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Reference documents

Reference	Document title	Document number	Issue	Date
SC	SCUBA-2 Science Case	SC2/SCI/01	1.2	5/5/01
FPRD	Functional and performance requirements	SC2/SRE/SC200/02	1.5	6/10/02
OCDD	Operational Concepts Definition document	SC2/SRE/SC200/03	1.1	6/10/02
BDK	Modelling the Sub-mm Atmospheric Emission	SC2/ANA/S100/13	1.1	1/11/01
Xtalk	Crosstalk levels for SCUBA-2	SC2/ANA/S100/21	1.3	26/7/01
BDK14	Array control procedures	SC2/ANA/S100/31	1.1	14/1/02
BDK18	SCUBA-2 scan-map simulation	SC2/ANA/S100/38	1.0	2/4/02
BDK23	The SCUBA-2 flat-field problem	SC2/ANA/S100/43	1.0	3/10/02

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Science Requirements for SCUBA-2

This document describes the science requirement input, needed to develop a preliminary set of observing modes and algorithms for SCUBA-2.

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1. Introduction: Science Drivers

This document describes the science requirement input, needed to develop a preliminary set of observing modes and algorithms for SCUBA-2. Areas to be addressed include optimum mapping strategies with SCUBA-2, point-source flux extraction, techniques such as dithering, flat-fielding, calibration methods, dark frames and sky and refraction noise compensation and novel observing modes such as polarimetry and medium resolution spectroscopy. Consideration is given to the science drivers in terms of observational limits (integration times and map sizes) and the type of observations astronomers are likely to want to take. Comparisons are made throughout the document with SCUBA.

The scientific aims of SCUBA-2 camera seek to capitalize on the successes of SCUBA by extending capabilities to large-scale projects covering many tens of degrees of sky, as well as deep and high fidelity imaging of selected areas. New kinds of targets and surveys that are currently unfeasible with SCUBA will become possible with the introduction of SCUBA-2. In summary, the main science drivers for SCUBA-2 are:

- *Maximise the survey potential*. Even though SCUBA has been a big step forward in terms of mapping large areas of sky, only an area about the size of a full moon has been mapped to any great depth (near the confusion limit). SCUBA-2 aims to map large areas of sky at least several hundred times faster than SCUBA to the same signal-to-noise.

- *Deep imaging*. This is very time consuming with SCUBA – relying on co-adding lots of frames of data over periods of many hours (especially difficult at 450μm, where it is rare to have extended periods of good, stable weather). SCUBA-2 aims to reach the extragalactic confusion limit at 850μm in around 1-2 hr, instead of ~50 hrs at the present time.

- *Improved image fidelity and map dynamic range*. SCUBA requires a minimum of 128 seconds to produce a fully-sampled map at both 450 and 850μm. In addition, because SCUBA can only record an AC signal (i.e. chopped signal) we are constantly subtracting two images of the sky. SCUBA-2 will aim to improve data quality by instantaneously sampling the sky, and operate in a mode that avoids the necessity to sky chop.

- *Imaging at two colours simultaneously*. Dual waveband imaging allows us to exploit both ends of the submillimetre spectrum, utilizing periods of good weather to exploit the higher angular resolution available at shorter wavelengths. SCUBA-2 aims to continue in this mode first demonstrated by SCUBA.

- *Act as a "pathfinder" for submm interferometers*. By coming on-line in 2006 SCUBA-2 should have at least a few years of observations before ALMA begins full operation. Wide-field surveys will be crucial to fully-exploit the capabilities of the new generation interferometers.

The instrument challenge is therefore to take these science drivers and incorporate new developments in detector technology to design the first "Submillimetre CCD Camera"! To achieve the science goals requires:

- Per-pixel sensitivities to be dominated by the sky background photon noise (fundamental limitation). This requires improvements of a factor of three over the current SCUBA detectors.

- The maximum (undistorted) field-of-view allowed by the telescope. This turns out to be 64 sq-arcminutes (c.f. to only 4.3 sq-arcmins for SCUBA) – a factor of 16 times larger field.

- Fully sampled imaged planes and DC-coupled electronics (no sky chopping) to improve image fidelity and map dynamic range, requiring 25,600 and 6,400 pixels at 450 and 850μm, and stable electronics at low frequencies.

- A dichroic beamsplitter to split the short wave and long-wave channels onto two separate arrays. Thus, simultaneous observing will be available at two colors.

2. Observational limits

For a perfect optical system the observational limits arise from (primarily) five noise sources: detector noise (including the read-out electronics), background photon noise (from the sky, telescope and instrument), sky emission fluctuations (“sky-noise”), refraction noise (“seeing”) and confusion noise. Ideally, the overall sensitivity should be limited by the background photon noise (see Figure 1), but for SCUBA-2 operating at 850μm the limit will ultimately come from background confusion noise. This then dicates how long integration times are likely to be and the final S/N obtainable.

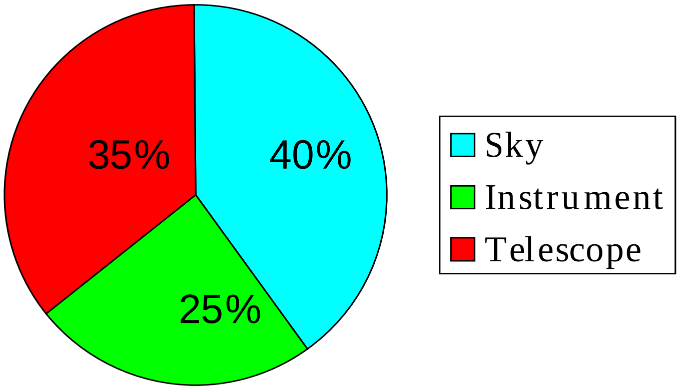

Figure 1: The estimated fraction of background power at 850μm under good sky conditions (the lowest sky background case) falling on a SCUBA-2 detector from the sky, telescope and instrument.

2.1 Confusion noise for deep surveys

The ultimate limit to how long an ideal instrument can integrate for is set by the background confusion noise. This depends on source density, telescope aperture and wavelength of observation. Once the confusion limit is reached S/N cannot be improved by increasing the integration time. Confusion noise levels depend on where you observe – in the Galactic Plane the levels can be as high as 0.1 Jy at short submillimetre wavelengths, whereas the extragalactic background (away from the plane) sets a more stringent limit and is more like a few mJy at 850μm.

The exact definition of confusion has always been subject of intense debate. In general, the definition most astronomers favour is that images become confused when you have about 1 source per 25 beams. This makes sense if you imagine that a source sitting at the centre of a 5 × 5 grid means that the next source is only 5 beams away assuming everything is perfectly spaced out like a grid. Certainly, once a limit of one source per 9 beams is reached, it is clear that evenly distributed sources will often have less than a beam gap between them. For some astronomers the 25-beam definition is rather conservative, but the precise choice depends on what fraction of your sources you care about being confused. If there is clustering present then confusion becomes an issue at even brighter levels.

For "blank-field" surveys in the submm there are very few examples of "confusion-limited" maps. A practical example is the SCUBA 850μm image of the Hubble Deep Field. At a flux limit of 2 mJy in the HDF there is 1 source per 30 beams (Hughes et al. 1998). So given the above definitions it is clear that 2 mJy is a realistic limit, and even at this level it is suspected from simulations of the data, that at least one HDF source is actually confused (i.e. a blend of two fainter sources). It should also be noted that sky chopping (for SCUBA) increases the confusion limit by about 25%. Hence, it is expected that SCUBA-2 will be able integrate for 1.6 times longer with SCUBA (i.e. the confusion limit is actually lower).

What does this mean in terms of integration time? The current models for projected SCUBA-2 performance (using per pixel NEFDs in "good" weather) suggest that SCUBA-2 images will be confusion-noise limited for an extragalactic background (time to reach 5-σ limit) in about 2.4 hr at 850μm and 78 hrs at 450μm.

Wavelength (μm)	NEFP per pixel (mJy/√Hz)	1-σ confusion limit (mJy)	Confusion map time (hrs)
450	90	0.17	78
850	30	0.32	2.4

Table 1: Estimated confusion limits and confusion map times for SCUBA-2

For galactic plane and star formation regions the confusion limits are much higher (typically as high as 0.1 Jy in some regions of the Galactic plane). An interesting exception to the discussion about confusion noise might be for sources that move on the sky – such as planets, asteroids, comets and Kuiper Belt objects, or others that are highly variable on short timescales.

3. SCUBA-2 observations

What kinds of observations do we want to take with SCUBA-2 take? The answer in a nutshell is deep images and large-scale maps at two simultaneous wavelengths.

3.1 Deep imaging

The minimum size of a SCUBA-2 image will be equivalent to the field-of-view on the sky (64 arcmin^2). Table 2 summarises the 1-σ noise level that should be attainable for integration times of between 1 and 50 hrs. Observing overheads are not included.

Wavelength (μm)	NEFD per pixel (mJy/√Hz)	Confusion Limit (mJy)	1σ, 1hr (mJy)	1σ, 5hr (mJy)	1σ, 10hr (mJy)	1σ, 50hr (mJy)
450	90	0.17	1.5	0.67	0.47	0.21
850	30	0.32	0.5	0.22	0.16	0.07

Table 2: Observational limits for deep imaging of a single field

3.2 Large-scale surveys

The second kind of observation that astronomers are likely to want to take is large-area surveys, of perhaps, many tens of degrees of sky. Figure 2 gives some examples of the surveys that could be undertaken with SCUBA-2 at 850μm (again telescope and other overheads ignored).

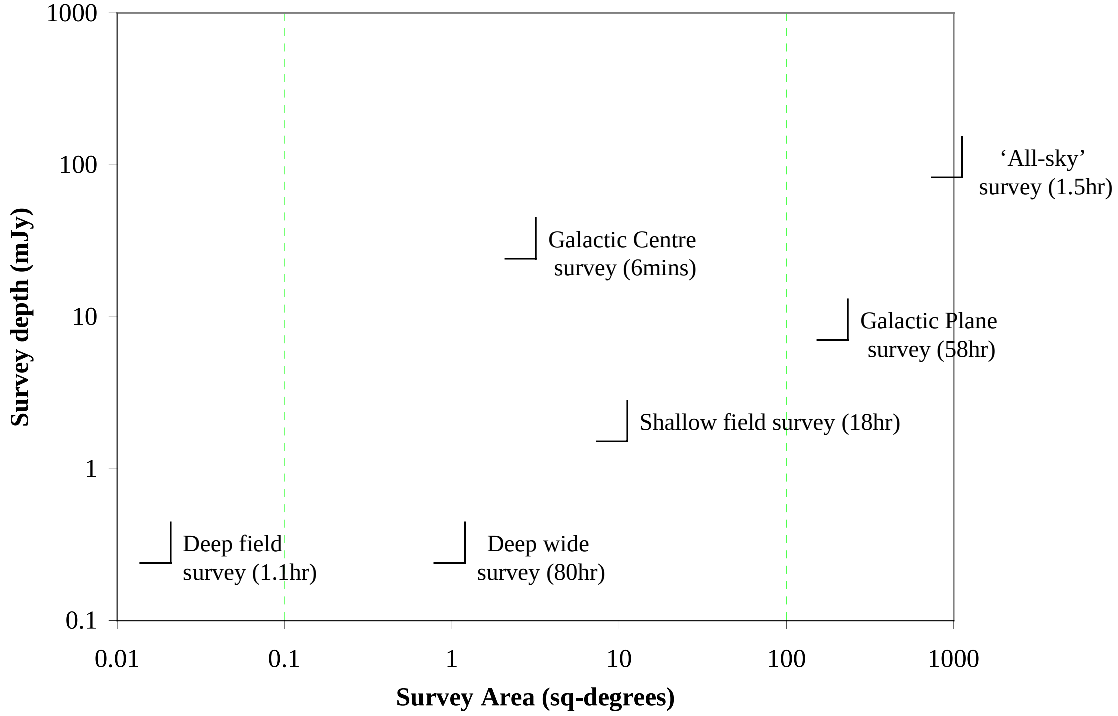

Figure 2: Examples of possible SCUBA-2 surveys at 850μm

3.3 Some practical examples

Consider a number of examples of typical observations from the Science Case.

- Large, face-on or edge-on galaxies. Grand spiral galaxies like M51 or edge-on galaxies such as NGC891 are well-matched to the SCUBA-2 field-of-view of 8 × 8 arcmins, and indeed the study of how the dust emission varies as a function of galacto-centric distance is one of the key science themes for SCUBA-2. This also applies to, for example, nearby supernova remnants, and to a certain extent high latitude clouds.

- Deep field survey. Deep field (extragalactic) surveys are also a key science area, not simply for source counts as a function of luminosity class and redshift but to investigate clustering on large size scales. Simulations by the Durham group suggest an 8 × 8 arcmin field is again well-matched to the size scales, so again for this kind of work a stare or dither map would be appropriate (i.e. deep images are needed, but not necessarily down to the confusion limit).

- Large-scale galactic mapping. These maps would be typically as large as practical. The scientific goals are expected to vary considerably. Shallow surveys will concentrate on large-scale structure e.g. giant molecular clouds and supernova remnants, whilst deeper surveys will investigate phenomena such as pre-stellar and sub-stellar cores and the nature of the Initial Mass Function at the low mass end. For *shallow surveys* the key is speed. Scanning at 600 arcsecs/sec (likely to be the fastest allowed by the detector time constant and the telescope) will give about 1 sec integration time per Nyquist-sampled point in the final map. In good weather this would correspond to an rms noise level of about 30 mJy at 850μm. This is coincidently about the same noise level achieved in the SCUBA Galactic Centre survey. Ignoring telescope overheads SCUBA-2 could map the same area in about 75 secs!

Protoplanetary/debris dust disks. SCUBA-2 could well target a statistically significant sample of protoplanetary dust disks. There are at least a few dozen that could be observed with SCUBA-2 as opposed to the handful with SCUBA. The key here is sensitivity and accurate astrometry rather than mapping speed. Most disks are only some 40-60 arcsecs in diameter. Going deep at 450μm, using the 7.5 arcsec resolution to identify low-level features (such as clumps and warps) is a key goal. High fidelity images and good dynamic range in the maps are a must.

The table and accompanying notes in Appendix 1 expands upon these examples, and describes some of the key factors for different types of observations.

4. Technical challenges

The technical challenges associated with taking SCUBA-2 observations will be mostly similar to SCUBA. Sky rotation because of alt-az telescope and the Nasymth platform location for instrument are two obvious ones. The limitations to achievable sensitivity have already been discussed and arise from are photon noise from background, sky-noise, refraction noise, detector noise (including electronics), and confusion noise. Limitations to image fidelity are expected to include how well we can mosaic maps together (producing "seamless" images).

It is important to remember that SCUBA-2 will operate in a fundamentally different way to SCUBA. SCUBA-2 is likely to have a significant advantage over the current SCUBA in that the detectors are DC rather than AC coupled. The current system requires dual beam chopping which removes the sky and the DC level in the map and has zeroes in the response in the spatial frequency domain. This means that map reconstruction has the potential to introduce artefacts into the data. This can significantly compromise performance, particularly with sources near the confusion limit.

However, as in the case of SCUBA, the single most important factor, which will govern the quality of data, is the atmosphere. The sky is not stable due to the dominance of water vapour in determining the atmospheric transmission. Furthermore, the fact that water is poorly mixed in the atmosphere means that water concentrations vary both temporally and spatially generating "sky noise" and "seeing" effects. This means that we have to find ways of dealing with problems due to variations in atmospheric transmission, sky-noise and refraction ("seeing") effects.

In summary, the SCUBA-2 observing strategies have to cope with:

- bad pixels or columns of pixels
- the one pixel gap between the 4 sub-arrays
- field distortion (although this is predicted to be much lower than SCUBA)
- field rotation (Alt/Az telescope with no field rotator)
- 1/f noise in detectors and electronics
- obtaining highly accurate and stable flat fields (due to high background power per pixel)

For large-scale surveys, it is a question as to how long can the telescope scan before it is necessary to do something else. With SCUBA this limitation is the transputer buffer size which only allows about 51 secs to be acquired per scan. SCUBA-2 scans are likely to be at least a few minutes (maybe not near zenith) without any corrections being necessary. This depends to a certain extent on which real-time corrections will be possible - i.e. if we can recover atmospheric attentuation, sky-noise and (maybe) refraction corrections in real time, the main limit may be the stability or linearity of the array (i.e. a dark frame observation may be needed at frequent intervals). A two-minute scan, at 600 arcsecs/sec, would image an area of some 20 degrees - perfect for the Galactic Plane. For surveys there is the question of how fast the telescope has to move at high elevations to maintain a scan speed of 600 arcsec/sec.

Requirements connected with image registration are also expected to appear. Registration is concerned with reconstructing maps on a suitable coordinate system (eg. RA,Dec). It implies consideration of the accuracy of positions of objects, and the final resolution obtained in the reconstructed maps. The aim is expected to be to achieve as near to limits set by the telescope as possible.

5. Preliminary types of observation

Having defined the observations we would ideally like SCUBA-2 to take, and also being aware of some of the technical challenges for the telescope, instrument, and observing software, it is now possibleto consider the basic modes of operation. Table 3 presents a comparison between SCUBA and SCUBA-2 for basic modes of operation.

	SCUBA (2Fλ-spaced feedhorns)	SCUBA-2 (0.5Fλ and Fλ bare pixels)
Pixels bigger than 0.5Fλ	Jiggling with the SMU; scanning in Nasymth coordinates	Same as SCUBA since Fλ pixels at 450μm, although, in principle, fewer steps should be needed
Small source maps (≤ array size)	Jiggle-map (with chopping and nodding)	Stare, or dither/micro-step map (stare with SMU offsets)
Large area (~few array sizes)	Mosaic individual maps together	Dither with large (several arcmins) telescope offsets
Very large areas (>>array size)	Scan-map using EM-II method and remove baseline; repeat scan, chopping in several directions to reduce systematic errors	Scan-map and fit and remove baseline

Table 3: Comparison between SCUBA and SCUBA-2 for basic modes of operation.

5.1 STARE map

STARE mapping is basically just a "point-and-shoot" mode, in which SCUBA-2 will "stare" at an 8 × 8 arcmin area of sky for a specified period of time. For a background photon-noise limited system the rms noise in the map should integrate down with the square-root of the integration time.

5.1.1 Scientific considerations

In this mode the map size is fixed to be the field-of-view on the sky. This may be most useful for quick observations like pointing and focussing, and also observations of compact calibrators (such as planets). If there are noisy pixels near the area of the array that is chosen to image the source, then some kind of micro-stepping or dither (see next section) will be needed.

5.1.2 Practical considerations

If there is significant 1/f noise then a dark frame measurement will be needed to allow a subtraction. This depends on the level of 1/f noise and the brightness of the calibrator. Based on the latest noise spectra from NIST, when biased near the top of the transition (worst case) the NEP is about 5×10^{-17} W/√Hz (close to DC) compared to about 7×10^{-17} W/√Hz for the lowest background 850μm photon noise. Hence for bright sources this level of 1/f would have a negligible effect (if this level of 1/f was the norm). The accuracy and stability of the flat-field is also an issue (see SC2/ANA/S100/43).

5.2 Dither (micro-stepped) maps

The STARE map mode will most likely not be the best approach for anything other than quick observations such as pointing or bright calibrators. More likely we will require a dither pattern to compensate for noisy pixels, and as for SCUBA, any low-level systematics (however unlikely e.g. flat-field inaccuracies etc) could be minimised (i.e. very low level structure that could appear real might be a systematic of the system etc.). There are various dithering schemes that could be adopted. Each provides a system of equations that can be inverted to recover sky brightness, DC offset and detector gain.

5.2.1 Scientific considerations

Although the main reason for the dither is to compensate for noisy pixels and (perhaps) non-linearities, this mode also has the potential to provide a bigger field-of-view. There will no doubt be calls for a small-step dither (e.g. for deep observations of compact objects - smaller than the 8×8 field) and a large-step dither (for sources that might have an angular scale a bit bigger then the field-of-view).

5.2.2 Technical considerations

The micro-step should be done by the SMU (ideally) which is much quicker than moving the telescope. Size of dither step will be dependent on edge-of-field aberrations induced by tilting the secondary mirror. For TES detectors it is expected that the gain can be controlled very well. The offset is expected to vary on a timescale of around 1 second (i.e. this is the 1/f knee). Potential serious concerns for deep maps may be the stability of the flat-field (i.e. linearity across the array due to things like detector gain etc).

5.3 Mosaicing stare or dither maps

In this approach, the observer takes individual frames and mosaics them together like with an optical CCD camera or IR array. SCUBA has also frequently been used in this mode – i.e. coadding, spatially-offset jiggle maps (e.g. of edge-on galaxies or star formation ridges).

5.3.1 Scientific considerations

The main scientific driver for this mode might be to follow a previously unknown extension of dust emission (e.g. an edge-on galaxy, or a ridge of sequential star formation). However, unless scan-mapping is, for whatever reason, inefficient for mapping regions like these, which may extend only a few field-of-views, then it is not clear whether we would want to mosaic individual STARE frames.

5.3.2 Technical considerations

The challenge here is determining the background and being able to coadd the data exposures together so that "seams" are not apparent in the final maps. SCUBA-2 could integrate for up to a few hours (to the 850μm confusion limit) on an individual field, so exposures have to be individually τ-corrected and noise weighted in the final coadd.

5.4 Slow scan mode

There is likely there will be a subtle trade-off between scanning slowly (say, at a similar similar to SCUBA i.e. 24 arcsecs/sec) or scanning very quickly (say, 600 arcsecs/sec, or up to the limit that the detector time constant will allow). The trade-off is whether the scan should be fast to cover a region a multiple number of times, or the scan be slow to spend more time per spatial point on the sky. It is possible that the lab commissioning may be able to address this issue, although it might be something that ultimately is opytimised at the telescope. There may also be issues associated in how the background is subtracted in the most optimum way.

5.4.1 Scientific considerations

This may be a mode that is appropriate to "medium-scale" mapping - say, an area of 2–3 degrees. This may include, for example, some giant molecular clouds. The key requirement here is to go deep - i.e. close to the confusion limit to study say, the low-mass end of the IMF. Registration and astrometry are also important here since it may degrade linearly in scanning very quickly. If so, this may be a advantage of a slow-scan mode.

5.4.2 Technical considerations

The undersampled 450μm array means that scanning becomes more complex. The ideal situation would be to scan along a line of azimuth (i.e. through the same airmass) to make atmospheric attenuation corrections simpler (and, in principle, more accurate). This may be a decision the observer needs to make depending on the importance of the short-wavelength data.

5.5 Fast scan mode

This involves fast scanning the telescope across a source in an (overlapping) raster pattern. The fastest speed is determined (most likely) by the detector speed of response. Scan speeds as high as 600 arcsecs/sec are likely to be possible. Note that fast scanning has much lower requirements on the flat field accuracy and stability and also on dark measurements.

5.5.1 Scientific considerations

An interesting question concerns the biggest map we would want to take in one go. As mentioned above a 2 minute scan, at 600 arcsecs per second, would cover a strip of 20 degrees × 8 arcmintes. This would be very attractive (especially from a Galactic astronomy perspective) allowing, for example, coverage of large sections of the Galactic Plane, mapping of high galactic latitude clouds, imaging of giant molecular clouds etc.

5.5.2 Technical considerations

The technical limitations are likely to be field rotation, data rate (unlikely), sky variations (but perhaps can correct in pseudo real-time?), and registration limitations (there may be errors in source positional and photometric accuracy). Background removal may also be more complex for a fast scan.

5.6 Drift scanning

Simply point the telescope at an area and let the Earth's rotation act as the scan speed and direction. This has been used successfully by the CSO in the past for S-Z measurements of large clusters.

5.6.1 Scientific considerations

With the telescope fixed there are likely to be less uncertainty with time-dependent signal spill-over (that could cause low-level systematics). This may be particularly important for very low-level background experiments like CMB fluctuations and S-Z measurements.

5.6.2 Technical considerations

The telescope control system can probably be easily adapted to cope with something like this. All that is really needed is to disable the tracking, add an on-source pulse and a knowledge of the sidereal rate.

5.7 Pointing

It is anticipated that a pointing observation will simply be a fully-sampled map. At the end of the observation the sky background plane will be removed (need a fast algorithm here) and a centroid fitted to the peak. The derived offsets in az-el will be sent back to the TCS and the telescope position updated accordingly. This is essentially the same method that is currently adopted with SCUBA, but at the present time correlated sky-noise is not removed in real time (ORAC-DR can give this information shortly after the completion of the observation, although the offsets currently have to be manually entered).

In terms of integration time, the current JCMT pointing catalogue contains about 60 sources which are considered to be suitable targets. They are typically greater than 0.5 Jy at 850μm and would require only a few seconds observation time with SCUBA-2. The extra sensitivity and full image plane sampling available with SCUBA-2 should allow many more sources to be usable (e.g. true point-like sources such as quasars and blazars). Potentially this has the advantage of less time being wasted on long slews between pointing and programme targets, leading to better accuracy in telescope centre definition.

5.8 Focussing

Focussing will most likely be carried out in a similar way to that adopted by SCUBA. However, we will simply carry out fully-sampled maps afor a number of SMU offset positions, with the peak being fitted by a parabola and passed back to the TCS for updating. One refinement is that we could slowly drive the SMU motors (say, 0.1 mm per second) through the focus curves and continuously integrate. The S/N should be more than adequate in 1 second for most sources. This depends on the pixel relative response as a function of sky background.

5.9 Sky-dip

Measure the sky brightness temperature as a function of elevation, and using a simple model for the tranmission of the telescope fit the resulting curve to derive the zenith sky opacity.

5.9.1 Scientific considerations

In principle, it may be possible to obtain the sky opacity at the position of a source by determining the elevation sky gradient in across the map. However, the necessity to measure the sky over a wider airmass will still most likely be required.

5.9.2 Technical considerations

Data could be taken on-the-fly (there should be ample S/N) to reduce overheads. This depends on how non-linear the pixel response will be to changing background power. A calibration system would be needed. The alternative, and probably the preferred option, is to use a line-of-sight radiometer.

6. Calibration and real-time corrections

SCUBA-2 data will require similar calibration information to that currently used by SCUBA. These are summarised in Table 4 together with anticipated real-time corrections that could, at least in principle, be applied.

	SCUBA (2Fλ-spaced feedhorns)	SCUBA-2 (0.5Fλ and Fλ bare pixels)
Atmospheric transmission	Skydips; CSO τ interpolation; frequent observations of calibrators; line-of-sight radiometer	Line-of-sight radiometer; use measured DC sky level to continously monitor the transmission; "short" skydips
Sky-background	Sky-chopping and telescope nodding; remove correlated sky noise in jiggle-maps; assume source structure stationary and sky varying for scan maps	Sky background can be subtracted (to first order) as a plane
Refraction noise	For photometry carry out a mini-jiggle to increase time averaged beam.	Uses differences in the sky temperature (τ-corrected) across the array to estimate refraction (compensate using shift-and-add or rapid pointing corrections to the SMU)
Flat-fielding	Scan a point-like source across each pixel on the array	Use a stable uniform load to flat-field
Dead area compensation (bad pixels, sub-array gaps)	Offset array centre for jiggle-map; sky rotation can fill in for long integrations	Small-scale micro-stepping (dithering) with the SMU (say, 1.5Fλ steps)
Field distortion and rotation	Re-sampling and interpolation onto an RA-dec grid	Re-sampling and interpolation onto an RA-dec grid
Spike removal	Eliminate spike on a per-pixel basis from the datastream	Eliminate spike from sampled frame and interpolate, if needed

Table 4: Comparison between SCUBA and SCUBA-2 for calibration and real-time corrections.

6.1 Opacity corrections

The preferred way to correct for atmospheric transmission would be to use using a line-of-sight radiometer (such as the 183 GHz radiometer currently in operation at the JCMT). Alternatives include skydips and extrapolation from the CSO tau meter (as is currently done with SCUBA). With

SCUBA-2 it is also possible that the sky transmisison will be monitored continually by using the DC sky offset across the array.

6.2 Sky-background removal

For SCUBA the techniques of sky chopping and telescope nodding remove the vast majority of the dominant sky background. The residual signal, which arises from spatial and temporal variations in the sky emissivity ("sky noise") can be effectively removed by correlation methods.

SCUBA-2 will operate in a completely different mode since it will have a DC-coupled array. There will most likely be different algorithms for different observing modes. For a STARE observing mode the sky background will most likely be subtracted on a per-frame basis by fitting a sloping plane (SC2/ANA/S100/S13). For scan mode the background will be subtracted as a baseline from individual scans. Ultimately, it will be the astronomer that will decide which areas of an image contain no source structure, and are therefore classed as "background regions".

6.3 Flat-fielding

The SCUBA-2 pixels will all have slightly different sensitivities, and so images must be flat-fielded to ensure they reflect real source structure and not pixel to pixel variations in sensitivity. The accuracy required for the flat-field will depend on the observing mode and integration, but is estimated of order 1 part in 10^7 for the stare-observing mode for a typical deep integration. Hence, it will be necessary to integrate for several hours to obtain the accuracy required. It is envisaged that the instrument could stare at a constant temperature source, placed at a pupil image, during periods when SCUBA-2 is not being used for astronomy (daytime). Skydips can also be a source of flat-fielding, as each pixel must measure the same sky opacity value.

6.4 Refraction noise compensation

Anomalous refraction ("submm seeing") is a significant source of error for SCUBA point-source photometry. The situation with SCUBA-2 is somewhat different, since as we will have a fully-sampled array (at least at 850um), the effects of refraction will be to "smear" the beam and cause position uncertainties. However, the total flux of the source should still be recoverable to a large accuracy. It is even possible that "tip-tilt" corrections to the SMU could lead to a "shift-and-add" method of observing similar to that used by UKIRT. Feedback information from edge pixels to enable rapid corrections to the SMU.

Water vapour fluctuations above the telescope cause transmission, emission and refraction variations. By correlationg the observed sky gradient across the array with pointing shifts it may be possible to correct individual frames for the effects of refraction before co-addition.

6.5 Flux calibration

There's no way around this - SCUBA-2 will still have to rely on primary and secondary flux standards. However, the speed of mapping and sensitivity of SCUBA-2 should allow new, fainter standards to be used (e.g. AGB stars, protoplanetary nebulae etc).

6.6 Spike removal

Spike removal is likely to be handled by the FPGAs in the SQUID readout card. A useful measurement to have would be the spike rate with the current SCUBA (on-despiking algorithm de-activated). Also the shape and energy in the spike pulse would provide some useful informatiion although it's not clear how easy this would be to obtain.

7. Instrumental characterisation

This section considers some of the instrumental checks that will be required to fully optimise the scientific performance of SCUBA-2.

7.1 Dark frames

It is likely that the level of instrumental 1/f noise will require the taking of regular dark frame exposures. This may have to be every 30 secs or at the end of a scan, and will require an exposure of about 1-2 sec for decent S/N. This necessitates a cold shutter be included as part of the instrument design.

7.2 Optimisation of array set up

To obtain the optimum closed- loop read out mode for each array it will be necessary to determine the pixel and SQUID bias, heater levels and feedback to the first and second stage SQUIDs. It is not yet know how often this will have to be carried out, but it is likely to be implemented as part of the (automated) set-up procedure (or done before extensive flat-field measurements). See SC2/ANA/S100/31 for more information.

7.3 Noise flat-field

A low-background "noise flat-field" could be obtained by integrating for say, several minutes looking at the cold shutter (minimum background case). This would essentially provide a health check on the noise performance of the instrument, and identify "hot pixels" (or pixel columns) that were to be avoided. This could be extended to be included in the "Array Verification" start-up - which in turn may be part of the flat-field measurement. In addition to the flat-field the array verification procedure could involve detector time constant checks.

7.4 Bad pixel avoidance

Based on the noise flat-field, a dither pattern could be automatically created to maximise the uniformity of the proposed observation.

7.4 Crosstalk

The effect of crosstalk manifests itself as an unwelcome or ghost signal falling onto a neighbouring channel. Crosstalk can be split into two components: *electrical crosstalk* (arising, for example, from the way the signal readouts are wired) and *optical spillover* (caused by the diffraction pattern of the telescope). It is the level of optical spillover that sets the (unavoidable) crosstalk limit for SCUBA-2. For nearest neighbours the diffraction pattern of the telescope means that optical spillover dominates. It is the electrical crosstalk from non-nearest neighbours that is potentially a problem. The specification for this depends on the map dynamic range (MDR) that is acceptable. A MDR of

200–300 might be reasonable and so this sets the crosstalk limit (Reference: "Crosstalk levels for SCUBA-2", ref: SC2/ANA/S100/21).

The crosstalk will be measured in the lab with the telescope simulator. It is unlikely to vary unless there are changes in the arrays or electronics at the telescope. If that is the case then deep beam maps will be needed to investigate whether any systemtic ghosting exists.

8. Getting science out of images - what are the requirements?

Ultimately, it is the quality of the science from the image that is most important. A worst case scenario might be that for very long exposures there may be systematic problems which for example, means that the rms noise in a map no longer integrates down with time, or aberrations build up on the edge of the array etc. There may also be limits connected with observing bright sources with very short exposure times.

8.1 Point-source flux extraction

Once an astronomer has an image, what does he/she want to get out of it? One thing is to extract point source fluxes from a map. This can be done individually by hand, or using one of the more sophisicated clump-finding algorithms (likely to be very important for wide field-of-view of SCUBA-2). Although we may have a S/N ratio of 100 or more, it is likely that the calibration accuracy will still be the limiting factor (although this is likely to improve with SCUBA-2).

8.2 Absolute and relative photometric accuracy

Absolute accuracy. This is the overall accuracy compared to other instruments and other wavebands. SCUBA-2 data will be combined with measurements using other facilities, and so a reliable absolute calibration scale for all of the facilities will be important. The accuracy achievable is dependent on the stability of observing conditions (i.e. the determination of extinction, refraction compensation etc.), stability of the instrument during an observation (flat-field etc.) and the accuracy of known flux standards. Based on the SCUBA experience it is likely to be more difficult to obtain a higher accuracy at 450μm, although line-of-sight radiometers will help.

Relative accuracy. This is the repeatability of a measurement both across the array(s) and also in time. For the deep surveys this is not a major problem, as S/N on faint objects will be low. However, for some other programmes it is crucial that the repeatability be very high. The accuracy achievable is dependent upon stability of observing conditions (determination of extinction, refraction compensation etc) well the instrument can be characterised (e.g. flat-field etc.), any time-variability of standards (avoid these if possible). Again, based on the SCUBA experience it is likely be more difficult to obtain a higher accuracy at 450μm, although line-of-sight radiometers will help.

8.3 Large-scale structure in maps

Since SCUBA-2 will not use the technique of sky chopping, source structure on all size scales should be preserved.

8.4 How to cope with multiple sources in the same field?

See section 8.1. There are sophisicated source extraction algorithms that are available.

8.5 Data mining requirements

Data mining is an information extraction activity that has as its goal the discovery of hidden facts contained within databases. SCUBA-2 will generate huge amounts of data and therefore it will be necessary to consider just how people can query and extract relevant information from the SCUBA-2 archive and databases.

8.6 How to avoid having to be an expert to get really good images...

SCUBA-2 must have user-friendly interfaces, excellent documentation and have a dedicated support team that is ready to answer queries from users.

9. Novel observing techniques

This section briefly mentions the possibility of carrying out imaging polarimetry and medium resolution spectroscopy using SCUBA-2. These ideas are much less well-defined…

9.1 Polarimetry

Submillimetre polarimetry is a powerful tool for studying magnetic fields in a variety of astrophysical phenomena. An imaging polarimeter for SCUBA-2, would take advantage of the extra sensitivity, imaging speed and improved image fidelity of SCUBA-2, which would allow completely new areas of astronomy to be studied.

It is envisaged that a polarimeter will operate in the same way as the current SCUBA instrument. There would be two basic observing modes: step-and-integrate (SI), slow and fast spinning. Firstly, 'step-and-integrate' mode will record data at 4 or more waveplate positions to the extract the Stokes parameters to derive the degree of linear polarisation and position angle. This is a proven method with the SCUBA polarimeter, but is a time consuming way of extracting polarization information. It will, however, be much faster with SCUBA-2 because of the large increase in sensitivity. Secondly, a 'continuous spin' mode is envisaged, in which the waveplate is set rotating at a fixed frequency. This introduces a sinusoidal modulation of the signal, and the resulting power spectrum gives the intensity of the polarized signal (retaining orientation as a function of time gives position angle). This method can be used to extract polarization information very quickly. The sensitivity of the polarimeter is ultimately governed by that of SCUBA-2 (with losses due to the analyser and waveplate). For example, consider an 8-arcmin diameter star formation region of mean flux 100mJy at 850 micron with an expected polarization level of 4%. A 3-σ polarisation detection with SCUBA would take over 50 days. With SCUBA-2 this drops to a very reasonable 2 hrs with the position angle being constrained to ± 8 degrees.

The main limit to polarimetry with SCUBA are short term opacity changes on the timescale of an observation (4 images). With SCUBA it takes about 6 minutes to obtain the Stokes images. This should be achievable in seconds with SCUBA-2. It is necessary to define more information on data rates, synchronisation betwen waveplate movement and data taking etc.

9.2 Spectroscopy

SCUBA-2 will have a Fourier Transform Spectrometer, based on the Herschel SPIRE Mach-Zender design. This design provides access to all four interferometer ports while maintaining maximum throughput and removing any polarization sensitivity.

The FTS proposed for use with SCUBA-2 will be of this new design and mount on the left Nasmyth platform of the JCMT. The maximum beamsplitter size dictates the field of view of the FTS. The current plan is to provide spectral mapping over one quadrant of the SCUBA-2 array (i.e. 1600 pixels each in the 450 and 850μm channels). Since the detectors are read out synchronously, standard FTS data collection methods, which would require 3200 sample-and-hold circuits, are impractical. The position of the translation stage will be recorded as a function of the SCUBA-2 master clock to an accuracy of <1 micron and the optical path difference corresponding to each pixel's sampled interferogram reconstructed during post processing. Once the correct path difference has been assigned to each pixel, standard phase correction and wavelength calibration will be applied. The FTS has a large software component, which will be developed in close consultation with the SCUBA-2 electronics and software teams. It is noted in passing that this is a very similar problem, only on a larger scale, to that faced by the SPIRE FTS instrument. The key features of the proposed FTS are summarized in Table 5.

Interferometer type	Mach-Zehnder, double input, single output
Scan Mode	Rapid scan, maximum scan time ~30 seconds
Spectral Bands	450 micron and 850μm simultaneously
Number pixels	TBD ~1600 in each band
Resolution	Selectable: 0.25 to 0.005 cm^{-1} , 150 MHz to 7.5 GHz
Beamsplitter	Intensity beamdividers

Table 5: Possible instrumental parameters for the SCUBA-2 FTS (taken from the SCUBA-2 CFI proposal)

Appendix 1: Practical types of observations

The following tables gives some practical examples of observations that astronomers may want to take with SCUBA-2.

Type of observation	Typical size of source/field	Flux (850μm) of source(s)	Obs mode used	Int time	RMS and S/N	Note
Planets, compact calibrators	Point-like	Usually 5–100 Jy	Stare map	5–60 secs	S/N>100 on peak, but need low level as well	1
Asteroids	Point-like (in isolation)	Typically 10–30 mJy	Dither map	0.5–5 mins	For a detection of 5–10σ	2
Kuiper belt objects	Point-like	2–3 mJy at most	Dither map	2–3 hrs	5-σ detection, but confusion limited?	3
Comets	Extended coma (up to 1 arcmin diameter)	50–500 mJy on peak tail flux ~ few mJy	Dither map	1–30 mins	Need only a minute for good S/N on peak	4
Pre-stellar cores	Usually elongated up to 1 arcmin diameter	50–300 mJy	Dither map	5–10 mins	To get low level structure at high S/N	5
Isolated protostars	Typically 30–50 arcsecs	0.2–5 Jy	Dither map	5–10 mins	To get low level structure at high S/N	6
Proto-brown dwarfs and the IMF	Fields of a GMC - maybe 8–10 arcmins in diameter	Down to confusion limit	Dither map	2–3 hrs per field	Wide-range of S/N expected	7
Giant molecular clouds	3–5 degrees across	Structure between 10 mJy and 10 Jy	Slow scan map	~7 hrs	Need 30 s per SCUBA-2 f-o-v for sensitivity	8
Galactic plane survey	Say, 20 × 0.5 degrees	Structure between 30 mJy and 10 Jy	Fast scan map	1 hr	Should detect most structure with >5-σ	9
Proto-planetary disks	30–50 arcsecs	Peak ~ 5–30 mJy Low level is ~2 mJy	Dither map	2–3 hrs	Will give better S/N than current SCUBA images	10
High latitude clouds	5–10 degrees in diameter	Low levels of 2 mJy or so	Slow scan map?	5–10+ hrs	S/N will again vary with different structures	11
Evolved stars	2–4 diameter arcminute shells	Mean fluxes for shells are 5–10 mJy	Dither map	2–3 hrs	Shells are faint but 2–3 hrs should see 5-σ results	12
Globular clusters	Condensed emission - few tens of arcseconds	Typically 5–10 mJy	Dither map	2 hrs	S/N of >10 on peak	13
Supernova remnants	2–8 arcmins diameter	Low level emission to ~5mJy	Dither map	2 hrs	At least 10-σ on low-level structure	14
ISM in nearby galaxies	5–10 arcmins	Peak ~ 50–500 mJy sp.arms ~ 5–40 mJy	Dither map with larger step?	1–2 hrs	Need low level structure away from nuclear region	15
Dwarf galaxies	1–2 arcmin	10–100 mJy on peak	Dither map	0.5–1 hrs	Condensed emission	16
Starburst galaxies	1–3 arcmin	Faint structure (<0.1 Jy) outside nucleus	Dither map	10-20 mins	To get low-level structure outside the nucleus	17
AGN/blazars	Point-like sources	Big range; variable on short timescales	Dither map	0.5 – 5 mins	High S/N achievable very quickly	18

Deep field survey	Point sources in extended field	Typically 2–20 mJy	Dither map (or slow scan-map)	~2 hrs per field	Confusion limited in around 2 hrs	19
S-Z effect	Increment in flux over 5–10 arcmins diameter	Integrated flux over field only a few mJy	Slow scan or drift map	Up to 8 hrs?	Overlapping strip scans across cluster	20

Notes:

1. **Planet/compact calibrator.** Generally will want high dynamic range beam-maps – down to 1% amplitude to take in the error beam. If use Uranus, for example, then this means a flux level of about 0.7 Jy – which will only take a few seconds for good S/N. In the case of a secondary calibrator, such as CRL618, which is only about 4 Jy, then a typical integration time might be up to a minute**.**

2. **Asteroids.** Large field-of-view a real advantage because of non-sidereal movement.

3. **Kuiper belt objects.** Smaller Centaurs may be even fainter. Background confusion may be the limiting noise source for these observations.

4. **Comets.** A major requirement is snapshot imaging as a function of heliocentric distance. Also as most cometary observations require daytime observing calibration is a key factor. Tail emission can be as low as a few mJy at 850μm – and was not really investigated at any great depth with SCUBA (e.g. for C/Hale-Bopp). Extended tail-emission probably needs 30 mins or more to investigate at good S/N.

5. **Pre-stellar core.** Can often be embedded in low-level filamentary structure. Scan-mapping may be the best observing mode to use in the long term.

6. **Isolated protostar.** Low level envelope structure is a needed to study radial profiles.

7. **Proto-brown dwarfs and the IMF.** Key here is to go as deep as possible to detect core masses close to the gravitationally bound limit. Could find 100's of objects in a single SCUBA-2 field-of-view (probably reach the confusion limit well before this!)

8. **Giant molecular cloud.** Need good sensitivity per sampled point, and so hence the suggestion of a slow-scan map. To reach the sensitivity limits needs about 30 secs per Nyquist-sampled point.

9. **Galactic plane survey.** Shallow survey is required, but still down to a rms of around 20 mJy or so (sufficient to pick out pre-stellar cores and Class 0 protostars). Will need to go deeper to pick out objects like (proto-) brown-dwarfs and very low-mass cores.

10. **Protoplanetary disks.** Good image fidelity is the key. Linearity and accurate flatfielding are a must to pick out asymmetries and clumpy structure.

11. **High latitude clouds.** Need good sensitivity per sampled point, and so hence the suggestion of a slow-scan map. Will be a struggle to map the entire cloud because they are so big.

12. **Evolved stars.** Many shells are quite thin (e.g. TT Cyg) with typical fluxes of only a few mJy. 450 μm data for extra resolution is a real requirement.

13. **Globular clusters.** Compact sources in general.

14. **Supernova remnants.** Some are as small as 6 arcmin in diameter (e.g. Cas A, Crad); others are much larger (> field-of-view of SCUBA-2).

15. **ISM in nearby galaxies.** Crucial thing here is how well-matched the SCUBA-2 f-o-v is to the size of many nearby edge-on and face-on galaxies (e.g. NGC891, M51). Confidence in low-level structure is also a key.

16. **Dwarf galaxy.** Likely to be small (tens of arcsec in diameter) and low surface brightness.

17. **Starbursts.** Apart from a few exceptions (e.g. M82 and NGC253) fluxes are generally faint - especially if the regions outside the nucleus are to be studied.

18. **AGN/blazars.** Sources are point-like. May get several in one field**.**

19. **Deep-field surveys.** Source counts and clustering on large-scales. Integrations to the confusion limit.

20. **S-Z effect.** Increment is faint (maybe 2-3 mJy over a 4-5 arcmin region). Need exceptional stability and linearity. Key improvements with SCUBA-2 are no chopping or nodding (lower systematics due to spillover etc).