SCUBA-2 DR Pipeline Project Office
University of British Columbia
6224 Agricultural Road
Vancouver, British Columbia
CANADA
V6T 1Z1

Tel: +1-604-822-2211
Fax: +1-604-822-5324
Email: jmolnar@ubc.ca
WWW: http://scuba2.jach.hawaii.edu

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Document Prepared By:	Tim Jenness	Signature and Date:	2005-05-26
Document Approved By:	Douglas Scott	Signature and Date:	2005-05-27
Document Released By:	Janos Molnar	Signature and Date:	2005-05-27

Contents

1 Introduction

This document describes the different steps required to reduce SCUBA-2 data,[24,13] and includes a general overview of the Recipe system, the basic steps required to reduce each observing mode[21] and optimisations to Recipes available for specific target types and scientific goals.

2 Recipes and Primitives

ORAC-DR uses *recipes* as high level representations of the steps required to reduce data for a particular instrument in a particular mode, where the name of a particular Recipe completely describes what that Recipe does. For example, a Recipe called SCAN_BRIGHT_POINT_SOURCE could be used to process SCAN map data where we expect a bright point source in the map; a Recipe called DREAM_DEEP_FIELD could be used to generate a deep co-add using DREAM data. The Recipe name comes from either the data header (as specified in the Observing Tool) or from the user of the Pipeline. ***Req. GR5***

A Recipe itself consists of building blocks known as *primitives*, where each Primitive refers to an astronomically meaningful step and, within reason, can be placed anywhere within a Recipe. An extremely simple Recipe may look something like this:

```
_IMAGING_HELLO_
_DISPLAY_FRAME_IMAGE_
```

which is the generic imaging QUICK_LOOK Recipe. Note that by convention Primitives are always in upper case and words in the name are separated by underscores. The ORAC-DR recipe parser requires that Primitives begin with an underscore to simplify the parsing (for more information on the details of ORAC-DR recipe formats see the ORAC-DR programmer's guide[17]). For more complex Recipe examples, Fig. 1 shows a Recipe for the current SCUBA system[11] and Fig. 2 shows a similar Recipe for UKIRT's UFTI.[3,28] From these examples we

Figure 1: The SCUBA JIGMAP_BRIGHT_POINT_SOURCE Recipe. Comments and documentation have been removed for clarity.

```
_PRE_PROCESS_
_FLAT_FIELD_
_SET_BAD_PIXELS_
_EXTINCTION_CORRECT_
_CLIP_BOLOMETERS_ NSIGMA=5.0
_REMOVE_SKY_NOISE_JIGGLE_ BOLOMETERS=r3 MODE=median
_SELF_CORRECT_POINTING_
_REBIN_FRAME_ PIXEL_SIZE=3.0 REBIN_METHOD=GAUSSIAN
_FIND_CALIBRATION_MAP_
_CALIBRATE_DATA_
_FIND_MAP_PEAK_
_REBIN_GROUP_ PIXEL_SIZE=1.0 REBIN_METHOD=LINEAR
_DELETE_TEMP_FILES_ KEEP=_reb,_ext,_sky,_cal
```

see that Recipes contain the outline of the reduction but do not contain any code indicating how the steps will actually be implemented in a real system. It is the Primitives themselves that contain the software code instructions on how the data should really be processed. In this way, the Primitives can be completely rewritten and replaced without affecting either the Recipes, the Pipeline infrastructure or other Primitives.

Figure 2: The generic infrared imaging BRIGHT_POINT_SOURCE Recipe. Comments and documentation have been removed for clarity.

```
_IMAGING_HELLO_
_BRIGHT_POINT_SOURCE_HELLO_
_SUBTRACT_DARK_
_DIVIDE_BY_FLAT_
_GENERATE_OFFSETS_JITTER_
_MAKE_MOSAIC_
_BRIGHT_POINT_SOURCE_TIDY_
```

3 Basic SCUBA-2 Recipes

Req. GR9
Req. MR1

This section describes the basic Data Reduction Recipes required to generate meaningful data for SCUBA-2. Section 4 describes the data analysis steps provided by the Pipeline after images are generated and Section 5 the Recipes optimized for specific science goals. Each use-case specified in the systems analysis[23,21,24] will be addressed in turn. The key constraint on the Recipes is that they cannot be so slow that the results are presented to the observer long after they would be useful for providing feedback to the observing process. This can be quantified by saying that an observation must be able to be reduced in less time than it took for the data to be taken by the instrument. In fact, for many cases this constraint is too loose, ***Req. PR5*** since there must be time available to mosaic and co-add the current observation to previous results. Some compromises may be required in the on-line variants of the Pipeline in order to keep up with observing.

In the following Recipes the _HELLO_ and _TIDY_ steps, which should be present at the start and end of each Recipe, are removed for clarity. The first Primitive, known as a _HELLO_ Primitive using the ORAC-DR naming convention, includes generic code that must be performed on all data from that instrument. The _TIDY_ Primitive cleans up temporary files after the frame has been processed.

The following Recipes describe the on-line implementations. In Off-line mode each Recipe will have an _OFFLINE variant and DREAM and STARE modes will start their processing from the raw 200 Hz frames. The current intention is that the code used by the DA system for real-time data processing (especially the DREAM algorithm and sky fitting for SCAN data) will be packaged up as DRAMA tasks suitable for calling from the Pipeline. ***Req. GR6***

3.1 Set-up Arrays and Flat-fielding

Req. PR3

Array set-up and flat-field observations will be made by the Data Acquisition system in engineering mode. The Pipeline will reduce the data (using Recipes supplied by the instrumentation group) and write the results in a format and location suitable for loading into the acquisition computer.

The details of this process will not be known until test arrays are available.

3.2 Start of night

When the instrument starts up the DA system slowly opens the dark shutter whilst reading out the array. These frames can be analysed by the Pipeline to verify that the instrument is working correctly (conceptually, the equivalent of the UKIRT ARRAY_TESTS).

Currently, we do not know exactly what analysis is required.

3.3 Skydip

Currently, we do not know exactly how a SCUBA-2 Skydip observation will be reduced, although it is clear that a raster skydip will not be possible. In simplest form the DA will write processed images containing the mean sky power for a fixed elevation and a routine will fit an atmospheric model to these images (probably based on the SURF[19] routine).

3.4 Dark frames

Dark frames can be taken as separate observations. These frames will be processed by the REDUCE_DARK Recipe. It is not yet clear what data processing will be performed to reduce the dark.

3.5 STARE mode

For STARE observations, the 200 Hz samples are despiked and co-added by the DA system. Simple dark and sky subtraction and flat-fielding will also be performed by the DA system. These images will all be in focal plane coordinates.

3.5.1 Sky removal

If the DA system only subtracts the array average as a simple sky removal technique, it may prove necessary to fit the sky emission with a tilted plane or a 2-d polynomial prior to resampling. Standard applications exist for this (e.g. The KAPPA surfit task) but for crowded fields it may be necessary to mask sources prior to fitting. Local averages, say of the nearest few hundred detectors, could also be used.[33]

Research into an optimal sky removal algorithm may be necessary.

3.5.2 Extinction Correction

The Pipeline can be configured to use either the opacity information stored in the file (the water vapor monitor, WVM[34]), the most recent skydip value or an external source such as the

CSO 225 GHz value. The default behaviour will be to use the WVM data scaled to an appropriate value for each filter[1] (the scaling factor won't be known accurately until commissioning is complete). After commissioning it may be possible to derive the extinction correction directly from the data (as is done for SHARC-II), but this is currently uncertain for SCUBA-2.

The images will be corrected by generating an image of the same dimensions as the STARE image but with values corresponding to the extinction correction ($\exp(A\tau)$, where A is the airmass of the pixel and τ is the zenith sky opacity for the filter in question). This can be achieved using standard array manipulation (including a rotation to define the elevation axis on the image) such as the KAPPA maths task.

3.5.3 Image resampling

Each image will be tagged with World Coordinate System information (WCS)[10,32,31] such that standard tools can be used for resampling the images from Nasmyth coordinates to an RA/Dec frame. The tools for doing this will be identical to those described for the Quick Look system.[14] Correction for pointing errors due to seeing or telescope errors can be corrected if bright sources appear in the frame with sufficient signal-to-noise.

3.6 DREAM mode

The DA system generates processed images and zero-points separately for each sub-array. For basic processing[21] all that is required is the extinction correction and image resampling. These steps will be identical to those described for STARE mode in §3.5.

Off-line, the Recipe will make use of all four sub-arrays to calculate the DREAM solution. This should lead to improved results at the joins between the sub-arrays and enhanced despiking techniques.

3.7 Pointing

The DR Pipeline is not responsible for ensuring that the pointing offset is fed back to the observing system. That is the responsibility of the JCMT Pointing and Focus Task[27] ***Req. PR1***

Pointing observations will be done in STARE or DREAM mode (although some initial testing should be done to ensure there is no offset compared with SCAN mode data) and will be processed by the Pipeline accordingly. The main difference is that all mosaicking and stacking will be performed in the AZEL offset coordinate frame (this will be one of the standard framesets[25] and is selected using the KAPPA wcsframe task). The centroid position (calculated using the KAPPA centroid task) will then be suitable even after multiple frames are combined.

The flux of the pointing source is also calculated in order to help with calibration and if the pointing source is known to be a primary or secondary calibrator a flux conversion factor (FCF) is also calculated.

Pointing offsets, integrated fluxes, FCFs (integrated in an aperture and also derived from the peak) and beam sizes will be logged by the Pipeline for easy monitoring by the stripchart system.[14]

3.8 X-, Y-, and Z-Focus

The DR Pipeline is not responsible for ensuring that the focus offset is fed back to the observing system. That is the responsibility of the JCMT Pointing and Focus Task[27] ***Req. PR1***

A reduced image is generated (either using STARE or DREAM mode) for differing positions of the secondary mirror on a bright point source. The relative intensity of the point source is monitored and a parabolic fit is made to the data to find the optimal setting for the secondary mirror. The images will only need to be resampled into RA/Dec if multiple DREAM reconstructions are required to build up signal-to-noise on weak sources.

If STARE mode works reliably for bright sources, it may be possible to focus by moving the secondary mirror rapidly during a single STARE observation. If that method is adopted then the Recipes will be modified to process each image (possibly including binning) in turn (the DA system may need to generate reduced images itself for use by the JCMT focus task,[27] in which case the Pipeline would simply use these processed images).

3.9 SCAN mode

In SCAN map mode the array is scanned across the sky whilst the bolometers are read out. The baseline reduction would be implemented as described in SC2/ANA/S100/038,[22] essentially identical to that required by the Quick Look system.[14] The sky is subtracted using the polynomial coefficients generated by the DA system and then the individual samples are regridded into a single RA/Dec output frame after correcting for atmospheric extinction.

At this time, it is not clear that this approach will be good enough for a science grade pipeline and investigations are ongoing.[29] The reduction technique will likely be independent of any particular scanning strategy.[30]

Matrix inversion techniques[20,26,2,33] are not currently suitable for the on-line Pipeline due to the substantial processing requirements, although these techniques may be available in the Off-line variant.

There will be a few different SCAN Recipes, for bright sources, extended sources, different resolutions, edge clipping, etc. Each Recipe will consist of many Primitives and some parameters which are set by invoking the individual Recipe.

3.10 FTS and Polarimetry Data Processing

Req. XR1

Both the SCUBA-2 Fourier transform spectrometer (FTS)[9,8] and SCUBA-2 polarimeter data processing strategies are discussed elsewhere.[7,16]

3.11 End of Night

At the end of the night, the instrument is shut down in an orderly manner whilst taking diagnostic frames. The Pipeline will use these frames to verify that the instrument is working properly.

We do not yet know what processing will be required for end of night data.

4 Data Analysis

This section describes additional Recipe functionality that is required in order to extract the maximum useful science from the data above and beyond the minimum functionality described above.

A science-grade Data Reduction Pipeline is expected to do more than simply generate an image from an observation. For optimum use of flexible scheduling the on-line Pipeline needs to provide images with minimal reduction artefacts as well as data analysis functionality. In Off-line mode the requirements are even more stringent, with a less restrictive time constraint allowing more advanced algorithms to be used in addition to the ability to use calibration information that was acquired after the particular observations were reduced.

4.1 Calibration

Req. PR6

Flux calibration will be similar to the current SCUBA scheme with a few enhancements (some of which could be back-ported to the SCUBA Pipeline[18]) and the following discussion assumes that the data are extinction corrected in some manner (whether from a WVM, skydip or external opacity monitors – the choice of opacity information is configurable by the Pipeline user).

Conceptually, flux calibration is simple: perform observations of a source of a known flux density, measure the flux conversion factor (FCF; to convert Volts to Janskys) and then apply this value to the science data. The complications are usually related to the shape of the primary mirror rather than inherent instabilities in the instrument itself. It is critical that the telescope is kept in focus and that temperature fluctuations are minimized (a problem if the Sun is inadvertently shining on the dish). Since, in general, the FCF will vary through an observing shift, the Pipeline must make use of all available data for tracking these variations. The current SCUBA pipeline calculates FCFs for all primary (planets) and secondary (e.g. CRL 2688, CRL 618) calibrators, but does not by default use them for calibration, since there can be large variations in FCF and it is not always clear that they should be relied upon. Instead, the SCUBA pipeline uses average values for the FCFs, derived using many calibration observations taken on previous nights, a procedure which is known to be accurate to approximately 8% at 850 μm and 20% at 450 μm.[12] The values are checked on a monthly basis, since in some cases changes in FCFs have been linked to cool-downs or cryogenic problems.

The SCUBA-2 Pipeline may still use global averages but will make use of additional information to track the FCF: ***Req. GR12***

1. Repeated observations of a pointing source can be used to measure drifts in the FCF, although care must be taken when using pointing observations that were taken prior to a large focus shift (this can only be verified off-line).
2. Observations in DREAM/STARE mode will be appearing every 1 to 2 seconds. Bright point sources visible in these frames can be used to correct for internal drifts (D.C. offsets or scale factors) during a single observation. This is essentially identical to combining infra-red mosaics (see e.g. CCDPACK[4]) and existing source extraction tools and/or

mosaicking packages may be suitable so long as they can be configured to search solely for point sources.

With these corrections, it should be possible to meet, and possibly exceed, the calibration requirement of 5% at 850 μm and 10% at 450 μm. ***Req. GR11***

Req. GR19

The ORAC-DR calibration system itself is extremely configurable and it will be possible, from the command line, to adjust how the Pipeline determines calibration values. ***Req. GR13***

4.2 Mosaicking and 'Group' co-adding

All except the shortest observations will require some form of co-adding and mosaicking. Additionally, separate but related observations will be combined into groups in order to create large area mosaics (within reason) and improve signal-to-noise in images covering small regions. The Pipeline will determine which observations to treat as a single group by using two techniques:

1. Specify observation grouping in the Observing Tool (this will require some modifications to the OT and will probably be restricted to those observations within a single minimum schedulable block). The translator will then store the group name in the **DRGROUP** FITS header. The Pipeline will combine all observations which share this header and display them. ***Req. DR4***
2. Automatically determine grouping from the FITS headers themselves (e.g. looking at the project ID and the source name).

Both techniques are used by the current SCUBA pipeline, although the latter is by far the most common technique (and is the only option for the current OT, but was available through the old SCUBA ODF system). For SCUBA-2 every science observation (DREAM, STARE and SCAN) generates images that can be combined, so there is no reason for these modes to be treated separately once the observations have been reduced to calibrated images. In that case, automatic determination of groups is simply a question of whether the observations are of the same region of sky rather than being concerned with observation mode and chop throw.

Wherever possible, bright point sources will be used to determine pointing corrections between observations prior to co-adding. Application of pointing corrections derived from pointing observations will not be possible on-line since in many cases a pointing observation is taken immediately after a science observation that needs to be corrected. ***Req. PR17***

All co-added images will come with variance data and the estimated 'average' noise across the map will be recorded, such that a plot of noise against integration time can be presented as more data arrive. ***Req. DR10***

In addition, related pointing observations will be combined throughout the night to generate high quality beam maps, although care must be taken over pointings observed prior to a large focus shift. ***Req. PR18***

4.3 Image analysis

As the data are acquired, for optimal flexible observing, the Pipeline should report the current noise in the data and also the signal-to-noise for all detected sources. The noise can be derived from the data (if blank areas are visible) and from the variance array. As each frame is processed the current noise should be made available and, as data are co-added (especially in DREAM/STARE observations), the noise should be plotted as a function of integration time so that the observer can see that the instrument is behaving as expected. Signal-to-noise determination of observations and group co-adds will require point source extraction and photometry.

The on-line Pipeline will not attempt to perform source extraction for extended sources. That is an Off-line or science archive function, and will require some algorithm research.

5 Specialist Recipes

Req. PR4

For some observations, the project investigators know approximately what type of data they expect and may want to use Data Reduction Recipes that are optimized for their particular scientific goals. It is definitely the case with SCUBA that the reduction Recipes (especially despiking, sky removal and noise determination) can be optimized depending on whether the field is known to include a bright point source or no sources at all (for a single observation). The larger field-of-view, smaller integration times and higher sensitivity may make this less of an issue for SCUBA-2; simulation data will allow us to get a better feel for the optimizations that can be applied during the reduction process. As an example, it may be that 450-μm deep field imaging observations could use more aggressive de-spiking and sky-removal algorithms than would be possible for a generic reduction Recipe. It also seems likely that there will be some choice of DR Recipes for reducing SCAN data, as described in SC@/ANA/S210/006.[29]

Observations of bright point sources may also allow optimizations, although the larger field-of-view of a single sub-array compared to SCUBA may make it possible to detect them automatically and react accordingly. If a bright point source is detected after simplistic processing, it may be possible to redo the reduction with the source masked out of the time stream. A Recipe that indicated that there would be a bright point source in the centre of a single sub-array would allow the optimization to happen without the second iteration. Pointing observations will clearly fall in this category.

6 The Off-line Pipeline

The on-line Pipeline is limited for a number of reasons:

1. It cannot use all calibration observations from the night, only those that have been taken earlier.
2. It has a time constraint such that it must keep up with observing and provide information required for making observing decisions.
3. Data from different nights cannot be combined.

4. There is no observer intervention, so unexpected effects in the data cannot be corrected for in real time.

The Off-line version of the Pipeline does not have these constraints. It will be possible to configure the Pipeline such that all calibration observations are reduced prior to reducing the science data. This will provide a much better view of the calibration stability of the night and allow decisions to be made regarding use of pointing observations to correct the pointing and flux errors and checks on whether a focus shift was large enough such that a FCF determination cannot be carried across the focus boundary. ***Req. OR4***

Additionally, there will be Off-line variants of all the key Recipes which will allow a more complete reduction of the data, involving the raw 200 Hz data rather than the DA-reduced images , but using individual Primitives developed for the DA system. In particular, a nearly lossless SCAN map reduction algorithm will be implemented and usable off-line, although care must be taken that there is an improved SCAN map reduction algorithm available which still enables a night of SCAN map data to be reduced in 24 hours. This is important if the JAC or an archive centre are trying to reduce data 'optimally' without falling behind the data acquisition (although, of course, not all nights will result in SCAN map data). ***Req. OR1*** ***Req. OR2*** ***Req. MR2*** ***Req. GR5*** ***Req. MR7*** ***Req. OR3***

The Off-line mosaicking software must be able to generate large mosaics of up to $20° \times 20°$, although the largest mosaics from surveys are the responsibility of the Science Archive (assuming one exists) and are not covered by this work package. ***Req. OR6***

7 Data Quality Parameters

As the Pipeline runs it will be calculating parameters that can be used to determine whether the Pipeline and/or the instrument are working to specification. These parameters will be written to log files and also calibration index files, suitable for use subsequently by the Pipeline and also for display in the stripchart system.[6] Each parameter will have a pre-defined acceptable range; if a parameter goes out of range the Pipeline will provide a warning message to the observer indicating a possible problem. ***Req. PR12***

The following data quality parameters will be calculated by the Pipeline:

Flux conversion factor

The flux conversion factor (FCF) will be calculated whenever a planet or secondary calibrator is observed. It will be calculated in both Jy/beam and in Jy/arcsec^2 (for a pre-defined aperture size or sizes[12]).

Beam size FWHM ***Req. PR18***

Whenever observations of known point sources (e.g. blazars from pointing observations) or sources of a known size (e.g. planets) are made, the beam size will be fitted (e.g. with the KAPPA psf task) and the results logged.

Error beam contribution

When the beam size is calculated, the Pipeline will also calculate the contribution from the error beam. This may be able to indicate to the observer when a focus observation is required.

NEFD

The NEFD (Noise Equivalent Flux Density) can be calculated for long exposures simply by knowing the effective integration time and the current noise. In addition to calculating a simple NEFD, it would be helpful to show the observer graphically how the noise in their data is decreasing as their observation progresses, including the NEFD predicted future performance. This plot will be generated by a Recipe and not be part of the stripchart function.

Bolometer noise statistics

The noise performance of the array can be calculated from the raw data frames (although this implies that the Pipeline will be accessing the raw data frames for DREAM/STARE which it is not designed to do in on-line mode; calculating these statistics will need some thought).

Sky Background

The DC sky background will be calculated for each frame. This will allow the observer to see how sky-noise is changing during observing.

At the end of the night, calibration plots for the entire night should be generated and made available as part of the OMP[5] nightly report system.

The format of these logging files is discussed in SC2/SOF/IC210/02.[15]

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A Primitive Descriptions

The following section documents some of the Primitives that are available from the SCUBA-2 Pipeline. This is not a complete list, and in particular Primitives for reducing SCAN mode data are still being investigated.

_ALIGN_ARRAYS_

This Primitive takes all the sub-scan frames from each sub-array and regrids them to a reference RA/Dec frame.

If a group file exists, that is the reference, else the first frame is chosen as reference.

_CENTROID_FRAME_

Find the centroid(s) of the current frame(s). Assumes that the centroid is near the origin in axis coordinates.

Assumes that the peak value in the map is the value of the pixel at the centroid position. This is not necessarily true though if the centroid position contains a spike.

_EXTINCTION_CORRECT_FRAME_

This Primitive corrects each frame for extinction. It can be run on a single mosaicked frame or with aligned subarray frames.

The `EXTCOR_MODE` parameter determines which extinction correction is applied. If set to QUICK then the image is corrected assuming a single value for the airmass across the array.

If set to FULL, then an accurate pixel-level correction is applied taking into account the airmass of individual pixels.

_FIND_BEAM_SIZE_

This Primitive carries out a fit to a calibrator using the KAPPA psf command to determine the beam size and position angle. An error is generated if the source is not a calibrator. The reported values are the full-width-at-half-maximum (FWHM) along the major and minor axes, and the beam position angle on the sky at the time of observation. The fit is performed in the sky domain so the FWHM is returned in arcsec.

By default, PSF does not assume that the beam is a Gaussian, but a flag may be specified to force the return of the equivalent best-fit Gaussian beam parameters.

_FIND_BRIGHTEST_SOURCE_

Find the position of the brightest source in the current frame. Makes no assumption that the centroid is near the origin in axis coordinates.

Assumes that the peak value in the map is the value of the pixel at the centroid position. This is not necessarily true though if the centroid position contains a spike.

This Primitive is designed to work on a single image and will fail if the current Frame object contains more than one file.

_FIND_INTEGRATED_INTENSITY_

This Primitive calculates the integrated intensity, in whatever units the map is currently using, around a single point source that is assumed to be in the centre of the image (using AXIS coordinates) and to be the only source on the map (so that the sky contribution can be calculated). The value is corrected for pixel area.

_FIND_SOURCES_

For the specified file, find all the sources and calculate the peak flux of each detected source. The results are written to a catalogue file.

_FIND_TOTAL_FLUX_

Finds the total flux of a source either by fitting or aperture photometry.

The total flux can be determined by fitting a Sersic profile to the source and integrating underneath that profile using a standard integral solution. If the fit is poor (defined by the axis ratio falling outside a pre-defined range) then the default aperture photometry method is used instead.

_GET_PIXEL_SCALE_

Determines the pixel scale for a given image by examining the information in the WCS extension. The calculation is carried out by defining three PIXEL positions in the image, converting these into positions in the desired output frame (e.g. SKY) and then using astDistance to compute the distance in radians between the positions in the x- and y-directions respectively.

Returns an error if desired frame is not in the frameset; currently this means that if there is no SKY frame the Primitive aborts.

_MAKE_MOSAIC_FRAME_

This Primitive takes all the aligned sub-frames and mosaics them into a single output image. A check is made to see if the number of files to mosaic is greater than the maximum allowed (a value which depends on the version of CCDPACK installed), and if so the process is divided into several steps to generate intermediate mosaicked files which are then mosaicked at the end.

_MAKE_MOSAIC_GROUP_

This Primitive takes all the aligned sub-scan frames from each sub-array or aligned frame mosaics and mosaics them into a single coadded output group image.

Does not require the use of _MAKE_MOSAIC_FRAME_. This Primitive supports the -batch command line option.

_MAKE_MOSAIC_SUBARRAY_

This Primitive takes the aligned sub-scan frames from each sub-array and mosaics them into a single output image. Its use is optional but it helps speed up _MAKE_MOSAIC_FRAME_ by reducing the number of intercomparisons.

_REMOVE_PLANE_FROM_IMAGE_

This Primitive fits a 2-D plane to an image.