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DOCUMENT

EChO Calibration and Data Processing

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1 INTRODUCTION

EChO - the Exoplanet Characterisation Observatory – is a survey-type mission dedicated to the characterisation of exoplanetary atmospheres. Using the differential technique of transit spectroscopy, EChO will obtain transmission and/or emission spectra of the atmospheres of a large and diverse sample of known exoplanets covering a wide range of masses, densities, equilibrium temperatures, orbital properties and host-star characteristics.

EChO will observe the combined light from the exoplanet and its host star. The transit spectroscopy method, whereby the signal from the star and planet are differentiated using knowledge of the planetary ephemerides, allows atmospheric signals from the planet at levels of at least 10-4 relative to the star to be measured. Photometric stability rather than angular resolution is therefore key, and in fact the most stringent requirement of EChO, driving many engineering design and operational aspects of the mission. For the brightest targets it will be possible to obtain high quality spectra in a single visit; for fainter targets the necessary signal-to-noise will be built up through repeated visits over the mission lifetime.

Robust calibration will be essential. At some level design alone cannot be relied upon and the calibration of the system must be monitored and verified periodically during the mission. The basic calibration requirement is to monitor and account for variation in instrument performance for "in-band" signals, and is summarised in the calibration requirements noted in the EChO Science Requirements Document (SciRD, [AD1]);

- R-SCI-190: An absolute photometric calibration accuracy of 5% (TBC).
- R-SCI-193: Absolute wavelength calibration....within 1/3 of the required spectral resolution element

In order to achieve these requirements, the EChO instrument must be calibrated both before launch and in-flight: the ground calibration will address parameters not easily accessible once on orbit; the in-flight calibration must address both long term variable parameters and those that change on the timescale of the observations.

In this note we provide a description of the calibration and data processing steps currently envisaged needed to produce the catalogue of exoplanetary transmission and emission spectra that is the scientific end-product of the EChO mission. In section 2 we provide an outline of observing with EChO, including a summary of the types of observations that will be made by EChO. In section 3 provide an overview of effects in the EChO measurements that are likely to need to be corrected for; in section 4 we detail the instrumental effects which either may or are likely to need correction in the data processing scheme, detailing these effects will be characterised on-ground and/or in-flight. The description of the in-flight calibration in section 5 then brings together both the observations required to characterise instrumental effects with the overall scheme for producing photometry to the required standard. Finally section 6 describes the data processing pipeline.

1.1 Applicable Documents

AD1	EChO - Science Requirements Document (SciRD)	SRE-PA/2011.037	Issue 3
AD2	EChO Interface Document – Part A	ESRE-F/2012.097/	Issue 1
AD3	Mission Requirements Document	SRE-PA/2011.038/	Issue 3
AD4	Ground Segment Implementation Plan	ECHO-PL-0008-RAL	Issue 1

1.2 Reference Documents

RD1	EChO Long Term Mission Planning Tool	ECHO-TN-0001-ICE	Issue 03

1.3 Acronyms

FGS	Fine Guidance Sensor
ICC	Instrument Control Centre
IOSDC	Instrument Operations and Science Data Centre
MIRI	Mid-InfraRed Instrument (James Webb Space Telescope)
MRD	Mission Requirements Document
RSRF	Relative Spectral Response Function
SCiRD	Science Requirements Document
SED	Spectral Energy Distribution
SOC	Science Operations Centre
SVM	Service Module (Spacecraft)

2 OBSERVING WITH ECHO

EChO is considered to be a survey-type mission and will characterise the atmospheres of a core sample of transiting exoplanets to be defined prior to launch. The primary objective of the mission is to study the physics and chemistry of the atmospheres of a representative sample of known exoplanetary systems around nearby stars. EChO will enable us to understand the atmospheres of a broad collection of exoplanets of various sizes (from Jupiter-like to a ~few Earths) orbiting diverse host stars (from spectral types F to M) and covering a range of effective temperatures (from 2000 K to a few hundred K). Our current knowledge of exoplanets is already unravelling a surprisingly large diversity in their physical properties and such diversity is also expected in the chemical characteristics of their atmospheres. Thus, the relevant parameter space is much broader than predicted from the detailed study of Solar System planets. The results of EChO, covering a statistically significant sample of planets, will address planet structure, formation and architecture and will ultimately place the Solar System and the Earth in the context of the wide variety of planetary systems in the Universe. Further details of the science objectives of EChO can be found in [AD-1].

EChO will use the technique of differential transit/eclipse spectroscopy over the optical to thermal IR wavebands (~0.4 – 16 μm) to determine the physical and chemical conditions of the atmospheres of a sample of ~200 known exoplanets. Through detailed measurement of the spectral energy distribution and spectral features of exoplanetary atmospheres, it will be possible to establish the chemical composition, energy budget, chemical abundances, thermal structure, optical albedo, and spatial and temporal variability of the atmospheric structure. Variations in the measured signal from spatially unresolved observations of an exoplanet at different points in its orbit around its host star will be used to determine the spectrum of the planetary atmosphere. The signal from both the star and exoplanet are collected simultaneously. The signal from the exoplanet – a very small fraction of the total – can be isolated by differencing observations made at various points of the exoplanet's orbit.

The combination of the very broad instantaneous spectral coverage and high photometric stability of EChO provides a unique opportunity to address science questions in very different areas of astrophysics. Examples of the additional science areas to which EChO will contribute beyond Exoplanets are described in AD-1.

A TBD fraction of the total observing time, currently foreseen to be 10-20%, will be made available to the astronomical community through open announcements of opportunity: proposals for both exoplanet observations and more general science are expected in response to these calls. There is no provision for a Target of Opportunity programme for EChO; however 5% (TBC) of the open time will be allocated to Directors Discretionary time (TBC) (see [AD-1]). The remainder of the time will be comprised of engineering maintenance, spacecraft maintenance e.g. orbit manoeuvres, giro calibrations etc., and instrument calibration (additional to the calibration activities within core observations)

2.1 Core Observations

We assume that the observation sequence for a science target during normal operations will follow the following outline:

- Acquire calibration target – observe for TBD minutes and carry out internal calibrator operation
- Acquire dark sky pointing – observe for TBD minutes
- Acquire science target – carry out internal calibrator operation
- Observe target for TBD minutes, during the observation internal calibration operations will be carried out at TBD intervals.
- Acquire calibration target – observe for TBD minutes and carry out internal calibrator operation
- Go-to next target

All the times are dependent on how long it takes to achieve the required calibration accuracy and how the instrument performs once in flight – i.e. the frequency of calibrator operations will depend on the rate at which various gains drift. The necessity or not of a dark observation will depend on our ability to correlate the dark pixels on the arrays to the ones used for observation.

At the start of the mission we will need to establish this correlation so assume that we will always take dark observations. As the mission progresses we will review and adjust the observing sequence in line with our increased knowledge of the instrument performance.

In addition to science targets we anticipate making longer calibration observations to determine the stability of the instrument calibration against known standards. If possible we will make these observations during ground contact to maximise observing efficiency.

Under all circumstances we will limit calibration observations to no more than 14% of the available observing time – equivalent to 1 day per week . We anticipate that this will also reduce as the mission progresses.

2.2 Open Time Observations

The current assumption is to have at least two AOs, one before launch and the other at some time after, with possible others depending on how demand for non-core science evolves over the course of the next phase and beyond. We would very likely prioritise the scheduling of targets that are part of the EChO core survey.

There are two categories of open time - time critical and non-time critical. Non-time critical could possibly be put into the gaps in the long term schedule while time-critical observations will need to be scheduled alongside the core programme. We also have a requirement for director's discretionary time, which may include exoplanet targets.

3 EFFECTS WHICH REQUIRE CORRECTION

The measurements to be made by EChO require that the stability of the system is either maintained, or monitored to allow removal of drifts in the system performance, to around 1 part in 10000. This will necessitate both a highly optimised design for the spacecraft and instruments, and a calibration scheme capable of monitoring the system performance to within the specified limits.

Several effects could be encountered in the EChO measurement process, and will need to be corrected for in the data processing/calibration. They can be gathered in 3 classes in order to distinguish between how they are monitored and controlled:

The astrophysical effects: These are associated with the observing "scene" and require measurement and monitoring schemes as they are outside of the design parameters of the mission.

- The stellar variations and the stellar signal in general – this is monitored directly during the observation
- The contribution of the zodiacal cloud of our solar system : it is an extended source which is due to the solar light scattering in the visible, and the thermal emission of dust in the infrared. We will utilise dedicated off –axis detector pixels to monitor the Zodiacal contribution.
- The contribution of the zodiacal cloud of the target : it is an IR excess compared to the stellar SED, associated to other effects on the transit lightcurve, either in the visible or in the IR spectral range.
- The contamination of the background stars in the target field
- The effects of the L2 environment such as proton impacts, scattered light from the Earth

Spacecraft induced effects: These are associated with changes in the pointing, temperatures and, possibly, mechanical stability of the spacecraft and, although the design minimises their impact, certain spacecraft housekeeping parameters will be required to be monitored.

- Telescope and associated baffle temperatures – monitored through housekeeping
- Absolute pointing performance – monitored through the AOCS and FGS system
- Pointing stability – monitored through the FGS
- Optical stability of the telescope – monitored through the FGS
- Mechanical micro-vibrations from spacecraft systems (reaction wheels, coolers etc) – monitored partly through the FGS and partly through housekeeping parameters associated with the sub-systems

- Variations in the straylight environment due to spacecraft orientation – monitored by off axis detectors

The instrument effects: these are mainly linked to the detection process and the associated detection chain.

- Detector dark currents variations with radiation and (more likely) thermal drift
- Radiation glitches in the detectors
- Detector gain variations (droop associated with readouts, drift due to radiation, drift due to thermal fluctuations etc)
- Detector ramp non linearity due to saturation
- Detector pixel spatial response non uniformity
- Detector afterglow following bright observations
- Instrument temporal optical transmission variations (aging and any possible association with thermo-mechanical variations)
- Instrument temporal optical distortion (possible thermo-mechanical variations)
- Ageing of the instrument performance (surface degradation, contamination etc)
- Variations in the instrumental thermal and straylight background (also see spacecraft)
- Offsets in the electronic chain
- Electronic cross talk / ghosts

This initial list is subject to review but captures the essential parameters that will need to be monitored and gives the outline for the measurements required under the calibration plan.

During the mission there will be a combination of long term housekeeping monitoring (temperatures, voltages etc), dedicated long term measurements (use of off axis detectors, dark detectors etc), short term measurements using internal calibration sources and medium and long term measurements on stellar calibration sources for both stability and absolute flux measurements.

4 DATA CALIBRATION AND CORRECTION

4.1 Detector Effects

4.1.1 Dark currents in the detectors

The detector dark current will need will need to be to be measured and subtracted from each pixel before gain effects are accounted for. Dark current can be monitored via dark pixels in each array (at least two will be required). Dark current is affected by array temperature hence thermistors should be put on the array housing to monitor this.

4.1.1.1 On Ground

The main aim of the ground test will be to measure the relationship between array temperature and dark current both for the dark pixels and for the science pixels. Note neither set of pixels will ever be truly dark as there will be some residual radiation from the environment; however this will be both at a very low level and representative of flight conditions.

4.1.1.2 In-Flight

If the relationship between dark current and temperature has been established for both the dark pixels and the science pixels on the ground, then the array temperature measured in-flight can be used to track changes in dark current on the science pixels. This can be further verified by tracking the dark pixels. Any changes in the long-term relationship between the current on the dark pixels and the array temperature will be monitored and the science pixel calibrations will be adjusted accordingly.

4.1.2 Ionising Radiation

Ionising radiation will affect the detectors. Individual radiation hits will lead to glitches which will be shown as sudden jumps in signal detected. A glitch may also cause a short term change in responsivity.

For a typical readout scheme where a series of non-destructive readouts are made allowing integration ‘up a ramp’ the effects of a glitch may not only cause the ramp to be contain the step function glitch effect but also a change in slope due to the change in responsivity. It may also be the case that a number of integrations following the glitch affected integration are also affected. Additionally a glitch may affect more than one pixel in the array. Strategies to remove the effects of glitches will be developed during ground testing but will need refinement once the real radiation environment is encountered.

It should be noted that bright stars, which can saturate the detectors quickly will require a high sample rate and short (1.5 second in worse case) integrations with ramp slopes being fitted on-board. Providing the effects are short lived, the time series of evaluated ramps can be filtered to find residual glitch affected ramps on the ground. For faint mode where samples are taken every 8 seconds and the ramp is 240 seconds, we expect to implement ramp based deglitching schemes on the ground as all samples will be sent to the ground.

4.1.2.1 On Ground

Some glitches will be detected during the ground test but as the test equipment is both under the Earth’s atmosphere and encased in a cryostat, the glitch rate will be significantly less than the in-flight rate. However glitches detected on the ground will allow an initial characterisation of their effects and allow us to implement initial strategies to correct for them.

4.1.2.2 In-Flight

The final strategy for dealing with glitches will be adopted in-flight. For faint mode initially a simple approach is likely to be adopted where glitches are identified and either the portion of the ramp following the glitch or the entire ramp is discarded. For bright mode we may use the goodness of fit determined on-board along with filtering.

As the true rate an effect of glitches can only be determined in flight it is important to have as much flexibility as possible with regard to the readout scheme. For instance if we find a very high glitch rate and the ramp section following a glitch is un-usable we may opt for shorter ramps and more destructive reads taking the penalty of a slightly higher read noise for the benefit or retaining more data.

4.1.3 Detector gain variations

While the effect on detector responsivity of ionising radiation hits is generally removed by one to a few destructive reads some residual change in responsivity can remain which over the period of hours may lead to significant upward drifts in responsivity and after a period of time the detectors will become both non-linear and unreliable and will need to be annealed. The most effective way to anneal the detectors is TBD and in the past missions have used photon, temperature and bias based methods.

4.1.3.1 On Ground

During the design phase we will determine which annealing strategy to use. This strategy will then be optimised during ground testing. Between anneals, the responsivity of the detectors will be tracked via observations of the on-board calibration source. The best strategy for using this source e.g. whether to regularly add it to an astronomical source signal during an observation or whether to move away from the source and add the calibration signal to sky dark, will be determined during ground test.

4.1.3.2 In-Flight

The annealing strategy should not need to be adjusted in flight. However in-flight performance will determine the requirements for the annealing frequency. Typically the expectation is that this will be 1-2 times per day. The ability of the annealing process to reset the detectors to same level of responsivity on each occasion will be verified via observations of astronomical secondary calibrators. The responsivity of the detectors between each anneal will be tracked via the on-board calibration source and verified via observations of astronomical secondary calibrators.

4.1.4 Detector ramp non linearity due to saturation

A bright source may effect a responsivity change in the detectors, typically reducing the responsivity. Providing the ramp is well sampled this non-linearity can be easily characterised and accounted for in the data processing.

4.1.4.1 On-Ground

The detector linearity will be characterised as part of the ground test campaign where the maximum sample rate can be used to produce well sampled ramps. A variety of ramp lengths and input fluxes will be investigated.

4.1.4.2 In-Flight

During PV phase high sample rate data will be taken to verify that the performance characterised on the ground is still valid.

4.1.5 Afterglow from a Bright Source

The responsivity change due to a bright source can persist after the signal on to the detectors has been reduced e.g. by removing the source, moving to a fainter target or by the source varying as the case will be for EChO. This effect can be detected in the short term via changes in ramp linearity i.e. the ramps become non-linear however these effects can be difficult to disentangle from source variation.

There are two possible approaches that can be adopted for EChO. The dominant source of flux is the host star which has a strong variation of flux with wavelength. If it can be assumed that stellar variation at one wavelength can be equated with another wavelength then a non-affected pixel at another wavelength can be used to track stellar flux and hence disentangle this effect. It is currently not known if this is the case as both ground and space-based exoplanet studies have not yet characterised this.

Another approach would be to use the on-board calibration source during an observation to provide a short term track of responsivity. If the on-board calibration source is used then it could be used to 'flash' an additional signal during an observation although this approach may carry a risk of the calibration signal itself also disturbing the detectors.

Alternatively we could consider a short slew, preferably along the slits. The calibration signal is then flashed on to pixels which were previously observing the source but are now observing dark sky. This would be followed by a short slew back to the source. This would avoid the calibration signal disturbing the detectors but may induce errors if the observatory is not able to re-point precisely enough.

Another method could be to select different rows for alternate observations to ensure a target is always observed on a row that was observing background during the previous observation. It is TBD whether this can be accommodated by the design.

4.1.5.1 On Ground

The effect of bright sources will be extensively characterised during ground test and the strategies for correcting these effects will be tested. In particular if an approach is adopted where the on-board calibration source is used, the best strategy for using this needs to be developed.

4.1.5.2 In Flight

In flight the adopted approach will be validated during PV phase and adjusted if necessary.

4.2 Environmental Effects

4.2.1 Ageing of the instrument performance

Ageing effects may include surface degradation and contamination; these will result in a long term change in measured signal.

4.2.1.1 On Ground

Very little can be done on the ground, this is due to the short duration of instrument test campaigns and the lack of testing in a flight-like environment with the entire spacecraft.

4.2.1.2 In-Flight

Ageing effects will be monitored via regular observations of standard sources which have a constant flux.

4.2.2 Variations in the thermal background

Slow temperature drifts, in the telescope and baffles and in the instrument temperature also affect the amount of radiation reaching the detectors. These drifts can be measured via thermistors placed on the telescope, baffles and satellite structures, and the instrument structure, optics mounts and baffles. Non-illuminated pixels on the detector array monitor the background signals and these can be correlated with the measured temperatures.

4.2.2.1 On Ground

During ILT detector performance will be monitored over the period of the test, typically 2-3 weeks. Also performance will be compared from one test to another. During these tests temperatures will be carefully monitored allowing any correlation with temperature to be disentangled from aging effects.

4.2.2.2 In Flight

A standard “dark” pointing will be established which will be visited on a regular basis. The frequency is TBD but this is likely to be once every 1-2 weeks. This will enable determination purely of thermal drift effects.

4.2.3 Variations in the straylight or Zodiacal background

Additional to the thermal background there may be a straylight or Zodiacal background which may vary with spacecraft orientation.

4.2.3.1 On Ground

This is an effect which can only be characterised in-flight.

4.2.3.2 In Flight

During PV phase dedicated checks will be made on the effects of spacecraft orientation on the signal detected and if effects are found these will be included in the calibration scheme.

Alongside observations of targets we will observe a nearby patch of dark sky (2 PSFs away should be sufficient here). This will enable us to detect whether there are any additional sources of radiation from the satellite, instrument and Zodiacal light by comparing this with the signals from our standard dark sky observations.

4.3 Electronics Effects on Calibration

4.3.1 Offsets and gains in the electronic chain

The electronics gain may drift with the temperature of SVM. Also aging of components over the timescale of the mission may affect gains or offsets.

This van be tracked via resistive elements in the detector arrays and a simple voltage ramp can be applied to the resistive channels to check the overall gain of the system.

It may also be possible to apply voltage stimulation direct into the amplifiers to test their gain and implementation will depend on the design of the electronics and the EMI controls required.

4.3.2 Electronic cross talk / ghosts

There may be some electronic cross-talk. Cross-talk can be monitored by analysis if the effect of a glitch hitting a pixel on the other pixels in the array. During flight glitches will be analysed to determine the cross-talk matrix. If it deemed necessary this matrix will be used to correct the detected signals.

4.4 Optical Effects

4.4.1 Absolute pointing performance

The absolute pointing is monitored through the AOCS and FGS system. Any error in the pointing will affect the absolute photometry. However as core science observations are relative measurements, in principle a slight offset will not affect the recovery of the exoplanet spectrum.

4.4.2 Pointing stability

The 1-σ pointing jitter of the satellite is currently base-lined to be of the order of 10 milli-arcsec from 90s to 10h (EIDA-R-0470) of continuous observation. This will be monitored through the FGS and will also be detected via shifts in wavelength of spectral features.

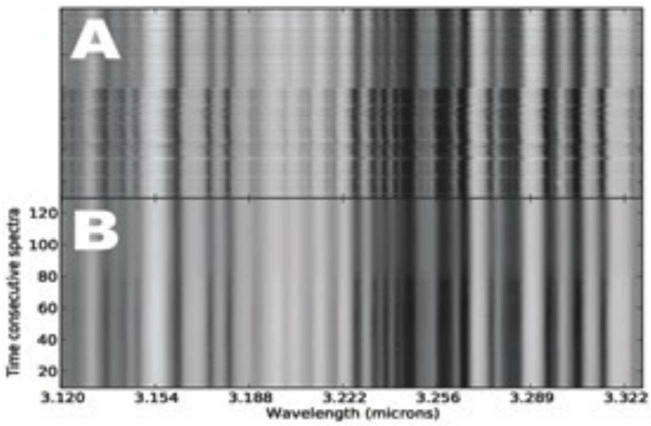


Figure 1: Example of time consecutive ground-based observations using a spectrograph (IRTF/SpeX). Each pixel row constitutes an individual spectrum. Dark lines are telluric and stellar absorption lines. Plot A: Observed spectra are shifted with respect to each other due to spectral jitter. Plot B: Spectra of plot A are resampled to a common grid.1

As Figure 1 shows, the fact that the spectra are time resolved means that any spectral jitter can be removed by re-aligning the spectra.

There will be a trade-off between using pixels that are oversized compared to the PSF – and therefore the effect of the spatial jitter is only governed by the intra-pixel response, and using many pixels to sample the PSF which will “wash out” both the inter and intra response variations. The latter will only be realistic if the noise from the detectors is sufficiently low to allow a significant amount of de-correlation as the PSF centroid can be “tracked” across the spatial dimension of the array. Spatial jitter must also be tracked via the FGS and in the case where the pixels are oversized in relation to the PSF this will be used to track spatial jitter.

4.4.3 Optical stability of the telescope

It may be the case that individual optical components within the systems, from the telescope to the detector, move with respect to each other. So if (for instance) the detector is badly mounted and vibrates when the cooler/reaction wheels/whatever else operates then will cause “jitter” in some sense that the images are blurred and distorted but it is not related to the AOCS and is not seen in the FGS. We may be able to correlate this with wheel/cooler ops and housekeeping.

We assume any microvibrations are of low level and in the 1-many Hz band and therefore can be integrated/filtered out.

4.4.4 Reduction in optical transmission

Thermo-elastic issues varying over short/medium timescales (hours/days) may affect the size of the PSF. This should be be seen in the fine guidance sensor and/or in the spatial dimension of the spectrometer providing sufficient pixel sampling is provided for in one or the other or both. Correlation with various temperatures may be identified and a model of the system behaviour established.

5 CALIBRATION OBSERVATIONS

5.1 Photometric Calibration

5.1.1 Absolute photometric calibration

The absolute flux calibration for EChO will use visible/NIR stellar standards. Previous MIR missions have achieved calibration accuracies in the few percent range (see for instance Jarrett et al, ApJ, 735, p112 ,2011).

We will use existing databases and collaborations with expert institutes with access to mission data from WISE, Spitzer, MSX and Akari to identify both the core calibration stars and those with uncalibrated MIR excesses in order to remove them from the standard calibration list.

We can also use Solar system objects as calibrators for extended source calibration (Mars, Uranus and Neptune) as well as a number of asteroids. The advantage of using these colder objects is that they have a radically different spectral energy distribution compared to stars allowing a useful cross check on the inter-calibration between the modules.

5.1.2 Relative Photometric Calibration

For the most photometrically stable sources we will use G-dwarf stars. Ciardi et al. 2011 has shown that 70 % of G dwarfs are stable in the visible to better than 10^{-5} (at least on a short time scale) and there are over 400 in the solar neighbourhood brighter than K=5 (histogram provided below). These are uniformly distributed over the ECHO sky and will be typically 10 times brighter than most of our targets allowing high S/N observations to determine accurately the slow variation with time of the instrument response and detector performance.

Before launch, we will conduct a systematic survey from the ground to study the properties of a sample of G dwarfs using activity indicators (CaII H&K, X Rays) in order to carefully select the lowest activity stars to become the calibrators. In addition, several bright stars (5.8< mV<9) were observed by CoRoT and exhibit very specific (and predictive) short term variability (solar pulsators), which can be used for in flight calibration.

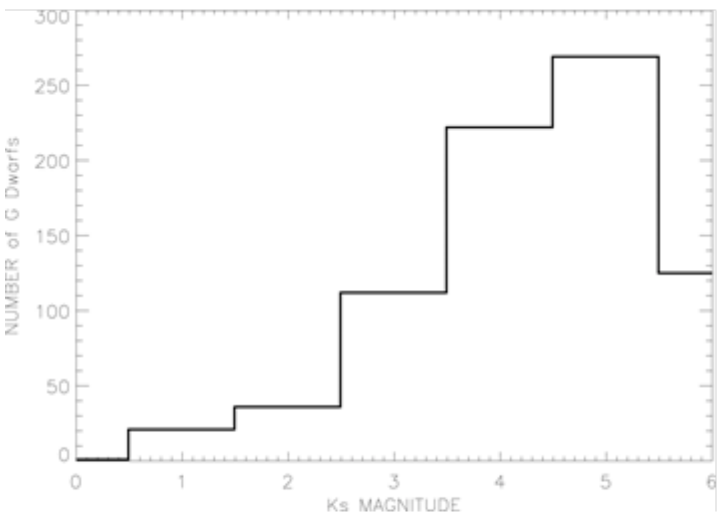


Fig 1: Ks magnitude histogram for close and bright G stars that could be used as calibration sources for EChO.

A third set of objects is the set of calibration targets associated with the core programme sources. Where possible the network of G stars will be used but this may need to be extended if the nearest network G star is too far away from the target or if there is a considerable flux difference between the network star and the target star. For these cases we will select G stars with similar fluxes, close to the science target. A study of potential target stars has shown that in almost all cases similar flux G stars can be found within a degree.

5.2 Strategy

5.2.1.1 PV Phase

During PV phase a network of the absolute calibrators will be observed to determine:

- The conversion factors counts to flux
- The linearity of the detectors in-flight
- The relative spectral response function

A subset of the absolute calibration sources along with potential secondary sources will be observed regularly to determine the instrument + telescope stability. A set of G stars will be observed to set up a network of photometrically stable secondary sources. The number of G stars required is TBD and is dependent on the frequency they need to be observed in routine phase. The current expectation is that the frequency of these observations will need to be between a few hours and once per day, hence 2-3 observations per day is adopted as our current baseline. Ground preparation will yield a list of potential targets. However we will only establish the true stability of these targets in-flight and hence we will need an initial list containing a larger sample than required for routine monitoring. Given that both the instrument stability and the stellar stability are being established during this phase observations of stars in the secondary network must be made adjacent to observations of primary calibrators. Short term stability during these observations will also be monitored via use of the instrument internal calibration source.

5.2.1.2 Routine Phase

The flux calibration in routine phase will be maintained on the short term via use of the internal calibration source, on the medium term via observations of secondary calibrators and over the long term via regular observations of primary calibrators. The frequency of these observations is TBD but roughly the absolute targets will need to be observed 1-2 times per week, the secondary targets 2-3 times per day and the internal source regularly during a day.

Below is a proposed calibration strategy used for the scheduling exercise. This is not pretend to be the optimal calibration strategy, just a plausible one for simulation purposes. We need to characterize the instrument on the hour time scale and 10 hours time scale.

Types of calibration: we define two types of calibration:
- Shortcal is a 1 hour integration
- Longcal is a 10 hour integration

The proposed scheme is to have in average one shortcal per 36 hours of mission time, and one longcal every 10 days. For a 4.5yr mission this results in about 1095 shortcal observations and 165 longcal observations.

Calibrators: a list of 500+ calibrator G stars is already identified. For the scheduling simulation all calibrators are considered interchangeable, so that one can choose from the list whichever target is most convenient. We suggest minimizing thermal effects to take a calibrator that is as close as possible to the latest observed target on the sky.
The diversity requirement is:
- to use at least 5 different stars for longcals
- that all longcal targets are also used in at least one shortcal
- that at least 20 different stars are used for shortcals

To provide some some flexibility for the scheduling of calibration observations, the interval requirements between them are expressed as the following:

- Shortcals: there must 20 +/- 5 shortcal observations per any 30-day period of mission time, with no more than 48 hours between two consecutive shortcals

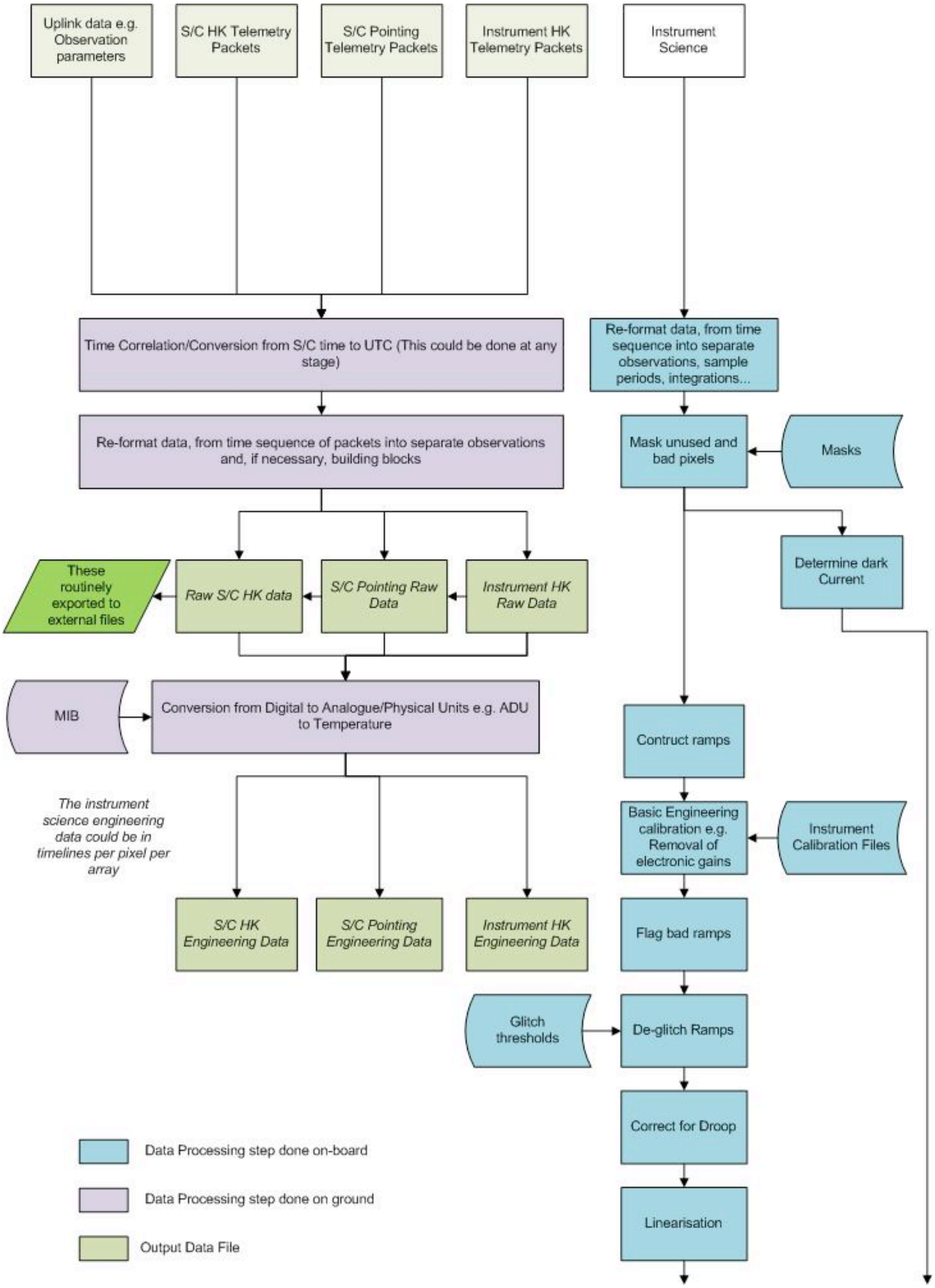
- Longcals: there must be at least 3 +/- 1 longcal observations per any 30-day period of mission time, with no more than 15 days between two consecutive longcals.

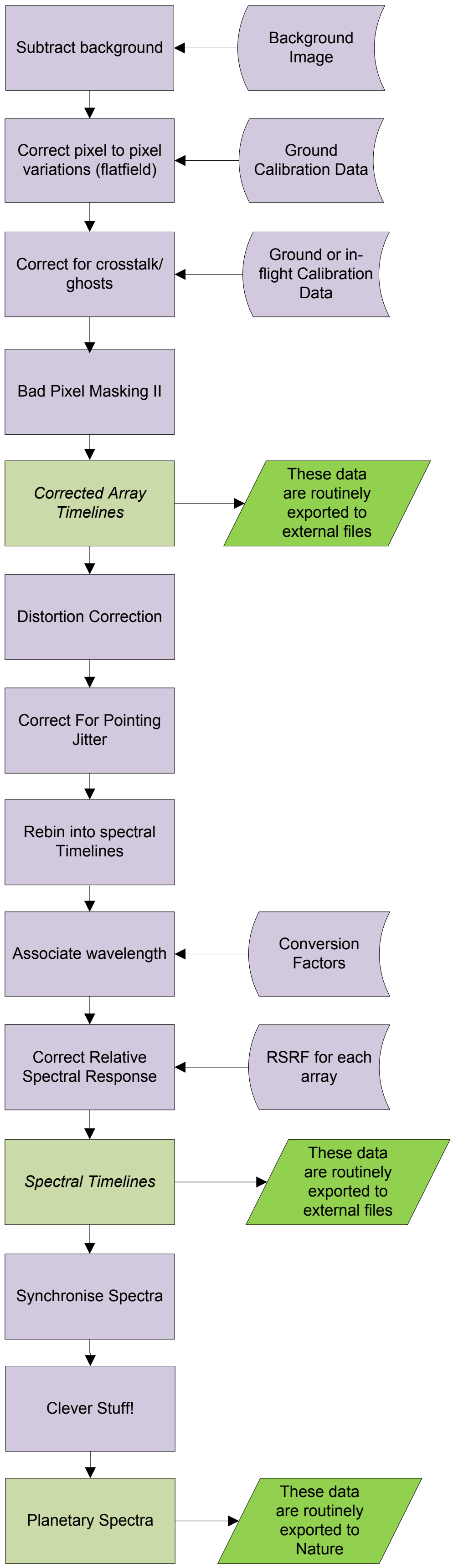
5.3 Wavelength calibration

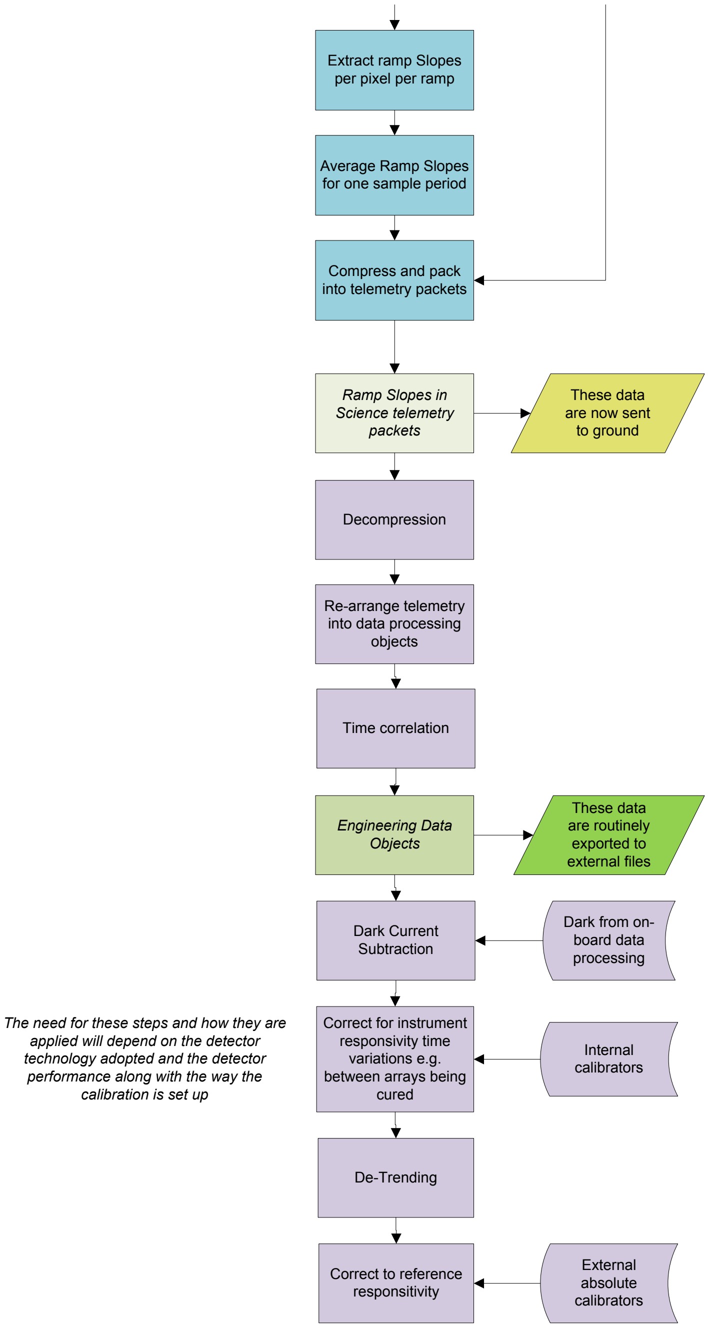
We will extensively calibrate the wavelength scale of the EchO instrument before launch and only expect minor changes once in orbit. The in-flight wavelength calibration verification of EChO will be carried out using astronomical sources only and no instrument level calibration source will be provided. Suitable targets for this are provided from the ISOSWS catalog and the brighter targets observed by Spitzer IRS. Typically the targets are evolved stars (PNe, SNR and AGB stars) and star formation regions. Any source seen with ISOSWS is likely to be suitable for EChO to observe with high SNR. Another possibility is to use Solar system planets but these are likely to be line confused at the resolution of EChO and are anyway secondary science targets.

6 THE DATA PROCESSING PIPELINE

The following flow charts show an overview of the data flow through the pipeline. The remainder of this section then details each step.


Uplink data e.g. Observation parameters
S/C HK Telemetry Packets
S/C Pointing Telemetry Packets
Instrument HK Telemetry Packets
Instrument Science
Time Correlation/Conversion from S/C time to UTC (This could be done at any stage)
Re-format data, from time sequence into separate observations, sample periods, integrations...
Re-format data, from time sequence of packets into separate observations and, if necessary, building blocks
Mask unused and bad pixels
Masks
Determine dark Current
These routinely exported to external files
Raw S/C HK data
S/C Pointing Raw Data
Instrument HK Raw Data
MIB
Conversion from Digital to Analogue/Physical Units e.g. ADU to Temperature
Contruct ramps
The instrument science engineering data could be in timelines per pixel per array
Basic Engineering calibration e.g. Removal of electronic gains
Instrument Calibration Files
S/C HK Engineering Data
S/C Pointing Engineering Data
Instrument HK Engineering Data
Flag bad ramps
Glitch thresholds
De-glitch Ramps
Correct for Droop
Linearisation
Data Processing step done on-board
Data Processing step done on ground
Output Data File


Subtract background
Background Image
Correct pixel to pixel variations (flatfield)
Ground Calibration Data
Correct for crosstalk/ ghosts
Ground or in-flight Calibration Data
Bad Pixel Masking II
Corrected Array Timelines
These data are routinely exported to external files
Distortion Correction
Correct For Pointing Jitter
Rebin into spectral Timelines
Associate wavelength
Conversion Factors
Correct Relative Spectral Response
RSRF for each array
Spectral Timelines
These data are routinely exported to external files
Synchronise Spectra
Clever Stuff!
Planetary Spectra
These data are routinely exported to Nature


Extract ramp Slopes per pixel per ramp
Average Ramp Slopes for one sample period
Compress and pack into telemetry packets
Ramp Slopes in Science telemetry packets
These data are now sent to ground
Decompression
Re-arrange telemetry into data processing objects
Time correlation
Engineering Data Objects
These data are routinely exported to external files
Dark Current Subtraction
Dark from on-board data processing
The need for these steps and how they are applied will depend on the detector technology adopted and the detector performance along with the way the calibration is set up
Correct for instrument responsivity time variations e.g. between arrays being cured
Internal calibrators
De-Trending
Correct to reference responsitivity
External absolute calibrators

6.1 On-Board Data Processing

The current observing scheme uses three observing modes, bright, normal and faint. The sampling scheme is currently under study with options such as sampling up the ramp, grouping samples and fowler pairs being considered.

- For bright objects Kmag < ~4
  a. The ramp length can only be a few seconds to avoid saturation.
  b. The maximum sample rate of 8 Hz will need to be used.
  c. Ramp lengths of 3 seconds are possible with the baseline Teledyne detectors; other detector technologies with larger pixel sizes will imply a move to 1.5 second ramps.
  d. If all samples are transmitted to the ground this would be about 250 Gbits/day. Therefore for this mode, only the evaluated ramp slopes and a goodness of fit will be transmitted to ground. This still gives a rate of 35 Gbits/day
  e. As a baseline the on-board processing will not need to deglitch ramps before evaluating ramp slopes, however there will be flexibility in the OBS to accommodate this if required.
- For normal mode
  a. 1 Hz rate is adopted
  b. 32 second ramps are adopted
  c. This gives a primary rate of 32 Gbits/day if all samples are transmitted to ground
  d. If we group samples into groups of 8 we can achieve a rate of 4Gbits/day with no goodness of fit transmitted
- For fainter targets
  a. The ramp lengths adopted are 240 seconds with 30 samples separated by 8 seconds.
  b. All samples will transmitted to the ground and the ramps and dealt with in data processing on the ground
  c. This gives a primary rate of about 4 Gbits/day

Non-used pixels will need to be masked before or after readout and therefore this calibration information will need to be stored on board.

The weekly allocated data rate (AD1) is 35 Gbits/week or 5 Gbits/day average. Assuming a a H/K rate of 0.2 Gbits/day, a realistic duty cycle of 90% and a compression ratio of 2, spending 10% of the mission in bright mode, 80% in normal mode and 10% in faint mode gives a data rate of 4.72 Gbits/day.

6.2 Data Processing to Level 0.5

The order of the following steps will be optimised during development.

6.2.1 Unpack and Decompression

Instrument science data will be compressed in order to maximise the amount of data which can be processed on the ground. The format of the science packets is TBD. The first step in processing this data therefore is to unpack the data and run the appropriate decompression algorithm. Data is likely to be re-organised into objects suitable for the data processing system

Data will clearly need to be split by observation. For science data processing efficiency e.g. by multi-threading, data will need to be split further. Examples of such splitting could be:

- By detector array
- By area on array i.e. into masked discarded data and data to process
- By integration
- HK should also be split by observation.

6.2.2 Raw Data

The unpacked telemetry constitutes level 0. It may be advantageous to store it in an external file if fewer resources are required to bulk re-process.

6.2.3 Time Correlation

The telemetry packets will likely contain spacecraft (S/C) and instrument specific time stamps as an instrument usually requires a faster clock that the spacecraft. The S/C time is converted to UTC, via methods supplied by the MOC. Time correlation will be required for all telemetry types, not just instrument and may be done at any stage of the data processing.

6.2.4 Masking

Bad pixels will need to be flagged. The advantage of doing this early is that these can be eliminated from further processing saving resources.

There may be other flags for pixels that show anomalous behaviour but are still processed. Such flags could include noisy pixels, pixels likely to saturate at a lower well depth etc.

6.2.5 Conversion to Physical Units

At this point the values correspond to digital outputs of the instrument electronics.

- Non-science parameters need to be converted to analogue values and a calibration is applied for each parameter to turn these into physical values such as volts, current, temperature etc. This calibration is derived before launch and is stored in the MIB. The data processing will either need to interact with the MIB directly or a set of tables will need to be extracted for use with DP.
- For the science data the values correspond to the measured counts plus the gains and offsets applied by the readout electronics which are corrected separately. Therefore this processing step is only applicable to non-science data.

6.2.6 Engineering Calibration of Science Data

For science data the effects of the readout electronics will need to be accounted for such as any offsets and gains in the readout chain. These effects are integral to the design of the instrument and will be verified on the ground before flight.

6.2.7 Re-construct ramps

The data processing system will need determine start and end points of each integration ramp. The markers for this will be contained in the housekeeping data and placed there by the on-board software. Note as mentioned in section 0 it is possible that this step may not be required for bright targets.

6.2.8 Level 0.5 Data

This refers to data where engineering conversions have taken place. It is essentially raw data but now in useful units. As the conversions are all static and well established before launch this data is unlikely to be affected by post-launch updates to the data processing. Therefore it is a useful data set to store in order to act as a starting point for re-processing. Another way of viewing this data is that is the lowest level any astronomer or calibration scientist is likely to want to start processing from.

6.3 Data Processing Level 0.5 to Level 1

6.3.1 Determine and Subtract Dark Current

There will be dark pixels on each array. The data rate is sufficient for these pixel values to be sent to ground at the same rate as the non-destructive readouts.
The optimum scheme for dark current subtraction is TBD and the options have been discussed in section 4.1.1.

6.3.2 Flag Bad Ramps

A process will need to be run to detect and flag glitches. There may be other effects causing bad ramps which need to be identified and algorithms may need to be developed to flag ramps accordingly.

6.3.3 De-Glitch Ramps

The nature of glitches is not yet known therefore is difficult to identify the exact algorithms which will be used. The de-glitching scheme adopted will depend on:

- If the slope after the glitch matches the slope before the glitch – then the whole ramp can be used
- Whether there are sufficient points before the glitch to still extract the slope
- Whether more than one ramp is affected, note due to the long duration of most ramps this is considered unlikely
- It may be possible to correct ramps following a glitch but this is TBD

Depending on the effect of glitches and our ability to correct for them, we may need to adjust ramp integration times to shorter ramps if the glitch rate is higher than predicted.

6.3.4 Correct for Droop

Somewhat confusingly this term has been used in two different ways:

- To describe a fixed signal added on to all readouts (Spitzer)
- To describe a drop in signal after multiple resets (MIRI)

In the case of MIRI this was cured by changing the clocking pattern so no longer became an issue and for Spitzer the droop correction was folded into the dark subtraction

Therefore this step a placeholder step in case anything will be needed for the EChO detectors

6.3.5 Linearisation and extract ramp signals

It is likely that the detector wells will not fill up as a constant linear rate. Typically after the wells fill to a certain level the rate decreases and the slope flattens. This non-linearity will be well characterised by ground testing under a set of known signal levels and it will also be verified in-flight with stellar data. To extract the ramp slope the ramp will either need to be fitted with an algorithm which takes the non-linearity into account this will be a two-step process first correcting the non-linearity then linearly fitting the ramps.

6.3.6 Correct for Responsivity Time variation

This step removes any medium-term time dependent effects such as changes of responsivity between annealing. These drifts will be monitored by using the internal and external calibrators.

6.3.7 De-Trending

This step takes into account any other effects such as changes of temperature, which are time variable which may impact measured counts.

6.3.8 Correct to Reference Responsivity

This step corrects to a standard astronomical responsivity reference. The observations of standard stars will be used to track this.

6.3.9 Background Subtraction

We will need to subtract an astronomical+telescope background. It is TBD whether this can be done solely by using pixels which see through the slits but are off source or whether additional dedicated background measurements are also needed. The current assumption is that dedicated backgrounds are observed.

6.3.10 Flatfield

A final correction for pixel to pixel responsivity variations. This could be done at the same time as correcting to reference responsivity. Either ground calibration or an internal calibration source could be used to establish the flat field. As the flatfield may change with time the internal source option is the current baseline. Should this prove inadequate it is also possible to use extended and semi-extended astronomical sources.

6.3.11 Correct for Crosstalk/Ghosts

This step is a placeholder in case a correction for crosstalk of ghosts is needed. This step is very likely to be dropped once instrument testing has established that these effects do not occur.

6.3.12 Bad Pixel Masking II

This is a placeholder in case we need to extract any further bad pixel information now we have corrected photocurrents. The method for identifying pad pixels is TBD although typically this would be from quality information gathered during processing up to this point. As understanding develops we may develop additional tests e.g. searches for outliers.

6.3.13 Correct For Optical Distortion

This step is a placeholder in case any spatial correction is needed before the 2-D image is used to extract a 1-D spectrum. As the signal will only be spread spatially by up to three pixels it is currently expected that no correction will be needed for curvature.
We may be able to correct for any mis-pointing using a PSF we can measure along the slit.

6.3.14 Correct for Pointing Jitter

A correction will be derived from the FGS and applied here. The spatial position of the star within the slit as tracked by the width of the PSF may enable a further refinement (TBD).
A spectral correction will also be derived from the data by analysing the time series as described in section 4.4.2.

6.3.15 Rebin Into Spectral Timelines

Remove spatial information to leave photocurrent per spectral element per unit time.

6.3.16 Assign Wavelength

Astronomical sources will be used to establish the wavelength of each spectral pixel. These wavelength values will be added to the science data.

6.3.17 Correct For RSRF and Convert to Astronomical Flux

The RSRF calibration files could have the conversion folded in. The RSRF and conversion factors will be derived from astronomical standards.

6.3.18 Level 1 Data

At this stage for each channel, for each integration ramp, there will be one data point per spectral element sampled. This constitutes level 1 data. It should be noted that there is no requirement of synchronisation of samples between channels.

This will be stored as a spectral cube per observation and it will be the furthest any processing goes on a single observation in the majority of programmes. The one exception to this are community programmes where a single spectrum is required.

6.4 Data Processing to Level 1.5

For community programmes where a single spectrum is required level 1 processing will average each spectral data point in each channel to produce a single spectrum. This single spectrum will constitute the level 1.5 product for this type of observation.

For exoplanet observations the level 1.5 processing will stack transits into a single 4-D dataset.

6.5 Data Processing to Level 2

For the core science programme and similar community programmes level 2 processing will extract the transiting body spectrum. There is likely to be other products required such as the stellar spectrum but these products are still TBD.

Data Processing to Level 3

It is TBD whether a level 3 product is to be produced. If it is this may be a catalogue including line lists for the exoplanet spectra.