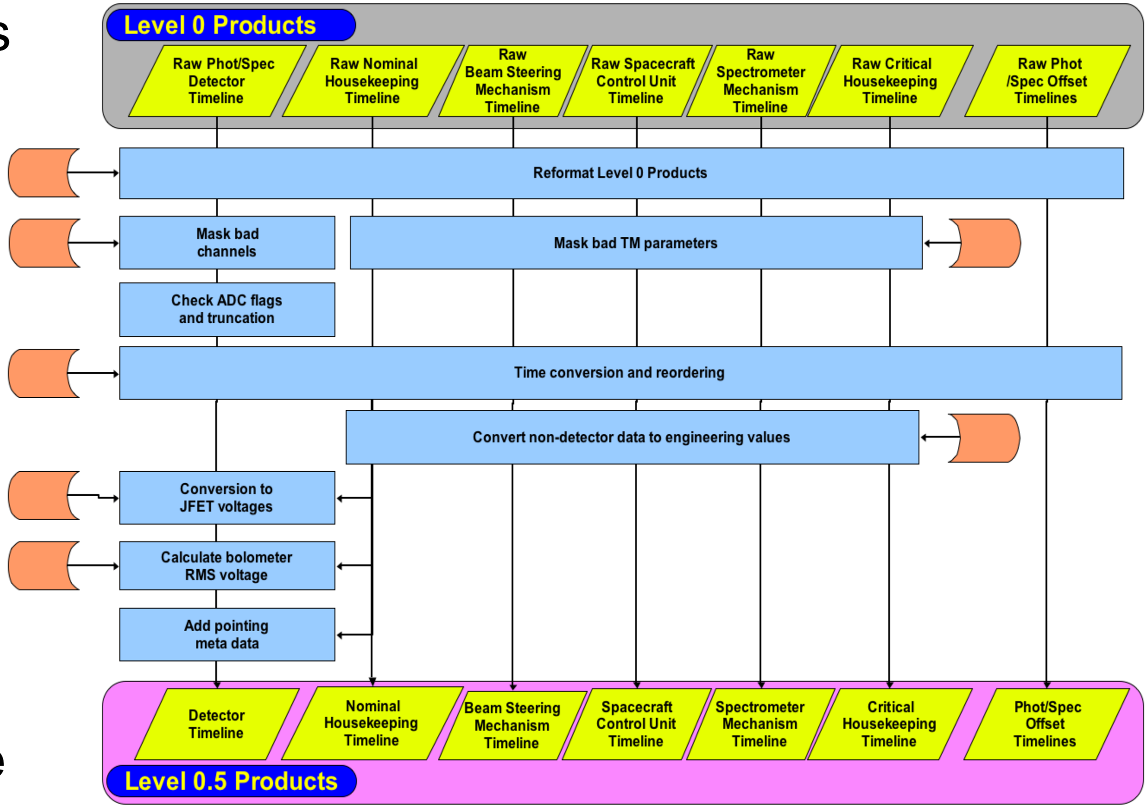
  (or collection of other contexts – c.f. a directory structure)

- ***Building Block***: a unit of SPIRE data related to one instrument operation

- ***Level xxx***: reflecting different stages of processing by the pipeline

Common Engineering Conversion

- **Engineering Conversion** is common to all SPIRE pipelines
- Converts **raw telemetry** values (Level 0) into **engineering values** (Level 0.5)
  e.g. voltages, resistances, temperatures
- Level 0.5 will be the best starting point for **interactive analysis**



Level 0.5 Detector Timelines structure

- A Photometer/Spectrometer Detector Timeline (PDT or SDT) contains 3 main tables: **voltage**, **resistance** and **mask**.
- These tables contain a column with the **sample time** (in TAI), and a column for each channel
- The mask table contains the flags for each sample

Index	sampleTi...	SSWR1 []	SSWA4 []	SSWA3 []	SSWA2 []	SSWA1 []	SSWDP1 []	SSWB3 []	SSWB2 []	SSWB1 []	SSWC3 []	SSWC2 []
0	1.5442946...	0	0	0	0	0	0	0	0	0	0	0
1	1.5442946...	0	0	0	0	0	0	0	0	0	0	0

Index	sampleTi...	SSWR1 [Ω]	SSWA4 [Ω]	SSWA3 [Ω]	SSWA2 [Ω]	SSWA1 [Ω]	SSWDP1 ...	SSWB3 [Ω]	SSWB2 [Ω]	SSWB1 [Ω]	SSWC3 [Ω]	SSWC2 [Ω]
0	1.5442946...	5340542.0	2318341.8	2111265.2	2170215.2	2352703.5	6241361.0	2231863.0	2026746.2	1785848.0	1815057.1	2164659.8
1	1.5442946...	5340606.0	2322028.2	2115278.5	2175085.8	2357838.5	6241325.5	2236974.0	2032328.2	1791549.6	1820285.6	2171830.8

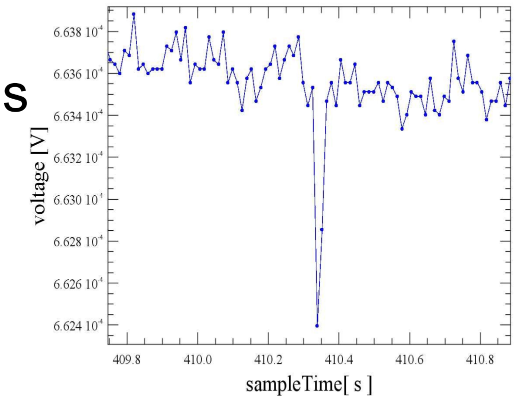
Index	sampleTi...	SSWR1 [V]	SSWA4 [V]	SSWA3 [V]	SSWA2 [V]	SSWA1 [V]	SSWDP1 ...	SSWB3 [V]	SSWB2 [V]	SSWB1 [V]	SSWC3 [V]	SSWC2 [V]
0	1.5442946...	0.0052852...	0.0026414...	0.0024572...	0.0024788...	0.0026621...	0.0058856...	0.0025411...	0.0023081...	0.0020923...	0.0020899...	0.0024352...
1	1.5442946...	0.0052853...	0.0026451...	0.0024614...	0.0024837...	0.0026672...	0.0058855...	0.0025462...	0.0023138...	0.0020984...	0.0020954...	0.0024424...
2	1.5442946...	0.0052852...	0.0026450...	0.0024612...	0.0024835...	0.0026671...	0.0058856...	0.0025461...	0.0023138...	0.0020984...	0.0020954...	0.0024426...
3	1.5442946...	0.0052852...	0.0026450...	0.0024610...	0.0024834...	0.0026671...	0.0058855...	0.0025462...	0.0023138...	0.0020982...	0.0020951...	0.0024426...
4	1.5442946...	0.0052852...	0.0026449...	0.0024613...	0.0024837...	0.0026670...	0.0058854...	0.0025460...	0.0023138...	0.0020982...	0.0020952...	0.0024424...
5	1.5442946...	0.0052851...	0.0026449...	0.0024614...	0.0024838...	0.0026667...	0.0058855...	0.0025460...	0.0023137...	0.00209833	0.0020954...	0.0024423...
6	1.5442946...	0.0052851...	0.0026450...	0.0024614...	0.0024840...	0.0026665...	0.0058856...	0.0025459...	0.0023136...	0.0020984...	0.0020951...	0.0024422...
7	1.5442946...	0.0052852...	0.0026447...	0.0024615...	0.0024837...	0.0026663...	0.0058855...	0.0025460...	0.0023134...	0.0020983...	0.0020951...	0.0024422...
8	1.5442946...	0.0052852...	0.0026447...	0.0024615...	0.0024836...	0.0026666...	0.0058857...	0.0025462...	0.0023135...	0.0020981...	0.0020953...	0.0024423...
9	1.5442946...	0.0052852...	0.0026448...	0.0024615...	0.0024838...	0.0026671...	0.0058856...	0.0025462...	0.0023137...	0.0020981...	0.0020954...	0.0024424...
10	1.5442946...	0.0052851...	0.0026450...	0.0024613...	0.0024836...	0.0026673...	0.0058855...	0.0025461...	0.0023139...	0.0020983...	0.0020955...	0.0024426...
11	1.5442946...	0.0052853...	0.0026447...	0.0024612...	0.0024836...	0.0026671...	0.0058853...	0.0025464...	0.0023140...	0.0020981...	0.0020954...	0.0024424...
12	1.5442946...	0.0052851...	0.0026448...	0.0024612...	0.0024836...	0.0026670...	0.0058854...	0.0025463...	0.0023138...	0.0020983...	0.0020954...	0.0024425...
13	1.5442946...	0.0052851...	0.0026449...	0.0024613...	0.0024838...	0.00266627	0.0058856...	0.0025460...	0.0023134...	0.0020983...	0.0020952...	0.0024423...
14	1.5442946...	0.0052853...	0.0026449...	0.0024613...	0.0024837...	0.0026664...	0.0058858...	0.0025461...	0.0023134...	0.0020984...	0.0020952...	0.0024420...
15	1.5442946...	0.0052852...	0.0026450...	0.0024614...	0.0024837...	0.00266694	0.0058855...	0.0025460...	0.0023134...	0.0020983...	0.0020953...	0.0024422...
16	1.5442946...	0.0052852...	0.0026450...	0.0024613...	0.0024837...	0.0026670...	0.0058857...	0.0025461...	0.0023136...	0.0020982...	0.0020953...	0.0024423...

Timeline Modifications 1

- **1st Level Deglitching**

  Identification & ***Reconstruction*** of glitched samples

  uses a Wavelet method to identify glitches (see poster)



- **Electrical Crosstalk**

  Correction for detector crosstalk due to electronics

  (very small effect)

- **Non-Linearity Correction**

  Linearization of detector response to strong optical loads

- **Clipping Correction**

  Reconstruction of "clipped" points at ZPD

  (for strong sources)

Most sources will be in linear regime

→ *these modules not significant*

(ZPD=zero path difference)

Timeline Modifications 2

- **Time Domain Phase Correction**

  Correct for time delay in detector signal

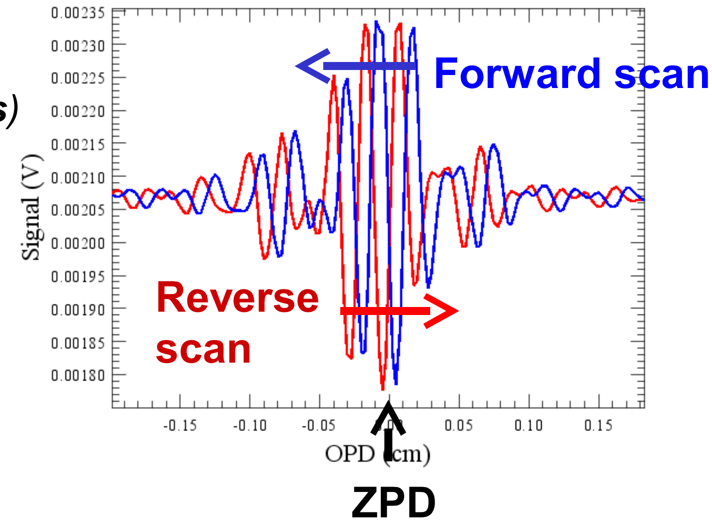
*(due to the **freq. resp. of the filters** & **thermal resp. of detectors**)*

correct in the ***timeline*** using a convolution:

$$V_{\mathrm{TDPC}}(t) = V(t) \;\square\; T(t)$$

*This applies a **phase shift** to align **forward** and **reverse** scans when converted to **interferogram space***

*Correction to **interferogram** is:*



- **Bath Temperature Correction**

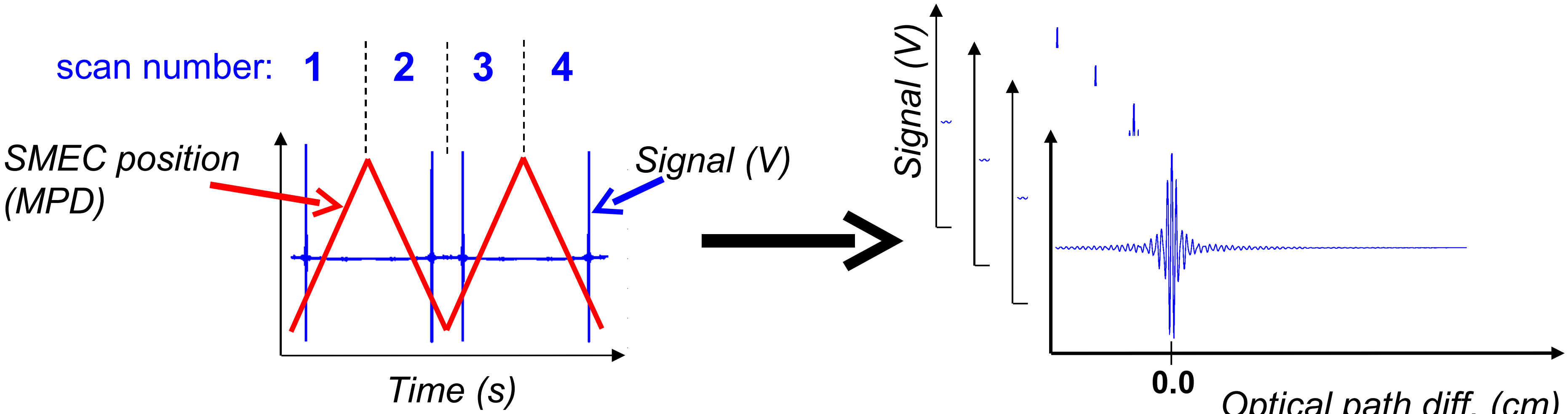
  Correction for fluctuations due to temperature drifts in detector base plate

  May not be necessary – temp fluctuations not on short enough timescale to affect optical band in spectrum

Create Interferogram

Timelines → ***Interferogram***

- Convert ***Mechanical Path Difference*** to ***Optical Path Difference***
- Interpolate **SMEC** position to a regularly-spaced **OPD** grid
- Interpolate **detector voltage** to regularly-spaced **OPD** grid
- Assign **pointing** information per scan per detector

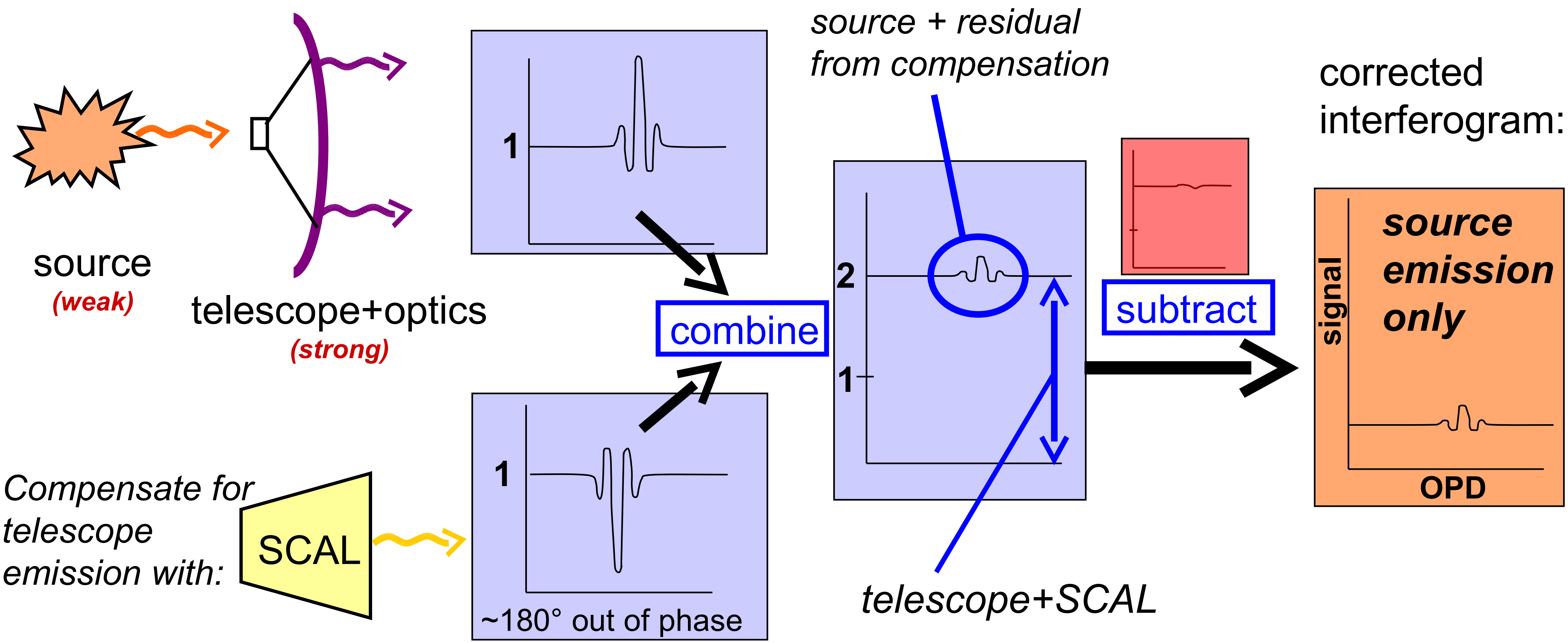


Modify Interferogram 1

- **SCAL, Telescope & Beamsplitter correction**

  Removes the **background**, which includes the telescope and SCAL emission

  - ***Subtraction*** *of reference interferogram measured on* ***blank sky***

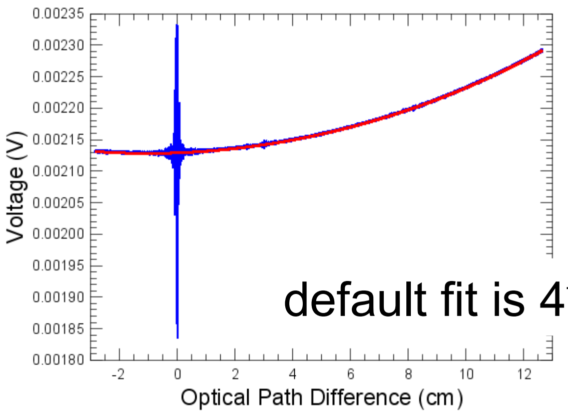


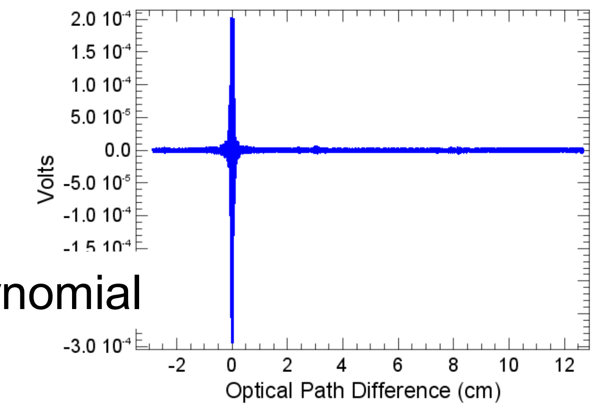
Modify Interferogram 2

- **Baseline Correction**

  Corrects for Vignetting in off axis detectors

  - *Polynomial or Fourier Component fit*





default fit is 4th order polynomial

- **2nd Level Deglitch**

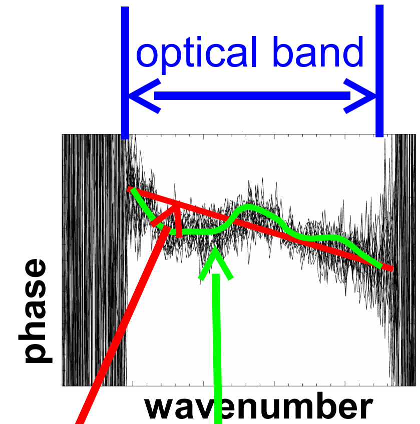
  Comparison of **samples** from different **scans**

  - *Glitch sample replaced using average from other scans*

Modify Interferogram 3

- **Phase Correction**

Corrects any remaining error in **ZPD** position



$$\text{Phase} = \frac{\text{Imaginary part of spectrum}}{\text{Real part of spectrum}}$$

⟶ *aim is to reduce imaginary part to zero*

Split correction into linear and non-linear parts: $\varphi_{\text{corr}}(\sigma) = \varphi_{\text{linear}} + \varphi_{\text{non-linear}}$

Output is a corrected interferogram

Low & **Medium** res: applied in *spectral* domain:	$\boldsymbol{V}_{\text{corrected}}(x) = \mathrm{FT}^{-1}\left[\boldsymbol{V}(\sigma) \times e^{-i(\boldsymbol{\varphi}_{\text{corr}}(\sigma))}\right]$
High res: applied in *interferogram* domain:	$\boldsymbol{V}_{\text{corrected}}(x) = \boldsymbol{V}(x) \;\square\; \mathrm{FT}^{-1}\, e^{\left[i(\boldsymbol{\varphi}_{\text{corr}}(\sigma))\right]}$

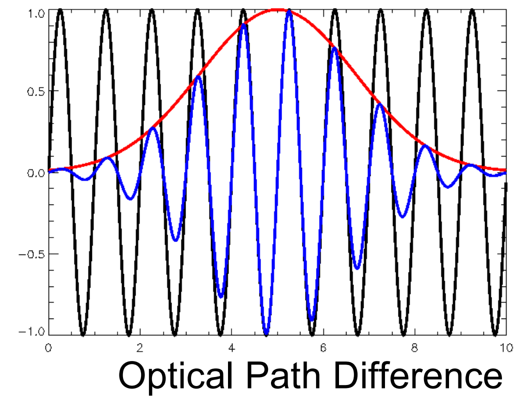
*difference due to fact that only **double sided** part of interferogram used to calculate phase in High res. case*

Modify Interferogram 4

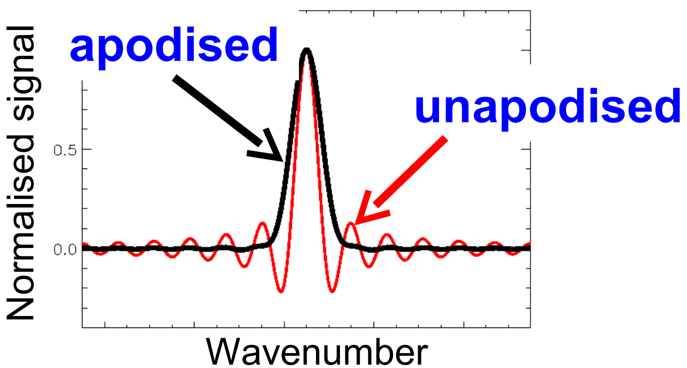
- **Apodisation**

  Tapers the edges of the **interferogram** to reduce **ringing** in line profile

  (at a cost to spectral resolution)

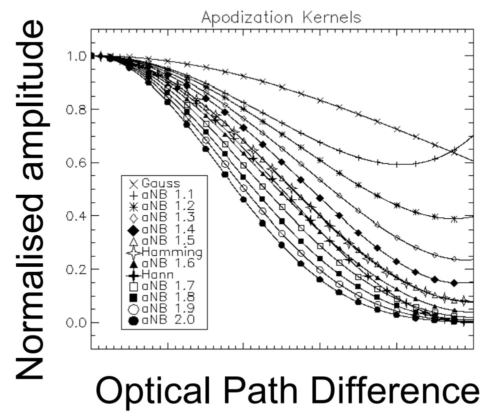


Effect on instrument line profile:



Can treat an apodised spectral line as a Gaussian to good accuracy (<5%)

*A **set** of apodisation kernels are available for **interactive** use:*



Fourier Transform of Interferogram

Interferogram → ***Spectrum***

- *Before transform, interferogram is **padded** with zeros*

→ *fixes the wavenumber grid for all spectra to be:*

*0.25 cm^{-1} **(Low)**; 0.05 cm^{-1} **(Medium)**; 0.01 cm^{-1} **(High)***

*[c.f. spectral resolutions: **1.0** cm^{-1}, **0.25** cm^{-1} and **0.04** cm^{-1}]*

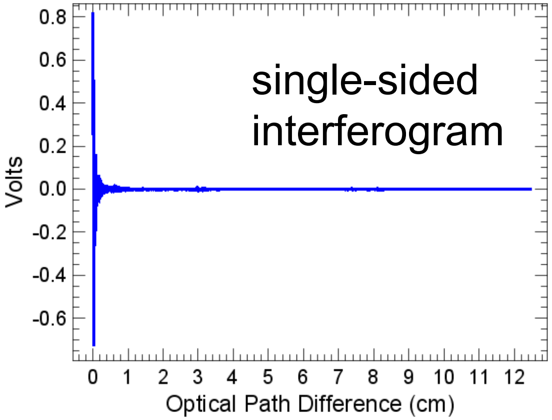
Phase correction has been applied

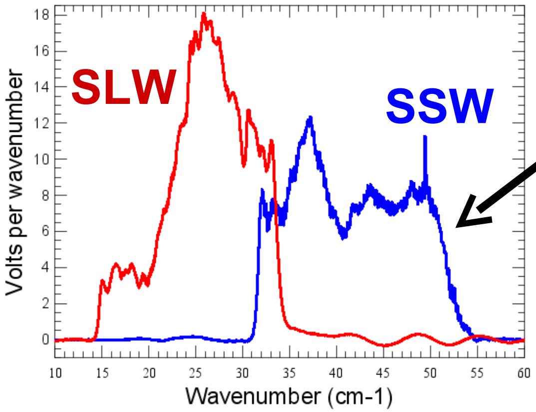
*(i.e. interferogram is **symmetric** about ZPD)*

therefore use single-sided transform

$$\boldsymbol{V}(\sigma) = \mathrm{FT}\left[\boldsymbol{V}(x) \Big|_{0}^{L} \right]$$

FFT algorithm is "FFTPACK"





*shape of **Relative Spectral Response Function** (RSRF) still to be removed*

Modify Spectra

- ## Flux Conversion

  Correction for **RSRF** & conversion to astronomical units

  Derived from measurements of Astronomical standard sources

  Volts per wavenumber → **Flux density**

  V/(cm^{-1}) → **Jy** [or W/m^2/(cm^{-1})]

- ## Optical Crosstalk

  Correction for detector optical crosstalk by applying *crosstalk matrix*

- ## Spectral Averaging

  Average of all scans on wavenumber by wavenumber basis to produce final spectrum

  (also keep forward & reverse scans separate for comparison)

Spectral Mapping

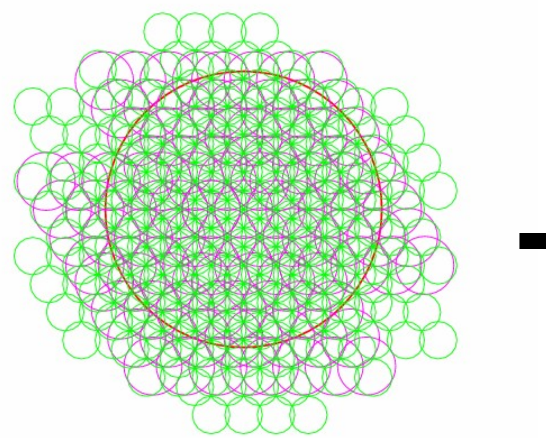
- **Spatial Regridding**

Applied only for intermediate or full sampling

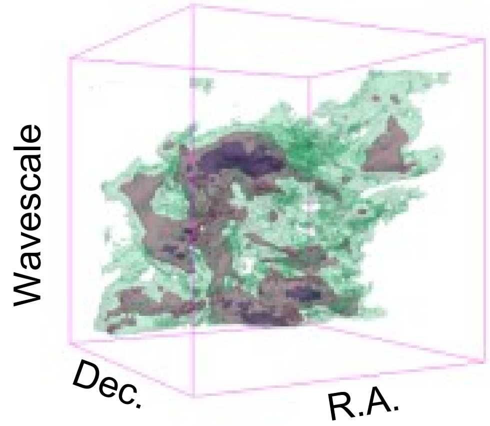
(1 beam or 1/2 beam spacing)

2D convolution of beam FOV with measured map

→ *regularly gridded spectral cube*



Fully sampled mode (16 point jiggle)



Summary of output Data Products

Level 1 product

For *each detector*

in *each band*:

one Table containing the *spectrum* in units of

Flux Density vs. Wavenumber

averaged over different scans

both unapodised & apodised versions

includes uncertainty per point and mask

Level 2 product

Only for intermediate (*1 beam spacing*) and fully sampled (*1/2 beam spacing*) maps

The Level 1 product is regularly gridded into a 3D spectral cube with axes longitude, latitude and Wavenumber

One cube for each band (SSW/ SLW)

Note: *the interferograms are also supplied with the Level-1 products*

Some Points to Consider...

Spectral shape

- Apodisation
- Fringing
- Averaging scans/scan directions
- Deglitching algorithm
- Merging different bands

Mapping

- Gridding algorithm
- Dead pixels
- Extended sources

Strong sources

- Clipping reconstruction