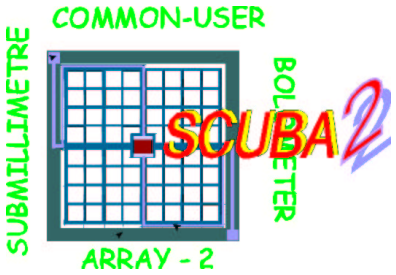


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# Document Title: Data Reduction Software Requirements Document

## Document Number: SC2/SRE/S210/001

## Issue: 1.56

## Date: 2005/05/05

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# Contents

# 1 Introduction

This document describes the Requirements for the various components of the SCUBA-2 Data Reduction Software. 'DR Software' refers to all the steps which deal with the data after they are acquired by the instrument. The Data Acquisition (DA) system is the responsibility of the ATC and is documented elsewhere.

The SCUBA-2 DR Software consists of 3 main parts: the Pipeline data reduction; the Off-line data reduction; and the Data Display System. The Pipeline runs at the summit, and delivers to the observer a set of high quality images each night. The goal of the Pipeline is to keep up with the acquisition of data to produce co-added images for near real time estimation of signal-to-noise ratios. And in particular it needs to reduce 16 hours of data in not much more than 16 hours, providing images which are already calibrated and as free of instrumental and atmospheric artefacts as possible given the time constraints. The Off-line system uses the same set of routines, but can offer enhanced data reduction capabilities when run at the observer's home institution later, but should still be able to reduce 16 hours of data in less than 24 hours. The Data Display System delivers near real-time, approximate co-added images and other diagnostics to the observer as the data come in. How these Software Systems interface with the Data Acquisition System is described in the Interface Control Document.[9]

The SCUBA-2 Software will run on top of the JAC Observing Tool and other JCMT software.[4] Hence the 'look and feel' from the point of view of the observer should be similar to using SCUBA with ORAC-DR,[8] but with some important differences, particularly because of the volume of data.

The total expected data-rate is approximately $8\,\mathrm{MB\,s^{-1}}$ (4 bytes per detector, $40 \times 32$ detector sub-arrays, 4 sub-arrays at each of 2 wavelengths, all read at $200\,\mathrm{Hz}$). Data compression will reduce this by a factor of $\sim$2. For DREAM and STARE modes the data reduction Pipeline will be using the $\sim 1\,\mathrm{Hz}$ images. However, in SCAN mode (and the raw data for the other modes) $1\,\mathrm{GB}$ will be generated approximately every 125 seconds. Since the data will accumulate at a much greater rate than for SCUBA, the Pipeline data reduction must have a level of automation which is at least as good as currently available using ORAC-DR with SCUBA.

There will be a finite number of available observing modes, each of which will allow several different choices for reduction method. The data files generated by the Data Acquisition system will contain a full set of FITS headers describing the data. The user will simply specify the choice of Recipe, with all the relevant information coming directly from the data files themselves. As a general principle, it should not be necessary for astronomers to be familiar with sub-mm data reduction techniques in order to successfully use the instrument. However, the Software also needs to be flexible enough for the expert user to be able to develop more sophisticated algorithms to reduce their data off-line.

The Requirements below are grouped into 8 areas, and labelled accordingly. A number of existing documents provide background information for these Requirements.[6,5,7,15,13,21,14,16,20,12,11] Where these Requirements have their origin in existing SCUBA-2 documents (mainly the 'Functional and Performance Requirements' document[5]) that is listed explicitly in square brackets at the end of the Requirement statement. Other Requirements come from the JAC, and are labelled as such. If no attribution is given for a Requirement, it should be assumed to be a new specification (the majority of which arose from discussions with the user community, particularly at the meeting of 26th April 2003 in Vancouver[18]).

# 2 General Requirements

There are a set of broad Requirements for the whole DR Software:

GR1. The Linux/x86 and Solaris/SPARC operating systems shall be supported for the DR Software. [JAC]

GR2. The DR Software shall be easy to use, and not require that the observer be an expert in sub-mm techniques or have detailed knowledge of the hardware. [FPR 5.2.5]

GR3. The Software shall conform to the JAC Software Requirements.[19] [JAC]

GR4. All of the DR Software shall be fully compatible with the JCMT Observation Management Project and other relevant software maintained by the JAC. [FPR 5.2.6, JAC]

GR5. The Software shall use the information prepared by the observer through specification of the MSBs (e.g. the name of the recipe as specified in the Observing Tool). [FPR 5.2.6, JAC]

GR6. Appropriate use shall be made of software already developed at the ATC for running the instrument, and of material already in existence for SCUBA, e.g. from the SCUBA User Reduction Facility (SURF[12]). [JAC]

GR7. The Software shall run robustly without user intervention. [JAC]

GR8. The Software shall recover from all common failure modes. [JAC]

GR9. There shall be a small number of data reduction Recipes to select from, with no free parameters. [FPR 5.2.7, JAC]

GR10. The Software shall be flexible enough to allow new observing modes and reduction recipes to be developed (by the software developers, but not necessarily by the typical user) if needed at a later stage. [FPR 5.2.8, JAC]

GR11. To satisfy the project wide requirement of calibration precision within a night of 5% at $850\,\mu$m and 10% at $450\,\mu$m, the DR Software shall contribute a negligible amount to this accuracy budget. [FPR 4.6.2]

GR12. There shall be a procedure to correct for calibration drifts. [FPR 4.6.2]

GR13. The DR Software shall be a purely data-driven system which can be run using no external files other than the data files themselves, or calibration data which can be selected using the header information. [JAC]

GR14. The DR Software shall have a facility for over-riding the header data with information from other files. [JAC]

GR15. The data generated by the Pipeline shall conform to a well-documented format and content, including reduced images and calibration information. As part of this there shall be a 'data expander' which writes out data in a usable format. This shall be a stand-alone application rather than part of the Pipeline.

GR16. All file sizes shall be kept less than $2$ GB and shall be able to be manipulated by systems with a 32 bit address space. [JAC]

GR17. Errors shall be propagated in all data reduction methods. [FPR 5.2.8]

***Although recognising that some of these may be hard to quantify, there are also general goals:***

GR18. The Pipeline should produce images which will be near to publication quality for the majority of users. Later Off-line reduction will provide some improvement through better calibration, or improved reduction algorithms, for example. [FPR 4.2.1.1]

GR19. The relative calibration precision within a night should not exceed 5% at 850 $\mu$m and 10% at 450 $\mu$m, although the actual reasonable expectation is governed by the observing strategy. [FPR 4.6.2]

GR20. The DR Software should support MacOS X. [JAC]

# 3 Observing Mode Requirements

Details of the required observing modes have already been provided, and are not part of the Data Reduction Software, although obviously reduction of data from each of the modes certainly is. However, a brief summary of some of the relevant information about modes is given here.

The modes are currently referred to as 'STARE', 'DREAM' and 'SCAN'. There may in fact be more than one Recipe for each mode. For STARE and DREAM, a standard jiggle pattern will be available in order to fully sample the $450\,\mu$m array, and to fill in the gaps between the sub-arrays. The Data Reduction Software needs to be able to properly reduce these jiggled frames. For SCAN mode, the images will be fully sampled by choosing scan directions in which trailing bolometers fill in the gaps left by leading bolometers.

The STARE mode is expected to be useful for engineering checks and for bright sources, but will not be relied upon for most science projects. The raw $200\,$Hz STARE frames will be grouped into short time sequences which will be subjected to spike removal, averaging and correction for relative pixel responses. The averaged images will be fed to the rest of the Pipeline at approximately $1\,$Hz, where they will be resampled and combined onto a non-rotating coordinate system (e.g. RA–Dec).

The DREAM mode (based on the 'Dutch REal-time Acquisition Mode' method for SCUBA[17]) is expected to be the most efficient way of going deep in a small field. It involves a rapid, closed scan pattern to link nearby detector elements, performed using the secondary mirror. Optimization of the pattern is still being investigated. Whether it works well will not be known definitively until real data are reduced at the telescope.

The DREAM reduction itself will be performed in the Data Acquisition computers. This will involve spike removal, sky drift removal, correction for relative pixel responses and the DREAM least-squares image reconstruction onto Nasmyth coordinates. This will happen at a maximum rate of $1\,$Hz, and field rotation requires that it be not much slower than $0.2\,$Hz. The DREAM output will also include the solved zero-points for each bolometer, as well as error estimates. The Pipeline will combine the individual DREAM frames onto a non-rotating coordinate system (e.g. RA–Dec).

The SCAN mode will be the preferred approach for mapping large fields. SCAN still needs to be investigated in more detail – the scanning pattern as well as the reduction algorithms. Since SCUBA-2 will not be chopping, atmospheric emission will dominate the astronomical signals by a large factor, and so needs to be removed with high precision if maps are to be made free of scanning artefacts. A basic reduction method needs to be established which is robust and fast to compute, and is integrated into the Pipeline Software. Other methods, which may be closer to optimal but require significantly more computing power, could also

be considered for the Off-line system. All of this needs to be investigated. Although the SCUBA-2 Project does not currently have a concrete plan for reducing SCAN mode data, it is reassuring that several other groups, using similar total-power instruments are making progress with these issues. The uncertainty about how easy it will be to make good images is the main reason for SCUBA-2 having 3 fundamentally different observing modes.

Given the existence of these modes, there are a few related Requirements on the Data Reduction Software:

MR1. All available observing modes shall be supported by the Pipeline. [FPR 5.2.2]

MR2. In Off-line mode the DREAM or STARE data shall be re-reducible from the raw 200 Hz time series as well as just the 1 Hz images, using the same algorithms as the DA System used to produce the 1 Hz images. [FPR 5.2.7]

MR3. There shall be an efficient SCAN reduction method which is computationally fast enough that it does not make the Pipeline fall behind. [FPR 4.2.1.3, 5.2.3]

MR4. Any reduced images shall not degrade the resolution by more than 10% of the FWHM, compared with a perfect telescope beam.

MR5. There shall be no unrecoverable astrometry errors introduced by the DR system which are worse than the resolution at 450 $\mu$m, i.e. no random errors worse than 6 arcsec.

***The following are additional goals for reduction of the various observing modes:***

MR6. Images obtained from each of the observing modes should be reduced in a way which gives demonstrably reproducible results on brightness and morphology of extended sources.

MR7. There should be the possibility of running a nearly lossless and artefact-free SCAN reduction algorithm off-line, even although that may take much more computing resources. [FPR 4.2.1.3]

# 4 Pipeline Requirements

A simplifying principle is that reduction will be carried out on a nightly basis, so that the full reduction of many nights of data shall not be the responsibility of the Pipeline Software.

The status of Archiving and Surveys is currently unknown, and so we must assume that any developing plans for SCUBA-2 archiving and Survey work will place no additional Requirements on the DR Software.

PR1. The Data Reduction Pipeline shall not be allowed to feed anything back to the Data Acquisition System (e.g. pointing and focus) during normal observing (i.e. engineering mode can generate reduced data for the instrument), and hence shall not be allowed to be a bottle-neck for taking data. [FPR 5.2.3, JAC]

PR2. By default the Pipeline be generating just images (which may subsequently be converted to polarization Stokes parameters or an FTS spectral cube).

PR3. Engineering recipes shall exist for performing array setup and flat-fielding tasks.

PR4. Specific Recipes shall be written that will be optimized for different situations, e.g. for when there is a bright point source in the map, when large areas are being mapped, or the map is going very deep.

PR5. The Pipeline shall be able to handle the expected data rate, with up to a 30% margin, so that quality control information is delivered in a timely manner in most circumstances. This means that the Pipeline running in near real-time at the summit shall be capable of keeping up with observing, i.e. that it can handle 12 hours of data in close to 12 hours of real-time. [FPR 5.2.3, JAC]

PR6. The summit Pipeline shall provide a fully automated calibration procedure.

PR7. The Pipeline shall handle each night's data separately.

PR8. The Pipeline shall generate and store calibration data from each night in order for it to be possible to use the information later.

PR9. The noise shall be estimated robustly and accurately based on detector element variances and integration times. [FPR 4.2.1.2]

PR10. It shall also be possible to obtain a noise map based on the variances of pixel values among individual images (this is separate from the local spatial variances in the final image, which includes confusion and source structure). [FPR 4.2.1.2]

PR11. A measure of the 'weight per pixel' (the number of recorded bolometer values contributing to each reconstructed pixel) shall also be available. [FPR 4.2.1.2]

PR12. As well as noise estimates, Recipes shall make basic data quality assessments, including the expected range of the data, so that data can be flagged for being out of normal range (indicating hardware or weather problems, for example, and useful in any re-reduction of the data). This shall apply to calibration measurements (daytime and night-time with the shutter closed) as well as more typical sky measurements.

PR13. All images generated by the Pipeline shall have a full astrometry header.

PR14. The Pipeline shall be able to process data from the two wavelength channels independently.

PR15. The Pipeline shall be able to combine the images of each sub-array which come separately from the DA system. [FPR 4.2.2]

***There are some additional Goals for the Pipeline:***

PR16. Observers will need to know that the observations are proceeding correctly and that the signal-to-noise (or in some cases the noise) is improving through the night. For flexible scheduling a signal-to-noise ratio criterion may be used to decide a project is complete, and so this should be able to be calculated in near to real-time. [JAC/OMP]

PR17. The Pipeline should be able to determine corrections for pointing drifts using bright sources in fields which are observed multiple times in one night.

PR18. The Pipeline should produce an estimate of the beam-shape at each wavelength, based on bright sources observed during each night.

PR19. The Pipeline should be able to compare reduced image data with source catalogues extracted from a previous night's data.

# 5 Off-line Requirements

The intention is for the Off-line system to use the same software as the summit Pipeline, but with some different Recipes. However, the Off-line mode will in general have a higher threshold for accuracy and a looser time constraint, since it will have access to more calibration information and overlap,n mosaicing to reduce edge effects, for example.

OR1. The Off-line system shall be able to reproduce all of the steps performed by the Data Acquisition System on the raw data. [FPR 5.2.7, JAC]

OR2. In Off-line mode the Pipeline shall be able to process all 4 sub-arrays as a single unit using the 200 Hz data.

OR3. In Off-line mode 12 hours of data shall be reducible in 24 hours, including calibration, but this can be implemented using multiple computers. [JAC]

OR4. Off-line mode shall use all the calibration information obtained during the night (as opposed to the on-line mode which can only use calibration data taken prior to the observation).

OR5. The Software shall provide Recipes which are optimized for mosaicing large areas and for carefully combining images taken in the deepest fields.

OR6. The Software shall be able to deal with at least $20^\circ \times 20^\circ$ maps (where the pixel area distortion in the tangent plane projection exceeds 10%), subject to staying within the 2 GB file size limit.

OR7. The Off-line DR Software shall allow users to include their own algorithms.

OR8. The Off-line Software shall be executable by observers at their home institution without access to commercial software or any restriction on the basis of software licenses. [FPR 5.2.2]

***The following are additional goals of the Off-line system:***

OR9. Spectral index plots are not a DR requirement, but they should be easy for users to make in the Off-line System, using information generated by the Pipeline.

OR10. The available Off-line Software should contain a decent, robust source extractor (similar to SExtractor[2,3] perhaps) which works well in uncrowded fields. This need not be optimized for use in very crowded fields, which is more complicated and research-area driven.

OR11. The Off-line extraction software should report a measure of how extended versus point-like each source is.

OR12. The available Off-line Software should make it relatively straightforward to search for variable or moving objects.

OR13. A full pixel-pixel covariance is probably beyond the scope of the Pipeline Software. However, the available tools should make it feasible for a dedicated user to calculate this themselves.

# 6 Display Requirements

The DR Software will also provide some display tools, for which there are an additional set of Requirements. A general principle is to display data as fast as reasonably possible, with the rate depending on observing mode.

DR1. There shall be a set of near real-time displays available to the observer. These displays may grab partially processed data from the Pipeline data reduction, but they shall not interfere with the running of the main Pipeline. [FPR 5.2.5]

DR2. An early version of the Data Display System shall be ready for use in testing the instrument. [FPR 3.6.3]

DR3. A map of the currently taken data shall be displayed in Nasmyth coordinates, but with an approximate (RA–Dec) overlay.

DR4. The most recently co-added map shall also be displayed separately. This shall be available in (RA–Dec) coordinates and be calibrated.

DR5. There shall be a means of viewing the array variations in a near real-time 'movie' mode during observing.

DR6. There shall be an Off-line means of viewing the array variations, including the ability to combine data from multiple files.

DR7. For the DREAM mode, frames shall be updated at the rate they are being written to disk (i.e. as fast as $1$ Hz), and with essentially no delay behind real-time.

DR8. The DREAM/STARE Quick Look system shall not fall behind in displaying the frames, and should drop the smallest number of frames in order to keep up.

DR9. For SCAN mode the image shall be updated every time an individual scan has been completed, with the display appearing before the next scan is complete.

DR10. There shall also be a plot of estimated noise in the co-added map. This will be calculated using knowledge of the detector variances and integration times in sub-images.

DR11. A map of the noise of the detector elements measured over a fixed time interval shall be available (used for assessing which detector elements are misbehaving for example).

DR12. A 'strip-chart' plot shall be used for displaying time-varying data generated by the Pipeline.

DR13. It shall be possible to display multiple strip-charts in a single user interface.

DR14. It shall be possible to display multiple data sets on the same strip-chart with shared $x$- and $y$-axes.

DR15. It shall be possible for the observer to adjust the time period covered by the strip-chart.

DR16. The $y$-axis for the strip-chart shall be configurable to either autoscale or to use values supplied by the user.

DR17. It shall be possible to pre-configure the strip-chart so that it can automatically locate the type and location of data it is expected to display (e.g. data from log files, parameter systems etc.).

DR18. It shall be possible for more than one strip-chart monitoring the same thing to be displayed at once (e.g. one for the observer and one for the telescope operator).

DR19. The strip-chart shall include a facility for displaying monitor information, including at least the median power across the array, FCF performance, opacity information (e.g. Water Vapour Radiometer,[22] the CSO tau meter[1] and sky-dips), and beam sizes.

DR20. Calibrated images of particular significance (e.g. mosaics) shall be displayed on a separate window so that they remain visible for longer periods than the ongoing co-adds.

***Some other items are also goals of the Display system:***

DR21. It should be possible to overlay catalogues of objects on the co-added images, or import other images to compare.

DR22. The display of a large area should allow the possibility of pan and zoom functions.

# 7 FTS & Polarimetry

The Fourier Transform Spectrometer (FTS) and Polarimeter offer additional functionality to SCUBA-2 and place additional requirements on the DR Software. The Polarimetry software is part of the DR package. The FTS software is provided by the FTS group, but needs to be fully integrated into the Pipeline. Here '[FTS]' and '[POL]' refer to Requirements which come from the Polarimetry or FTS work packages.

XR1. The FTS and polarimeter shall be incorporated into the same reduction Pipeline, but shall require their own Recipes. The first steps in the reduction processes shall produce images, which the FTS or polarimetry Recipes can then process. [FPR 5.2.8]

XR2. Polarization magnitudes and orientations shall be calculated and displayed on the reduced total intensity image by the Pipeline. [POL]

XR3. There shall be polarization histograms, along with magnitude and angle signal-to-noise estimates. [POL]

XR4. Any Software explicitly needed for handling FTS and polarimetry shall be delivered when those parts of the instrument are delivered.

***There is an additional Goal:***

XR5. The Display System should provide a means for viewing selected FTS interferograms, spectra, and spectral images. [FTS]

# 8 Simulations and Testing

A simulation of the Data Acquisition System is being developed, which will provide 1 Hz images of each sub-array. These will be used initially to test that the Pipeline Software can keep up with the data rate. The reduction methods also need to be tested for artefacts produced by the instrument or the sky. The production of the necessary simulations is largely the responsibility of the DA work packages. However, it is expected that development of the DR Software will help define precisely what sorts of simulations are required in order for realistic testing to be done and to define specifications for improving the data simulator. In addition the DR work package is responsible for providing an efficient algorithm for reducing SCAN mode data.

TR1. A full working Pipeline shall be available at commissioning for each of the anticipated observing modes. [FPR 5.2.8, 6.1]

TR2. Each observing mode shall be tested and documented. [FPR 5.2.8, 6.1]

TR3. Observing strategies for scanning the sky, similar to techniques used by other instruments, shall be carefully examined. [FPR 4.2.1.3, 4.3.2]

TR4. Several strategies shall be investigated for reducing SCAN data, in order to select the most appropriate one for building into the DR Software. [FPR 4.2.1.3, 4.3.2]

TR5. The testing of SCAN mode reduction shall be used to define specifications for improving the data simulator.

# 9 External Requirements

There are also several Requirements which arose in planning the DR Software, but which are clearly requirements on other parts of the SCUBA-2 Project. The DR Software work package does not need to fulfill these Requirements, but these define dependencies on other parts of the project which may not already have been documented.

ER1. A standard polarization observing mode shall be defined. [Requirement on the Polarimetry work package]

ER2. The DA System shall not write files larger than 2 GB in size [Requirement on ATC].

ER3. A set of 200 Hz simulations of the entire array need to be generated in order to test the Software. These simulations need to include sources of noise and instrumental artefacts which are as realistic as possible. [Requirement on ATC]

ER4. The simulations shall generate data files which conform to the final SCUBA2 DA/DR system interfaces so that they can be used for sub-system testing. [Requirement on ATC]

ER5. Simulated skies shall include extended emission as well as point sources, and sources covering the anticipated range of brightness. [Requirement on ATC]

ER6. STARE mode shall be investigated to determine how successful it might be in the presence of realistic atmospheric and instrumental noise, and to determine which simple operations on the raw data result in the best images. [FPR 4.2.1.2, 4.2.2; Requirement on ATC]

ER7. Further simulations of DREAM mode should be carried out in order to optimize the dither pattern and speed, and to make the algorithm as efficient as possible in the presence of realistic sources of noise. [FPR 4.2.1.3; Requirement on ATC]

ER8. The FTS work package shall provide a fully automated reduction system (recipes and algorithm engines) integrated into the standard SCUBA-2 Pipeline infrastructure, matching the interface described in SC2/IC210/03.[10] [Requirement on FTS]

ER9. There shall be no additional Requirements placed on the Data Reduction Software from Archiving or Survey teams, without consultation and adequate additional effort to maintain the DR Software schedule. [Requirement on Archiving and Survey teams]

# 10 Acronyms

ATC – Astronomy Technology Centre

DA – Data Acquisition

DR – Data Reduction

DREAM – Dutch REal-time Acquisition Mode

FWHM – Full Width at Half Maximum

FITS – Flexible Image Transport System

FPR – Functional and Performance Requirements[5]

FTS – Fourier Transform Spectrometer

MSB – Minimum Schedulable Block

OMP – JAC Observation Management Project

ORAC-DR – JAC data reduction pipeline reducer

SCUBA – Submillimetre Common User Bolometer Array

SURF – SCUBA User Reduction Facility

WVM – Water Vapour Meter

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