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SCUBA-2: A large format submillimetre camera on the James Clerk Maxwell Telescope

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ABSTRACT

SCUBA-2 is a second generation, wide-field submillimetre camera under development for the James Clerk Maxwell Telescope. With over 12,000 pixels, in two arrays, SCUBA-2 will map the submillimetre sky up to 1000 times faster than the current SCUBA instrument to the same signal-to-noise. Many areas of astronomy will benefit from such a highly sensitive survey instrument: from studies of galaxy formation and evolution in the early Universe to understanding star and planet formation in our own Galaxy. Due to be operational in 2006, SCUBA-2 will also act as a "pathfinder" for the new generation of submillimetre interferometers (such as ALMA) by performing large-area surveys to an unprecedented depth. The baseline design, projected telescope performance and scientific impact of SCUBA-2 are discussed in the paper.

Keywords: Submillimetre astronomy: JCMT, large-format superconducting arrays: SCUBA-2

1. INTRODUCTION

The late development of ground-based submillimetre astronomy can be attributed to two main factors: *atmospheric limitations* and *the lack of key technologies*. Even from dry high-altitude sites atmospheric transparency is often poor as the high background power and sky emission variability limit the observing sensitivity. However, enormous technological advances have been made during the past decade. Single-dish telescopes (of 10–15m class) are now routinely operating with high efficiency in the submillimetre. On the other hand, instrumentation has only recently (last 5 years or so) advanced from the single-pixel photometer to the first generation multi-element arrays.

It is also fair to say, with the benefit of hindsight, that few astronomers prior to the start of the last decade had appreciated the importance of the submillimetre waveband as a crucial one for astronomy. The impact of the first generation array receivers – such as the SCUBA camera[1] on the JCMT – has been immense. In particular, they have led to major advances in our understanding of the astronomical *origins* questions: how planets, stars and galaxies form. For example, in cosmology SCUBA has been described as having an impact "as big or bigger than the Hubble Space Telescope" having shown that the farIR/submm background is in fact composed of high-z ultraluminous dusty galaxies, allowing us to study galaxy formation and evolution in the early Universe. However, despite making several pioneering breakthroughs in this previously unexplored wavelength regime, SCUBA has really only given us

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a glimpse of what is still to come. With only 128 pixels in two arrays, surveying large areas of sky, or imaging to any great depth, is still painfully slow.

The first submillimetre interferometers are already starting to come on-line. The Smithsonian Submillimeter Array (SMA) will soon provide the astronomical community with access to sub-arcsecond spatial resolution at submillimetre wavelengths. Towards the end of the decade the Atacama Large Millimeter Array (ALMA) promises the unique combination of both superb sensitivity and milli-arcsec resolution. Although these facilities will provide unprecedented resolving power to study astrophysics on the smallest size-scales, they have relatively limited sensitivity for mapping large areas of sky. The submillimetre is still largely unexplored territory with only an area comparable in size to the moon having been effectively imaged to any great depth. *Single dish telescopes, equipped with large-format imaging arrays, will remain the most efficient way to conduct large-area surveys, and will therefore provide a wide-field complement that is essential to fully-exploit the capabilities of interferometers.* Moreover, a potential problem with interferometers is that image fidelity to the true sky is by no means certain: for example, they are notoriously prone to miss extended, large-scale structure. Imaging arrays such as SCUBA also suffer from this problem: not only is the sky instantaneously undersampled, but observing techniques such as sky-chopping propagate noise and limit the scale-size of visible source structure. The next logical step is to develop the submillimetre equivalent of a CCD camera—a large-format array containing many thousands of pixels, that instantaneously samples the sky without the necessity to sky-chop. *This forms the basis for the SCUBA-2 camera.*

2. SCIENCE DRIVERS FOR SCUBA-2

The scientific aims of the proposed 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[f]. Some highlights from the potential scientific impact are described in section 5. 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 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.

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[f] The scientific case is available at http://www.roe.ac.uk/atc/projects/scuba_two

- 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. This requires 25,600 and 6,400 pixels at 450 and 850μm, and ultra stable electronics at low (DC) 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.

No other instrument (either current or planned) offers such a unique capability. SCUBA-2 will have a sensitivity limited by the sky background, a large-area mapping capability a factor of 10 better than a compact ALMA, a resolution on the sky three times better than Herschel, and a unique, simultaneous dual wavelength operation.

3. INSTRUMENT DESIGN

The SCUBA-2 instrument design represents a number of technical challenges. An overview of the design is given here, with a detailed description of the detector technology presented in the companion paper (Duncan et al.).

3.1 Detector arrays

Conventional bolometers (such as those used in SCUBA) are not practical for the pixel count required for SCUBA-2. Recent advances in superconducting detector technology, including the development work for the SPIRE instrument[2], have demonstrated that large-format arrays of thousands of pixels should soon be possible. SCUBA-2 proposes to fill the re-imaged telescope focal plane with state-of-the-art transition edge sensors (TES)[3]. TES devices have unique advantages. They have low impedance, and thus low sensitivity to microphonics (a problem with SCUBA). They are instrumented using Superconducting Quantum Interference Devices (SQUIDs), which consume much less power than conventional FETs, and can operate at the same temperature as the detectors. In addition, because of their high sensitivity and extreme electro-thermal feedback mode of operation, they operate faster than conventional bolometers of the same thermal properties. Most importantly, the existence of a cryogenic multiplexing scheme[4] makes it possible to instrument the full field-of-view with a practical number of wires. Without the multiplex advantage the 6 wires that would be required for each TES element would lead to >100,000 wires emerging from the detector array – a formidable number, inevitably causing great difficulties in construction.

Figure 1 shows schematic drawings of the novel SCUBA-2 pixel design and a concept for the array geometry. The design consists of an upper detector chip and a lower multiplexer (MUX) chip, which are held together with indium bump bonds. The detector chip consists of two silicon wafers diffusion-bonded together, with the top wafer micro-machined into a grid to provide support for the array. The upper surface of the bottom wafer forms the radiation absorber, and is ion-implanted to give a surface impedance match to free space. The backshort for the absorber is formed by the TES device itself, which covers the entire underside of the pixel, and is one-quarter wavelength distant from the absorber. This integral backshort design greatly simplifies the construction of the array. Electro-magnetic modeling of the pixel and array geometry shows that the absorption efficiency is likely to be ~80%.

3.2 Signal readout

In each TES, incoming submillimetre radiation produces a small amount of heat that is translated into a signal current and measured by a SQUID ammeter. A separate SQUID series array further amplifies the signal by a factor of 100, to around the mV level, before it is taken out of the cryostat to room temperature electronics. The SQUID ammeter is biased with a constant current. The signal current passes through an input coil where it produces a flux through the SQUID. This flux then results in a signal voltage at the SQUID output that is non-linear and varies in a periodic, roughly sinusoidal fashion with applied flux. In order to linearise the SQUID output a Flux Locked Loop (FLL) circuit is used to maintain a net zero flux through the SQUID. This works by measuring the output from the SQUID series array and then feeding back an appropriate signal into a feedback coil on the SQUID such that the flux produced is equal in magnitude but in the opposite sense to the input flux. Each SQUID then needs a total of six connections: two for the bias current, two for the output voltage and two for the feedback coil. Each pixel also has a heater resistor that is used to compensate for variations in the sky background signal and maintain a roughly constant power input to each pixel.

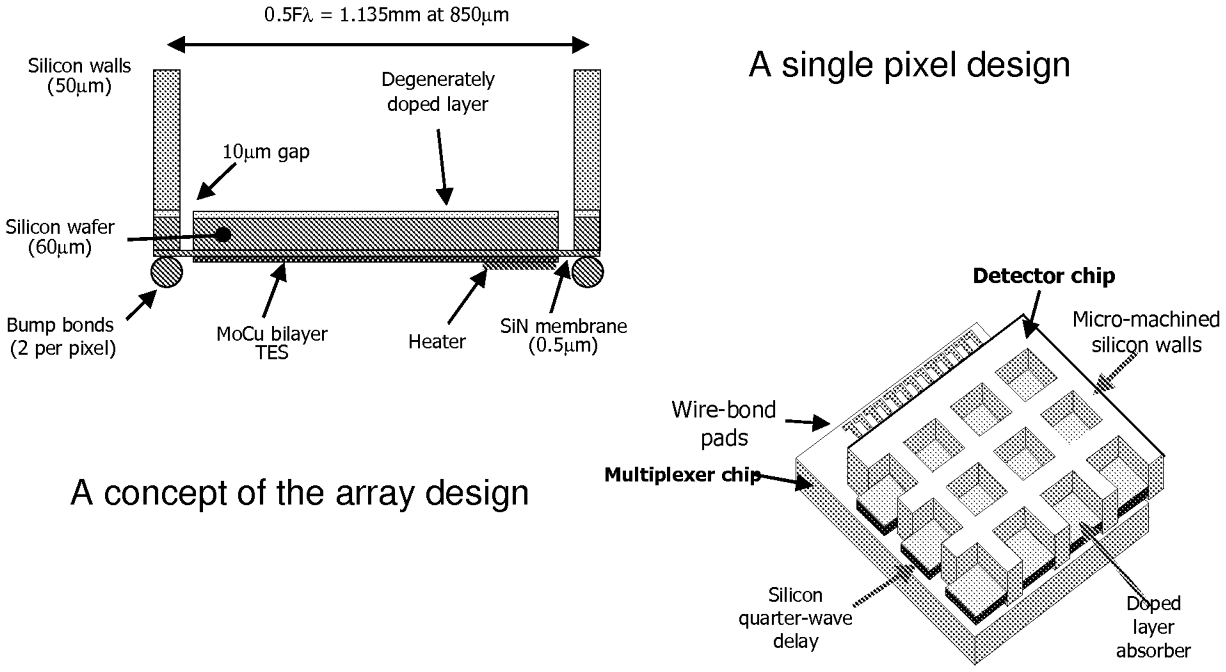

Figure 1: Schematic drawings of a single SCUBA-2 pixel and the array concept (not to scale).

Each pixel requires six wire connections and its own series array. As this is impractical, SCUBA-2 will overcome these problems by employing an innovative multiplexing scheme. This is done by connecting all the SQUIDs in a column in series and then using a set of row select lines to turn on each row of SQUIDs in turn. The SQUIDs in each column, which are switched off, contribute no signal current and so it appears that a single pixel is being read out. In addition, the feedback coils can also be connected in series and only one SQUID series array is required per column. With this scheme the number of wire connections is significantly reduced as only two bias lines, two feedback lines, and two output lines are required per column. In the real device the first stage SQUIDs for each pixel in a column are connected in series, and the outputs are transformer-coupled to the input coil of a second stage SQUID. The output of the second stage SQUID then feeds the SQUID series array. Figure 2 shows the design for the signal readout system (not shown are array address, bias and SQUID feedback lines).

3.3 Pixel architecture and field-of-view

The choice of pixel architecture was a crucial decision in the design of the camera as it sets the direction of the array development programme. Filled (bare) arrays allow instantaneous "snap-shot" imaging of a field and give the maximum speed for mapping large regions of sky. Feedhorn-coupled arrays – spaced by either Fλ or 2Fλ in the focal plane – have a considerable heritage as demonstrated in SCUBA and BoloCAM[5]. However, because of the instantaneously undersampled field they have a lower mapping speed and possibly a reduction in image fidelity. In addition, vast numbers of high efficiency feedhorns, in some cases made from superconducting materials, would have to be developed. The main disadvantages for filled arrays are that more pixels are required to cover a given area, they are more susceptible to stray light (that can potentially degrade sensitivity), and are less efficient at detecting point-sources with a known position. The goal was for SCUBA-2 to use filled array architectures with the pixels spaced by 0.5Fλ in the focal plane in order to maximize the survey speed.

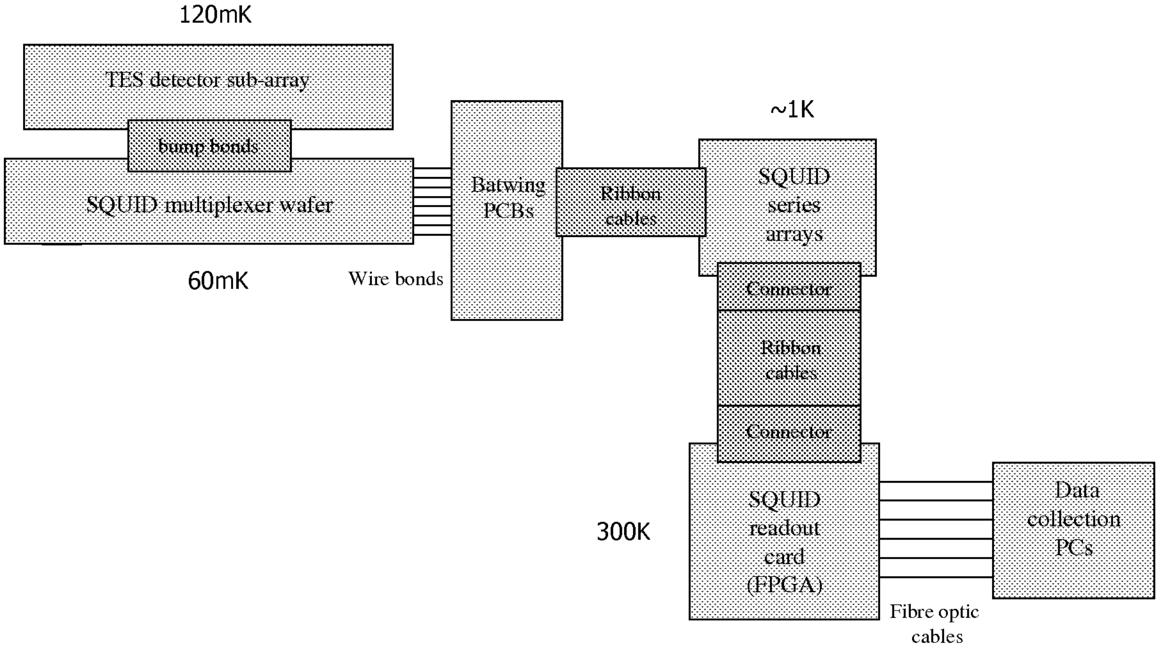

Figure 2: The SCUBA-2 signal readout from the TES arrays to the data collection PCs.

One of the most challenging areas in developing the arrays is the design of the SQUID multiplexer that reads out the detector signals. Unfortunately, the current MUX layout means that it would be extremely difficult to implement the design for a fully sampled 450μm array – there is simply not enough space on the SQUID MUX chips to read out the detector signals. To solve this problem would require a significant amount of additional time and effort that is incompatible with project time constraints. The easiest solution was to cut the number of pixels and adopt a baseline Fλ-spaced array at 450μm. Although this reduces the large-area mapping speed and potentially makes the observing modes more complex, the benefits of avoiding a costly re-development programme far outweigh the loss of speed. There are also constraints on the size of silicon wafer that can be processed (this is 3-inches). Each SCUBA-2 array will therefore be composed of 4 sub-arrays that will be butted together to give the full field-of-view. The one-pixel gap between the sub-arrays has implications for the observing methodology (see section 4.1.2).

3.4 Optical design

At the telescope Cassegrain focus the full field-of-view is 600mm in diameter. It is clearly impractical to have a detector array that size and cool it down to low temperatures. Hence, the telescope field de-magnification has to be compatible with a realistically achievable array size. This depends on how the arrays are to be made and the geometry and optimization of a single pixel. Each pixel has to be > λ in size to efficiently couple to the incoming radiation. This dictates that the array needs to be ~100mm square and hence the optics has to match the large telescope field to this size. This presents quite a challenge in the optical design! SCUBA-2 will be too big to fit into the cabin that rotates with the telescope, and so the optics has to relay the light through a narrow bearing tube to the mezzanine level of the JCMT. This means the optical path is complex, needing 9 aspheric, off-axis mirrors (see Figure 3). The modeled performance of this design delivers diffraction-limited images with >90% efficiency.

3.5 Cryogenic and mechanical design

The sensitivity (NEP) levels required for SCUBA-2, together with power handling considerations for the TES devices operating in a variable background environment, mean that the detectors must operate in the 100mK regime. The lower the detector temperature the lower the detector noise contribution to the overall NEP. It is also important to maximise the temperature differential between the detector and bath temperature to minimise the effect of bath fluctuations. It can be shown that adopting a bath temperature a factor of 2 lower than the detector temperature can achieve this in practice. Thus there is a trade-off associated with operating temperature. A fridge with sufficient cooling capacity at the bath temperature is needed (cost and complexity implication) whilst at the same time the detector temperature should be minimised.

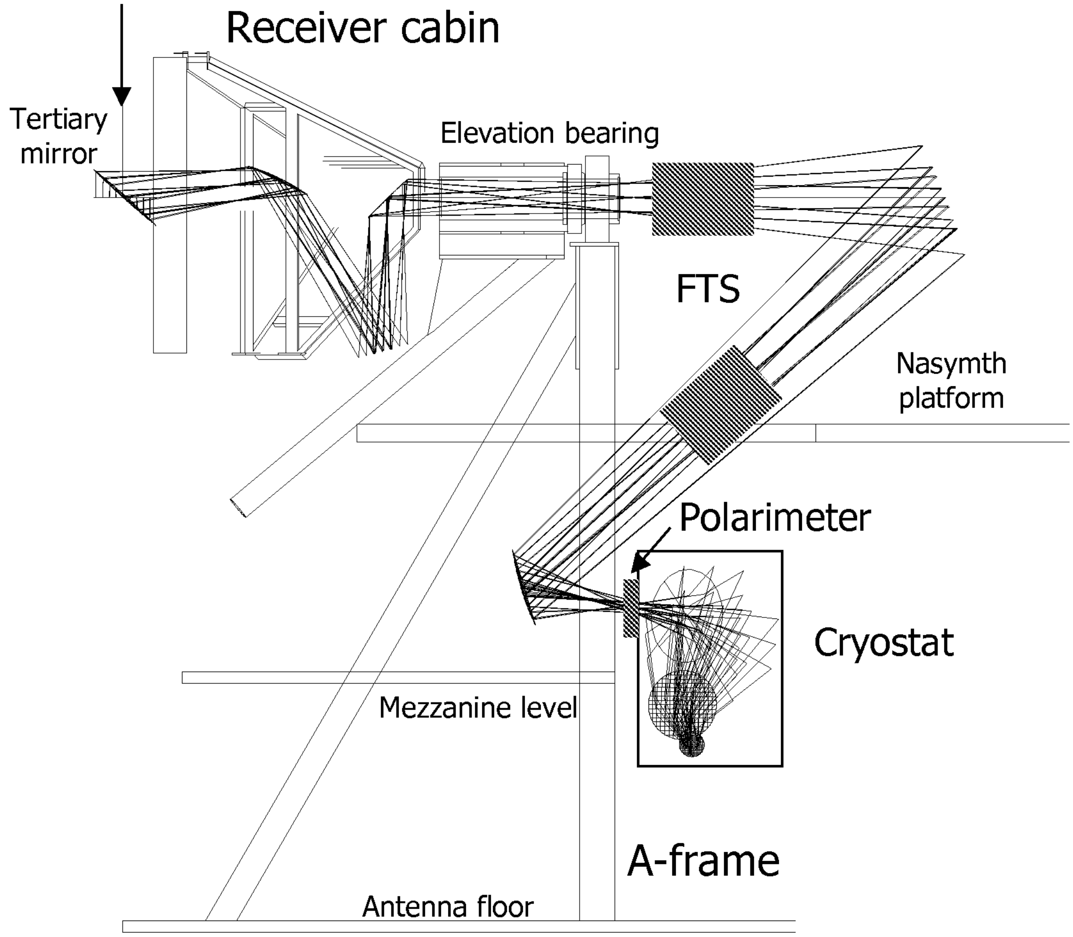

Figure 3: The optical path for SCUBA-2 on the JCMT. Possible locations are also shown for a spectrometer (FTS) and a polarimeter.

The SCUBA-2 arrays will be cooled to ~100mK by a dilution refrigerator (DR). To reduce operational and support costs a liquid cryogen-free design is being used. The only liquid cryogen needed is likely to be nitrogen for the rapid pre-cool of the instrument at the start of a cool-down. Maintenance will mainly consist of regular servicing of pumps and compressors. A dilution refrigerator with ~100μW of cooling power at 100mK will be required. The design will incorporate a 4K pulse tube cooler (PTC) with the DR to provide a liquid cryo-free system. In addition the DR will use oil-free pumps to circulate the ^{3}He mixture, eliminating blocking of the cold insert (a problem with the current SCUBA) and hence maximizing operation time. The DR operation will be automated and may be operated and monitored remotely. A second PTC will cool the radiation shield (~60K) and cryostat mirrors (4K). The 1K focal plane box, which will surround the array modules, will be cooled by the still of the DR. Figure 4 shows a schematic diagram of the layout of the "1K focal plane box". The two arrays are held in separate modules that can be easily removed if needed.

4. OPERATION AND PROJECTED PERFORMANCE

4.1 Modes of operation

SCUBA-2 will operate in two basic ways, namely in an imaging and a survey mode. One of the main drivers for the instrument will be to maximise observing efficiency (on-source time) for both modes. SCUBA jiggle-map is an example of a well-optimised observing mode[6]. Observing efficiency is typically 75% with this mode (which includes sky chopping) and so this is being used as a benchmark for SCUBA-2.

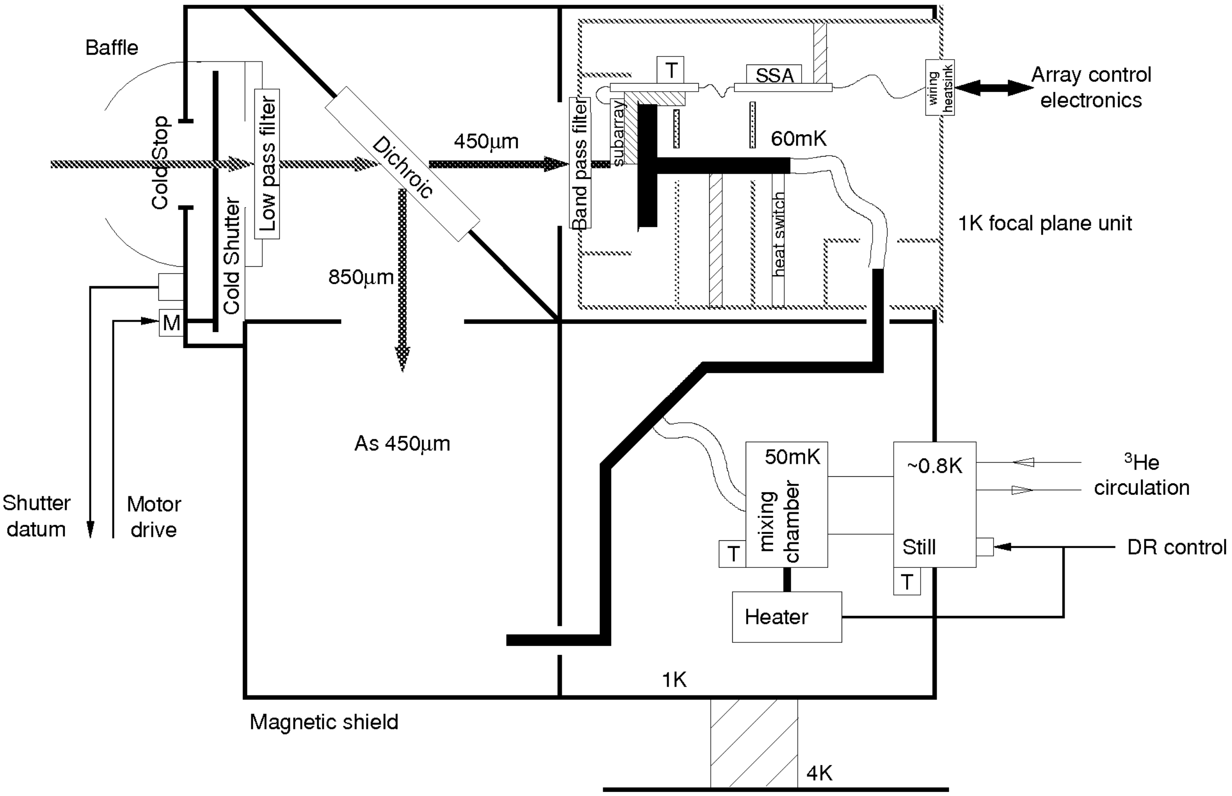

Figure 4: The layout of the 1K focal plane box, highlighting the modular design of the cryostat.

Unlike SCUBA, which can only record an AC (i.e. chopped) signal, the signal output of the SCUBA-2 pixels will be DC-coupled to the signal-processing electronics. This will lead to significant efficiency improvements, since half of the integration cycle is not spent on blank sky. There is no need for sky chopping, leading to better image fidelity, sensitivity to source structure on ALL scales. It also gives a lower confusion limit i.e. by not continuously subtracting two images of the sky. However, the main complication is that 1/f noise from detectors or electronics must be at an acceptable level. A cold shutter will take "dark frames" to compensate for any 1/f noise and any other instrumental drifts. In summary, it is envisaged that SCUBA-2 will provide JCMT with the following observing modes:

- **Imaging mode**: observing regions of sky equivalent to the array field-of-view or mosaicing together offset frames to produce an image up to a few arrays in size
- **Survey (or scan) mode**: mapping large areas of sky, potentially up to tens of degrees at a time
- **Spectroscopic/polarimetric mode**: Imaging polarimetry and medium resolution spectroscopy will be possible with additional hardware

Operationally, SCUBA-2 is likely to differ from previous JCMT instruments in that it must be capable not only of *'normal' observing programmes* (scheduled as blocks of between a few hours and several shifts), but also for conducting large-area *'semi-automated' surveys* of the sky (perhaps carried out by one person remotely from Hale Pohaku or Hilo). In particular, the latter mode requires well thought out observing strategies and data reduction pipelines, as well as a stable and reliable instrument.

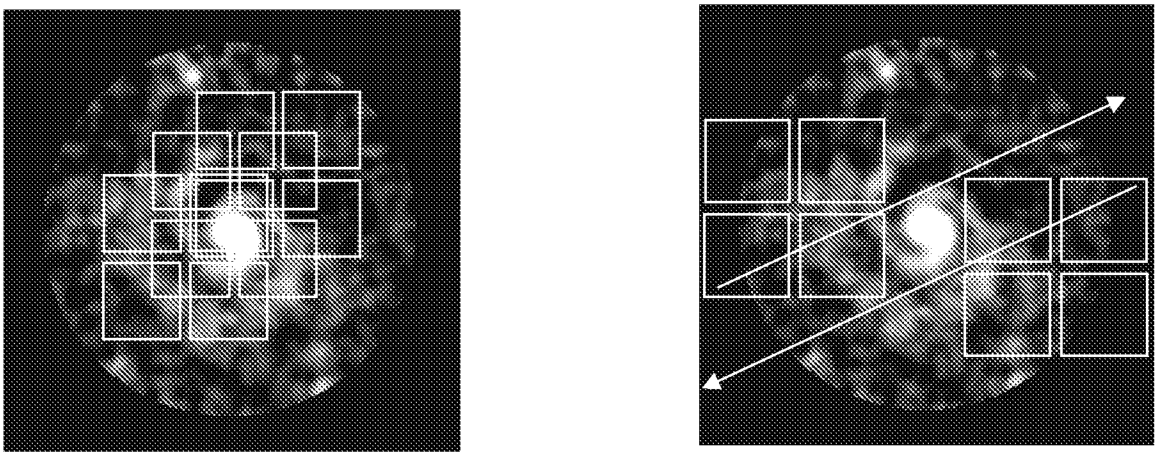

Figure 5: Illustration of the SCUBA-2 observing modes. (a) Imaging mode with offset stare patterns, (b) Survey mode with interleaved scans. Image of M51 courtesy of Remo Tilanus.

4.1.1 Imaging mode

The most simple observing mode to visualise is 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. In this mode the map size is fixed to be the field-of-view on the sky. A requirement for any instrument that will perform *deep imaging* is that the rms noise in the map should integrate down with the square root of the integration time. That is, the longer you integrate the "deeper" the map will be. Since SCUBA-2 will be a DC-coupled system any excess noise from the detectors or electronics, not removed by dark frames, may cause a residual "floor" or deterioration in the rms noise. Since a "confusion-limited" map will be obtained in about 1 hour at 850μm, it should be a requirement that the noise integrates down for *at least* this time period.

In addition to the complications of residual 1/f pedestal, the brightness of the atmosphere with respect to the astronomical source, means that a simple stare mode requires a highly accurate flat-field. The SCUBA-2 pixels will all have slightly different sensitivities. To ensure the astronomical images reflect real source structure these pixel to pixel variations in sensitivity have to be calibrated out. The accuracy required for the flat-field depends on observing mode and integration time but is most severe for a stare-mode (estimated to be 1 part in 10^7 for a one-hour observation). There are also potentially several factors that can cause the flat-field to vary. These include drifts in the electronics (must be made as common mode as possible), 1/f noise in the detectors or SQUIDs, variations in the detector responses as a function of background power (i.e. caused by relative changes in the bias setting). Hence, any flat-field changes will need to be monitored and corrected in real time (most likely using the cold shutter). However, the accuracy required may still not be achievable in practice for ultra-deep (or even reasonably shallow) observations. Alternative methods of "staring" are being considered, including a mode based on the DREAM observing strategy[7], developed for SCUBA (but never implemented due to the high sensitivity of the SCUBA bolometers to vibration from the secondary mirror unit). DREAM avoids the flat-fielding problem by using each bolometer to make a mini-map overlapped with its neighbors and then combining the result. Initial simulations of "DREAM-2" have been very successful.

4.1.2 Micro-stepping

Since the SCUBA-2 450μm array will instantaneously undersample the sky it will be necessary to fill in the gaps by using a small micro-step or jiggle (similar to that carried out with SCUBA). This will also compensate for the one-pixel gap between sub-arrays. Imaging mode will compensate for bad pixels (and/or rows/columns of dead pixels) and seams between the sub-arrays. If there are noisy pixels or bad columns of pixels then a more complicated micro-step may be necessary. If long integrations are needed sky rotation could fill in these gaps. The step will be done by the SMU, which is much quicker than moving the telescope. The size of the step may be dependent (limited) on edge-of-field aberrations induced by tilting the secondary mirror.

4.1.3 Mosaicing frames

It will be possible to mosaic individual SCUBA-2 frames together similar to an optical CCD camera or IR array. SCUBA has also frequently been used in this mode – i.e. coadding, spatially offset jiggle maps. 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). An obvious issue is whether mosaicing stare-maps or scanning is the most appropriate mode for objects that are extended by, say, a few fields-of-view. In mosaicing maps the challenge is likely to be in subtracting the sky background level in such a way that when the data frames are coadded the final image does not contain "seams".

4.1.4 Survey (scan) mode

One of the major SCUBA-2 scientific goals is to conduct unprecedented wide-field surveys of the sky. The baseline mode here would be to scan the telescope very quickly across a source in an (overlapping) raster pattern. The detector speed of response and the ability of the telescope to maintain astrometric information within the confines of the observation will determine the fastest speed. Scan speeds as high as 600 arcsecs/sec are likely. Scanning has much lower requirements on the flat-field accuracy and stability since the background will be removed by fitting a baseline to the raw data from each pixel. A 2 minute scan, at 600 arcsecs per second, and assuming no overheads would cover a strip of 20 degrees × 8 arcminutes. Shallow all-sky surveys could, in principle, be completed in just a few hours. Such a survey would ideally be one of the first observations after completion of commissioning.

There is likely to be a subtle trade-off between scanning slowly (say, at a similar to SCUBA – 24 arcsecs/secs) or scanning very quickly (600 arcsecs/sec). The trade-off is whether we should scan fast and cover a region a multiple number of times, or scan slow and spend more time per spatial point. Maintaining image registration and astrometry are also important here. There may also be issues associated in how the background is subtracted. The undersampled 450μm array makes scanning more complicated. Ideally, scanning should be along a line of azimuth (i.e. same airmass) to make atmospheric attenuation corrections simpler (and, in principle, more accurate).

Large area surveys carried out in this mode will likely be made public to the JCMT community immediately and may ultimately involve areas of thousands of square degrees. In this mode, JCMT will operate each night in a systematic and pre-planned way. Aside from instrument/telescope or weather problems, *the telescope and camera combination should function semi-automatically with little intervention, so that efficiency is maximized and observing practices are consistent.*

4.2 Instrument performance model

Models of the overall SCUBA-2 instrument, including the telescope and Mauna Kea site, have been constructed for each wavelength. This has allowed predictions to be made of the performance of SCUBA-2 under a variety of conditions. The key components of the model are described below:

- *Atmospheric model.* The Rice and Ade model[8] for the atmospheric transmission of the Mauna Kea site was used to estimate the background sky power and photon noise levels under various amounts of precipitable water vapour. These are summarized in Table 1.

- *Detector NEP.* Ideally, the overall instrument sensitivity should be limited by the background photon noise (from the sky and telescope) and not by the intrinsic detector or electronics noise. This means adopting a detector noise equivalent power (NEP) of half that of the minimum background noise. Given the large numbers of pixels in SCUBA-2 some extra engineering tolerance must also be allowed for in detector NEP. The 850μm array sets the most stringent limitations and requires an ideal detector NEP $< 3 \times 10^{-17}$ W/√Hz.

Parameter	450μm	850μm
Minimum background power (pW)	92	7
Maximum background power(pW)	150	19
Minimum background limited NEP (W/√Hz)	2.9×10^{-16}	6.5×10^{-17}
Maximum background limited NEP (W/√Hz)	3.7×10^{-16}	9.5×10^{-17}

Table 1: Estimated background power levels and minimum NEPs[g]

- *Array architecture.* Pixel spacing of Fλ and 0.5Fλ in the focal plane are assumed for the 450 and 850μm arrays. In addition, a finite 50μm wall thickness is included between pixels in the square array geometry. The 8 × 8 arcminutes field-of-view is included in the mapping speed calculations.

- *Filters and passbands.* The filter passbands will be designed to match the atmospheric transmission windows at 450 and 850μm, and are to be similar to the current filters in SCUBA. This will require bandwidths of ~65 and 35GHz at 450 and 850μm. A high efficiency dichroic is also included in the instrument design.

- *Optical system (including telescope).* The illumination of the telescope will be controlled by a 1K cold stop. This will give a "top hat" illumination with a tapered profile. Realistic Strehl ratios and surface micro-roughness estimates for re-imaging mirrors have been included in the model. The telescope will have a primary surface with a large-scale error of ~20μm rms, and so this has been used in the calculation of telescope effective area.

In addition the model assumes the following:
- all overheads due to telescope movement and field overlapping are ignored
- an observing efficiency of 70%
- the effects of sky-noise and refraction variations are ignored
- high absorption efficiency (75%) for the detectors

The output of the model is an estimate of the overall sensitivity as a function of sky transmission. This is the noise equivalent flux density (NEFD), which is the flux density that produces a signal-to-noise of unity in one second of integration. The calculations ignore the effects of spatial and temporal variations in atmospheric emissivity on short timescales ("sky-noise"). Mapping speeds to extract point source fluxes and cover large areas are also calculated.

Parameter	450μm	850μm
Per-pixel NEFD (mJy/√Hz)	75	32
Point-source NEFD (mJy/√Hz)	107	22
Point-source mapping speed (w.r.t. SCUBA)	10	12
Large-area mapping speed (w.r.t. SCUBA)	810	980

Table 2: Summary of NEFDs, point source and large area mapping speeds (with respect to SCUBA)

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[g] Sky transmission for minimum and maximum background is estimated to be 50 and 2% at 450μm and 85 and 20% at 850μm.

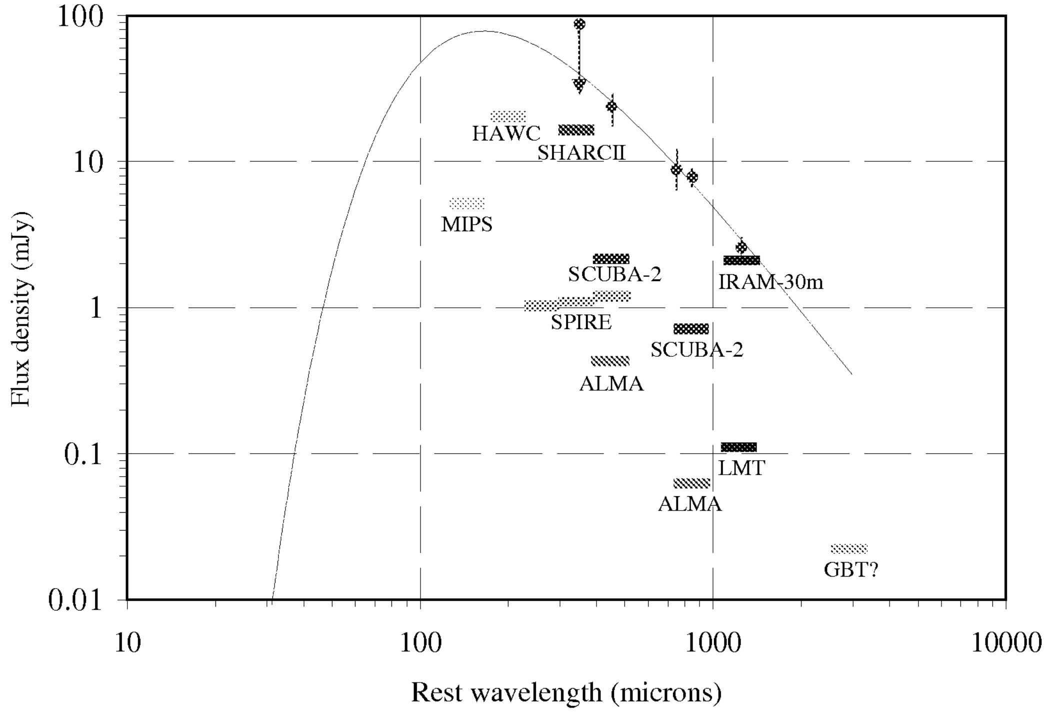

Figure 6: Measured spectral energy distribution of the high-z radio galaxy 8C1435+635 (from Ivison et al. 1998[9]) with a modified blackbody fit for T=30K dust with β=2. The SCUBA 450 and 850μm detections (3-σ and 10-σ) are amongst the points shown and the total integration time for this simultaneous observation was 4.7 hrs. Also shown are the 5-σ detection limits for other bolometer arrays (and ALMA in compact mode) for the same integration time.

4.3 Point source sensitivity

In terms of the sensitivity to point sources SCUBA-2 will be considerably better than SCUBA due to improved performance of the TES superconducting detectors, improved optical design (better transmission and baffling), and intrinsically better performance of the telescope (particularly at high frequencies). Table 2 summarizes the estimated point-source sensitivities derived from the SCUBA instrument model[h]. It can be seen that SCUBA-2 is expected to be a factor of ~10 times faster at detecting known-position point sources than SCUBA. Figure 6 shows the 5-σ detection limits of a number of future submillimeter/millimeter instruments compared to SCUBA-2, for the same integration time as the SCUBA 450/850μm detections.

4.4 Mapping speed

The biggest contribution that SCUBA-2 will make to submillimetre astronomy is in surveying large areas of sky to great depth. *SCUBA-2 therefore seeks to maximise the survey speed.* This is defined as the speed with which areas of sky can be surveyed to a given depth. It is inversely proportional to the time taken to image to that depth:

Survey speed ∝ (area to be mapped) / (time taken to reach a given depth in a single frame)

The predicted mapping speeds for large areas of sky (greater than the array field-of-view) with respect to SCUBA are summarized in table 2. These estimates assume an observing efficiency of 70%. The large-area mapping speeds are also summarised in Table 2. Figure 7 illustrates the kinds of surveys that could be carried out with SCUBA-2 and the time estimates for each.

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[h] The effective point-source NEFD is lower than the per-pixel NEFD at 850μm since the signals from neighboring pixels (0.5Fλ spacing) can be co-added to improve the detection sensitivity.

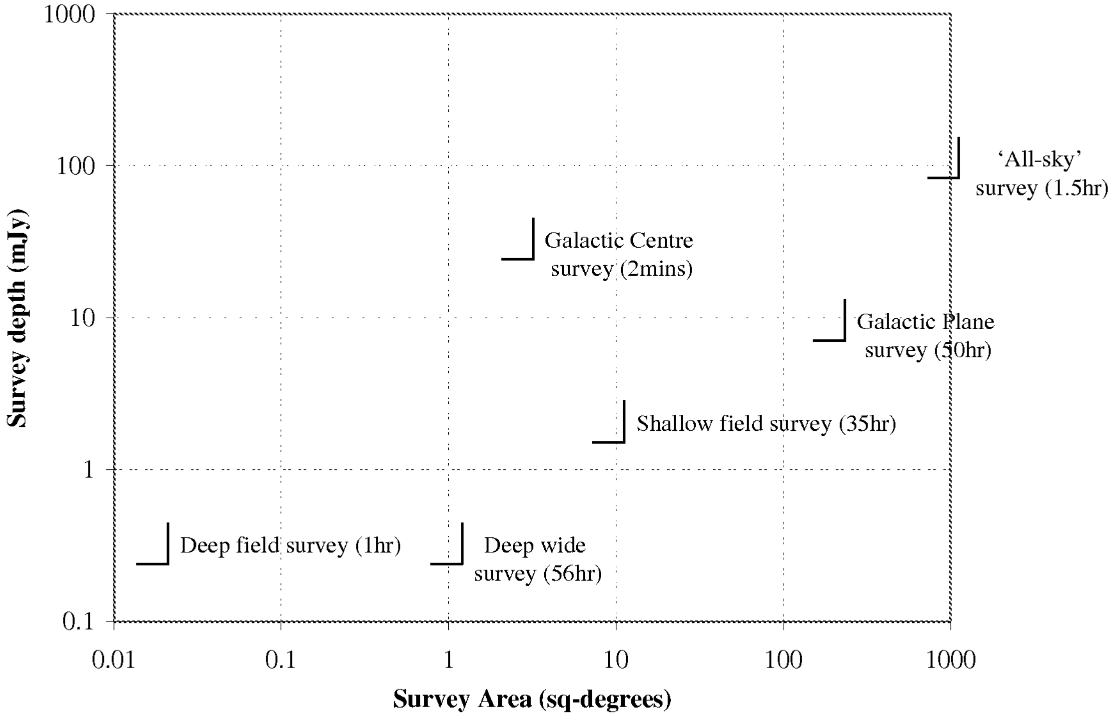

Figure 7: Examples of the wide-field surveys that could be carried out with SCUBA-2.

5. SCIENTIFIC IMPACT

The science case for SCUBA-2 covers almost all areas of astronomy from the study of Solar System objects to probing galaxy evolution in the early Universe. *In particular, SCUBA-2 will allow projects to be undertaken that are currently impossible with SCUBA.* Some examples of these for both galactic and extragalactic astronomy are given in the next two sections.

5.1 Galactic astronomy highlights

The Galactic science case for SCUBA-2 ranges from the earliest stages of cloud evolution to stars at the end of their lifetimes, and from the smallest cores to Galaxy-wide scales. Some potential highlights include:

Star formation in our Galaxy. Star-formation remains an unsolved problem. So far only ~1 square degree has been imaged of the dozen or so giant molecular cloud complexes within 1 kpc of the Sun. A full survey with SCUBA-2 will reveal future stars ranging from tens of stellar masses down to brown dwarfs – or smaller (SCUBA has detected cores down to Jupiter-like masses). Such surveys will provide the vital clues to whether there is one single formation mechanism for all bodies from massive stars to sub-stellar objects – even isolated 'planets' freely floating in space.

The origin of dust. Despite the fact that submillimetre astronomy relies on the existence of interstellar dust, very little is known about its origin. It is generally assumed that about half the dust in the interstellar medium has been produced in supernovae, but there is almost no evidence that this is the case. The ideal way to test this is to observe supernovae remnants which are young enough that little dust will have been swept up from the ISM, but even young supernova remnants are too large and with too low surface brightness to be mapped with SCUBA. The other source of dust, evolved stars, produce extended dust shells that are detected many arcmin from the parent stars. SCUBA-2 will be ideal for mapping both types of object—and thus answering the question of where and how dust is formed.

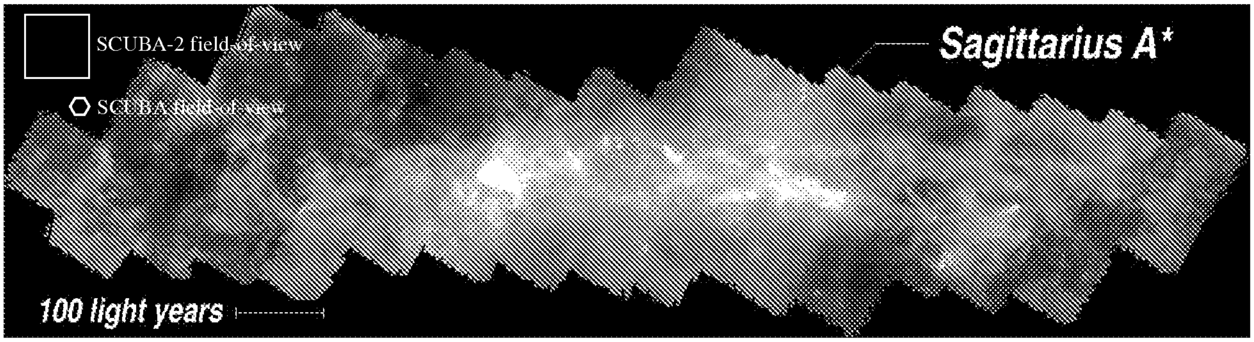

Figure 8: The SCUBA image of the Galactic Centre (Pierce-Price et al.[10]) took 120 hrs to complete. SCUBA-2 could image this entire area in about 7 minutes to the same signal-to-noise.

The formation of planetary systems. The study of debris disks of cold dust around nearby stars can give vital clues to the planetary formation process[11]. Not only do such images give us an effective 'time series' showing how our early planetary system evolved from a circumstellar disk, but perturbations, seen as clumps and cavities in the observed image, have the potential for actually pinpointing the locations of young planets. Although SCUBA has made pioneering breakthroughs in this area, it has lacked the sensitivity to study more than a handful of such objects. The imaging power of SCUBA-2 will enable the study of more than 25 further systems within 20pc of the Sun.

High latitude clouds. Recently, cloud cores have been detected at high latitudes above the Galactic Plane. Are these transient density fluctuations or very rare sites of new stars being born in the Galactic Halo? SCUBA-2 will be the most efficient way to search for these cores—not only may they reflect star formation in an unusual environment, but they could also mimic distant bodies such as high-z galaxies. Comprehensive number counts are thus essential.

Galactic Plane survey. There is NO survey of the entire Galactic Plane in the submillimetre. The best available are the 8-arcmin resolution maps of optically thick CO emission[10]. Since dust is a much better unbiased mass tracer, the SCUBA-2 Galactic Plane survey will give the first true census of the star-forming cloud population and the total mass of cold dust in our Galaxy. At the moment, more is known about the dense clouds in the Andromeda Galaxy than about those in the Milky Way! With SCUBA-2, a 180 × 2 degree survey would take only 50 hours, reaching a level to detect even the coldest pre-stellar core population. Such a survey with SCUBA would take over 5 years.

Interstellar magnetic fields. With SCUBA-2 (and its polarimeter) it will be possible to make not only the first wide-field polarisation images of our Galaxy (where the large-scale magnetic structure in dense clouds has never been explored), but also to extend this for the first time to other nearby spirals and starburst galaxies. Does the global magnetic field play a major role in channelling gas flows and intensifying star formation activity? This is generally believed to be the case, but the details remain elusive.

5.2 Extragalactic astronomy highlights

The extragalactic astronomy case builds upon the remarkable impact of SCUBA on our understanding of the dust-obscured star formation in both the local and distant Universe. In particular, SCUBA-2 will provide unique insights into the earliest phases of the formation of massive galaxies in the early Universe. Potential highlights include:

Galaxy formation in the early universe. Submillimetre observations offer equal sensitivity to dusty, star-forming galaxies over a uniquely wide range in redshift ($1 < z < 10$), and hence instant access to the high-z universe. Current SCUBA surveys have uncovered only a few hundred submm galaxies—the vast increase in mapping speed afforded by SCUBA-2 would allow the first statistically reliable study to be undertaken (see Figure 9). Follow-up of the current samples suggests that these sources represent a population of dusty galaxies at $z = 1–4$ which contain half of the massive star formation occurring at these epochs. The submm population therefore represents an important phase for understanding the formation and evolution of the galaxies we see in the Universe today. However, these follow-up studies indicate that the counterparts to the submm sources are extremely faint in all other wavebands and we must therefore rely on their submm properties to further our understanding of their nature and evolution.

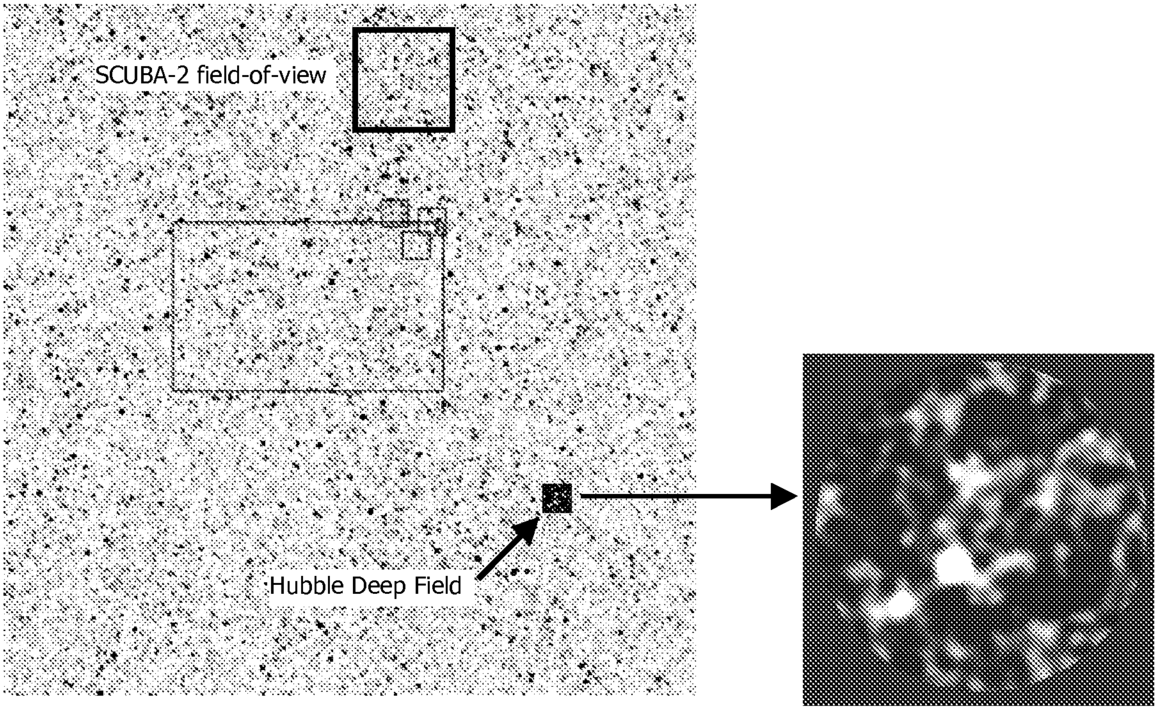

Figure 9: A simulated deep cosmology survey with SCUBA-2[12]. The small image towards the lower right is the submm image of the Hubble Deep Field[13]. This is currently the deepest submm map ever taken requiring 50 hours of the best weather on Mauna Kea. The other boxes represent other surveys which are considerably less deep. SCUBA-2 will map this entire 1 sq-degree area to the depth of the current HDF map (confusion limit) in only 20 hours.

Cosmic History of Star-Formation. It is known from studies of the CMB that the Universe started off in a very uniform state, with no real structures. At some point the "Cosmic Dark Ages" came to an end through the birth of the first stars within primordial galaxies. Nuclear energy was converted to light in stellar interiors, and had important heating and ionization effects on the surrounding medium. Exactly how this process began and evolved is currently one of the greatest cosmological puzzles. Recent work in the submillimetre has shown that luminous infrared galaxies evolve more strongly than their more normal optically-bright counterparts. It has also become clear that luminous obscured galaxies at high redshift contribute a substantial fraction (arguably the majority) of the total emitted radiation in the Universe. Roughly half of all the stars that have formed by the present day probably formed in highly obscured systems. To trace the star-formation history of the various galaxy types over cosmic history with high precision requires much larger samples than currently available. SCUBA-2 will allow us to trace this cosmic star-formation history.

Large-scale structure. Do the bright submillimetre sources discovered in SCUBA surveys represent forming ellipticals or merely short-lived bursts of violent activity in less massive galaxies? If they really are the progenitors of massive ellipticals then they should be strongly clustered (on scales of 30 arcminutes). SCUBA-2 surveys of many degrees of sky down to the confusion limit will be crucial to address this question. If the submillimetre sources do represent the formation of the massive ellipticals that dominate the cores of rich clusters of galaxies in the local Universe, then these surveys will also provide an important tracer of the growth of large scale structure in the very early Universe, $z > 2$–4.

Understanding galaxy populations and evolution. Galaxies are the fundamental building blocks of the Universe. By comparing submillimetre observations with optical, infrared and radio data it will be possible to investigate the relationship between galaxy populations selected in different wavebands (e.g. Lyman-break galaxies, Extremely Red Objects or X-ray selected AGN and QSOs). Fundamentally, this will allow a test of the existence of an evolutionary cycle connecting the various classes of high redshift galaxies. Given the faintness of submillimetre galaxies in the optical/UV this approach is the only viable route to understanding the properties of these enigmatic galaxies.

The Local Universe. The submillimetre is a crucial regime to study star formation in nearby galaxies. Recent work suggests that surveys carried out at mid/far-IR wavelengths have missed the bulk of the cold dust emission since it lies in cold, extended, low-surface brightness disks, often far from the galactic nucleus. The imaging power of SCUBA-2 will be a very effective way to study star formation far from the galactic nucleus, with the possibility of resolving individual giant molecular clouds. In addition to studying individual nearby galaxies, SCUBA-2 will be vital for determining the low-z benchmarks, such as the local luminosity and dust-mass functions, which are needed to interpret information from the deep cosmological surveys[15]. Unbiased submm surveys of the local Universe have been severely hampered by the small field-of-view of the current arrays. SCUBA-2 will be able to carry out an inventory of cold dust in the local Universe, with the possibility of even detecting new types of galaxy.

The Sunyaev-Zel'dovich effect. Cosmic microwave photons change energy as they are scattered by hot gas in galaxy clusters. The S-Z effect has become a unique probe of conditions in rich clusters. Most observations have been in the radio, but the submm provides valuable additional information since it detects the upscattered photons. So far results have been disappointing since current array sizes and sensitivities make it nearly impossible to remove atmospheric effects. Moreover, even in the radio most observations have targeted known clusters. "Blank field" searches for clusters in the submm are likely to be more effective than their X-ray counterparts since they reach to higher redshift and are directly sensitive to the column density of gas. Detailed surveys, possible with SCUBA-2, allow the investigation of a wide range of cosmological questions beyond those probed by distant dust-emission: formation and evolution of clusters of galaxies; internal structure of clusters; large-scale motions in the Universe; and evolution of the cosmological background, including the nature of the Dark Energy.

6. SCIENTIFIC COMPETITIVENESS

SCUBA-2 will be a highly sensitive, wide-field imager capable of mapping large areas of sky in unprecedented detail. SCUBA-2 on the JCMT in 2005/6 will maximize the competitiveness of the telescope in the era of the development of other array instruments. Table 3 presents of sample of new instruments that will come into service over the next 10 years.

Instrument (telescope)	Year of operation	Wavelength (μm)	Relative imaging speed	Resolution (arcsecs)
SCUBA (JCMT)	1999	450	0.0014	7.5
		850	0.001	14
MIPS (SIRTF)	2002	160	24	45
BLAST	2003	350	2.4	30
		750	0.005	75
HAWC (SOFIA)	2004	200	1.7	45
BoloCAM (LMT)	2005	1100	0.13	6
SCUBA-2 (JCMT)	**2006**	**450**	**1.1**	**7.5**
		850	**1.0**	**14**
SPIRE (Herschel)	2007	250	26	18
		450	0.3	36
Compact ALMA	2010	450	0.05	0.03
		850	0.12	0.06

Table 3: Comparison of SCUBA-2 performance to other instruments[i]

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[i] Imaging speed calculations are relative to SCUBA-2 at 850μm. For completeness, a ν^3 dust-spectrum is assumed and sensitivity levels at other wavelengths are calculated with respect to this.

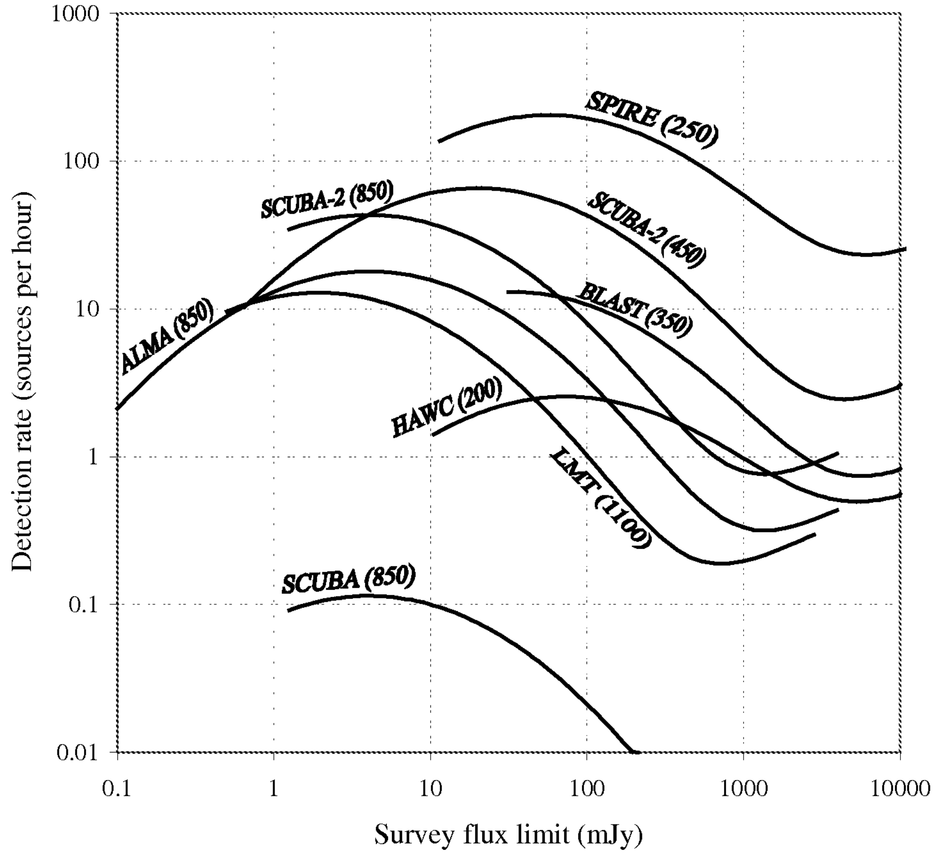

Figure 10: The detection rate as a function of 5-σ survey depth for a range of galaxy surveys (adapted from the model of Blain[16]). The curves stop at the confusion limit on the left (one source per telescope beam) and where the source count falls below 1/4π sr^{-1} on the right.

Two figures of merit are highlighted. The *imaging speed* is how quickly an instrument can map a region of sky to a given sensitivity limit, and is a function of the detector sensitivity and field-of-view of the instrument (with the former also depending on the telescope aperture and quality of the observing site). The *resolution* is how well an instrument can pick-out detail, and depends on the wavelength of operation and telescope aperture.

Using SCUBA-2 for imaging surveys is well illustrated in Figure 10, which compares the effectiveness of the above instruments in carrying out deep extragalactic surveys. Although instruments such as SPIRE can rapidly cover wide areas (and hence, in principle, detect lots of sources), their surveys quickly become 'confusion-limited' in that their relatively poor resolution means they cannot discriminate between more than one source in the same telescope beam (below about a flux limit of 10 mJy for SPIRE at 250μm). However, SCUBA-2 is not only effective at mapping large areas but can also image down to very low flux limits. This means, for example, in the nearby Perseus molecular cloud, SCUBA-2 has a sensitivity sufficient to detect cores of only a few × Jupiter mass. Single dish telescopes, equipped with large-format imaging arrays, will remain the most efficient way to conduct large-area surveys, and will provide a wide-field complement that is essential to fully-exploit the capabilities of interferometers. For example, SCUBA-2 could follow-up large-scale, shallow surveys by SIRTF, with ALMA detailing individual sources at high resolution.

It should also be noted that SCUBA-2 would not only be competitive with but also very complementary to other facility instruments. For example, it would provide vital longer wavelength information to a SIRTF study of the spectrum of a protostar or of the high-z cosmic submillimetre background. By combining data from SIRTF (at 160 micron) – close to the turnover of the greybody spectrum – with data from SCUBA-2 (450/850) on the constant slope Rayleigh-Jeans tail, it will be possible to directly measure both the dust temperature and grain emissivity, and hence accurately constrain the mass of an object in a model independent way. With this vital data point we can, for example, decide whether a dust core is pre-stellar or contains a warm protostar that has commenced nuclear fusion. In addition, by measuring the far-infrared/submillimetre colours it is possible to obtain strong *direct* constraints on the redshifts of distant dusty galaxies (without any optical identification being required). This is vital, as otherwise many of these sources would remain completely enigmatic, as they are too faint for optical spectroscopy – even with 8m-class telescopes.

Table 4 presents a selection of example observations that SCUBA-2 could undertake with time estimates compared to the same observation with SCUBA.

Example observation	Integration time (hrs)	
(850μm)	SCUBA	SCUBA-2
Point-source photometry to a 5-σ flux limit of 2 mJy	7.5	0.6
Map of the Hubble deep field to noise level of 0.5 mJy	32	0.5
Galactic Plane survey (20×2°) to noise level of 30mJy	850	0.9
Survey of a 5° diameter molecular cloud to noise level of 10 mJy	4700	5
Deep extragalactic survey of a 1-deg^2 area to noise level of 0.5 mJy	22000	23

Table 4: Examples of possible SCUBA-2 observations at 850μm. A much wider area would be covered for the Hubble Deep Field observation.

7. SUMMARY

SCUBA-2 represents a major innovation from current submillimetre instruments. Incorporating state-of-the-art technology will allow the realisation of the first large-format "CCD-like" camera for submm astronomy. The science applications for such an instrument are tremendously exciting and very broad-based, ranging from the study of Solar System objects to probing galaxy formation in the early Universe. *SCUBA-2 will map large-areas of sky up to 1000 times faster than the current SCUBA.* The improved sensitivity and imaging power will allow the JCMT to really exploit periods of excellent weather on Mauna Kea. Undertaking wide-field surveys with SCUBA-2 are vital to fully exploit the capabilities of the new generation submm interferometers. Finally, the new technology has applications beyond SCUBA-2, and thus represents a major strategic investment on behalf of the JCMT funding agencies.

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