SCUBA-2

A Submillimetre Wavelength Camera for Astronomy

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Introduction

The most successful submillimetre astronomy instrument over the past decade has been SCUBA, a camera that is mounted on the James Clerk Maxwell Telescope (JCMT) in Hawaii, a joint project of the national astronomy organizations in the United Kingdom, Canada, and The Netherlands. As participants in the JCMT consortium, Canadian astronomers have been closely associated with the amazing successes of SCUBA, some of which are described below. Now, as many other observatories in the world are developing competing instruments, Canadian astronomers are building on this success. With a huge step forward in technology SCUBA-2 will be a next generation submillimetre camera that will far surpass those available anywhere else in the world, helping Canadian astronomers to stay at the forefront of this field at the centre of modern astronomy.

The SCUBA-2 project is a joint initiative of a group of institutions in Canada and the United Kingdom including the Astronomy Technology Centre (ATC) at the Royal Observatory, Edinburgh, the University of Cardiff and a large Canadian SCUBA-2 Consortium. Major Canadian participants are: the University of Waterloo, University of British Columbia, University of Lethbridge, and Université de Montréal. Initial funding for the development of SCUBA-2 came from the JCMT Instrument Development Fund. Funds for the construction of SCUBA-2 were provided by the Particle Physics and Astronomy Research Council (UK) and the Canada Foundation for Innovation (CFI).

The JCMT is the world's largest radio telescope capable of working at submillimetre wavelengths (it operates at wavelengths between 0.3mm and 3mm or 300 to 3000 microns). The biggest restriction to observing at submillimetre wavelengths is water vapour in the atmosphere, which strongly absorbs the signals from the astronomical sources being observed. In order to minimize this the choice of site is vitally important. Located at the summit of Mauna Kea (4092m) in Hawaii at the highest point in the Pacific Ocean, the telescope is above 97% of the water in the atmosphere. Due to its distance from sources of industrial pollution and city light pollution as well as its exceptional weather characteristics Mauna Kea is one of the premier observing sites in the world.

Two major types of instrument are present on the telescope. Spectroscopic instruments are used to study line emission from different types of molecules. Continuum instruments (such as SCUBA and SCUBA-2) detect interstellar dust emission enabling investigation of the physical characteristics of dust and its role in the star formation process. Several devices are available that enhance the operation of the major instruments. For example, polarimeters can be used in conjunction with both spectroscopic and continuum instruments to determine interstellar magnetic field geometries. In order to minimize background noise that would otherwise make observing impossible these instruments are cooled to extremely low temperatures, less than 0.1 degrees above absolute zero in the case of SCUBA.

SCUBA

The JCMT began operation in 1987 with a sensitive single channel bolometer, the best detector then available, that measured the brightness of one spot on the sky – a single pixel. To make an image required such a laborious process of scanning this across the sky that only a few modestly-sized images were ever made.

A first generation of "Common User" instruments was built with funding from an initial Instrument Development Fund that was set up by the JCMT partnership. The most successful of these instruments was **SCUBA**, the **S**ubmillimetre **C**ommon **U**ser **B**olometer **A**rray which was delivered to the JCMT in late 1996. This instrument consisted of two arrays, simultaneously imaging at two wavelengths (450 and 850 microns), with a total of 131 pixels. Its imaging speed is approximately **5,000 times greater** than the previous single channel instrument.

Exciting scientific results came from SCUBA almost immediately. Astronomers used SCUBA to find, for the first time, galaxies forming at the edge of the Universe in the distant past. SCUBA played a leading role in showing that the physical processes that select the masses of stars have already done so while the protostellar clouds are cold and large, before these clouds begin their gravitational collapse to form stars. Polarimetry (the measurement of the polarization of light) with SCUBA showed an amazing correlation between interstellar magnetic field geometries and the structure of interstellar clouds. Observations with SCUBA have found the dust leftover from the process of forming stars and planets in nearby solar systems, finally confirming established theoretical predictions. These and other examples of the exciting scientific results found with SCUBA are described in more detail below.

Table 1: Impact of SCUBA Publications (1999)

Instrument	**Description**	**# of Citations**
Hubble Space Telescope	Optical/UV; in space (NASA/ESA)	415
SCUBA	Submillimetre; ground-based (UK, Canada, The Netherlands national facility)	368
ROSAT	X-rays; in space (NASA)	205
Compton GRO	Gamma Rays; in space (NASA)	196
Keck	Optical; ground-based (CalTech and U.Calif.)	180
BeppoSax	X-rays; in space (ESA/NASA)	180
SOHO	Studies the Sun; in space (ESA/NASA)	121
CTIO 4 meter	Optical; ground-based (US national facility)	110
William Herschel Telescope	Optical; ground-based (UK, The Netherlands national facility)	84
Rossi XTE	X-rays; in space (NASA)	83
Hipparcos	Optical; in space (ESA)	72
ASCA	X-rays; in space (Japan/NASA)	68
Palomar 200 inch	Optical; ground-based (CalTech)	65
Kitt Peak Nat.Obs. 4 meter	Optical; ground-based (US national facility)	52

Further evidence of the success of SCUBA is obvious in the recently compiled "Citations to High Impact Papers, published in 1999" (Georges Meylan, Space Telescope Science Institute, Baltimore); these are shown in Table 1. By this measure SCUBA is by far the most successful ground-based astronomical instrument to date, and compares very favourably with space-based instruments (which of course cost far more).

SCUBA-2

The idea for SCUBA-2, came from an "upgrades design study" for SCUBA in mid-1998. In Feb. 1999 an International Review of the JCMT endorsed SCUBA-2 as the top-priority project for the strategic direction of the JCMT. A decision was made to use superconducting detector arrays (May 2000), and research agreements were signed in late 2000 to begin the fabrication of detectors.

SCUBA-2 will produce an enormous step forward in imaging speed over that of SCUBA, currently the best instrument of this kind in the world. There are two reasons for this increase. First, each pixel of SCUBA-2 will be more sensitive and more stable than the SCUBA pixels such that in common usage the sensitivity will be only limited by the background of the sky. Second, the number of pixels in SCUBA-2 will be enormously greater than in SCUBA. SCUBA-2 will consist of two sets of detectors, operating at wavelengths of 450 or 850 microns. Each detector will have 5120 pixels, for a total of 10,240 pixels, at 0.1 degrees above absolute zero, a factor of almost 100 greater than the 131 pixels in SCUBA. Together these improvements will result in **SCUBA-2 having a factor of 1000 increase in speed in making images** (over SCUBA). To put this in context: the entire operational lifetime of SCUBA is approximately 2500 nights. In less than three nights, SCUBA-2 will be able to reproduce all 2500 nights of observations undertaken with SCUBA. The ability of SCUBA-2 to observe large amounts of the sky in a short time (it will be a "wide-field" imager) will globally transform astronomical research at submillimetre wavelengths. In addition to the improvement in imaging speed at submillimetre wavelengths SCUBA-2 will also be equipped with two ancillary instruments: a polarimeter, providing scientists with the ability to measure magnetic fields in the interstellar medium, and an imaging Fourier Transform Spectrometer, that will permit intermediate resolution spectroscopy of large areas of the sky.

Research Opportunities with SCUBA-2

In many cases radio telescopes are used to study objects that are completely invisible to more traditional optical telescopes. One of the common sources of astronomical radio signals is interstellar dust: small grains of solid material. Interstellar dust blocks visible light and re-emits the absorbed energy as infrared or radio waves. In many kinds of object the radiation from this dust presents the strongest detectable signal. Such objects include stars in their youngest stages, surrounded by gas and dust disks that have not yet coalesced to form planets. Radiation from dust is often used as a probe of the material in other galaxies as well. These galaxies range from nearby objects to those at the farthest edge of the observable universe where the light from the creation of the first stars can be still detected. For several years SCUBA has been in the forefront of studies of radiation from dust.

Galaxy Formation in the Early Universe

Observing in the submillimetre offers equal sensitivity to dusty, star-forming galaxies over an enormous range in redshift ($1 < z < 10$), and hence access to the Universe at epochs from about half way back to only 5% of its present age. Current SCUBA surveys have uncovered about 100 submillimetre galaxies, which have changed our view of early star formation. **The vast increase in mapping speed afforded by SCUBA-2 would allow much more ambitious and statistically reliable studies of galaxies to be**

undertaken. Follow-up of the current samples suggests that the brightest sources represent the formation of the massive elliptical galaxies, which contain about half of the massive star formation occurring at these early times. SCUBA-2 will allow us to probe more normal galaxies as well. The population revealed in the submillimetre has proven to be extremely faint at other wavelengths. Figure 2 illustrates the mapping speed of SCUBA-2.

Cosmic History of Star-Formation

We know from studies of the Cosmic Microwave Background that the Universe began in a very uniform smooth state, with few 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 waveband 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 for the first time allow us to trace this cosmic star-formation history.**

Large-Scale Clustering.

If the bright submillimetre sources uncovered recently really do represent forming massive (elliptical) galaxies, rather than merely short-lived bursts of violent activity in the progenitors of more modest galaxies, then they ought to be strongly clustered together. To detect this clustering requires surveys of many square degrees, **which are currently impossible, but become relatively easy using SCUBA-2**. Since massive elliptical galaxies dominate the cores of rich galaxy clusters, such surveys will provide an important tracer of the growth of large scale structure in the very early Universe.

Understanding Galaxy Populations and Evolution.

Galaxies are the fundamental building blocks of the Universe, and yet we still have only a very sketchy understanding of the physical processes that select out objects of the particular sizes and shapes which we see in our cosmic backyard. Submillimetre observations are important for unveiling the "dark side" of galaxies. By comparing submillimetre observations with optical, infra-red, X-ray and radio data, it will be possible to investigate the relationship between populations selected in different wavebands. SCUBA-2 will be the best instrument available anywhere for studying the submillimetre emission from these galaxies. Fundamentally, this will allow a test of the existence of an evolutionary cycle connecting the various classes of high redshift galaxies. An issue intimately connected with this is the relationship between the formation of galaxies and the growth of the super-massive black holes that are believed to dominate their central regions.

The Sunyaev-Zel'dovich Effect in Galaxy Clusters.

Cosmic microwave photons change energy as they are scattered by the hot gas in clusters of galaxies. This so-called S-Z effect was postulated by two Soviet cosmologists 30 years ago, and has become a unique probe of the conditions in rich clusters. Most observations are carried out in the much easier radio band, but the submillimetre provides valuable additional information, since it detects the upscattered photons. So far results have been disappointing because the array size and sensitivity of current instruments makes it nearly impossible to remove atmospheric effects sufficiently. Moreover, even in the radio the vast majority of observations have targeted known clusters. "Blank field" searches for clusters in the submillimetre 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, of the sort that will for the first time become 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.

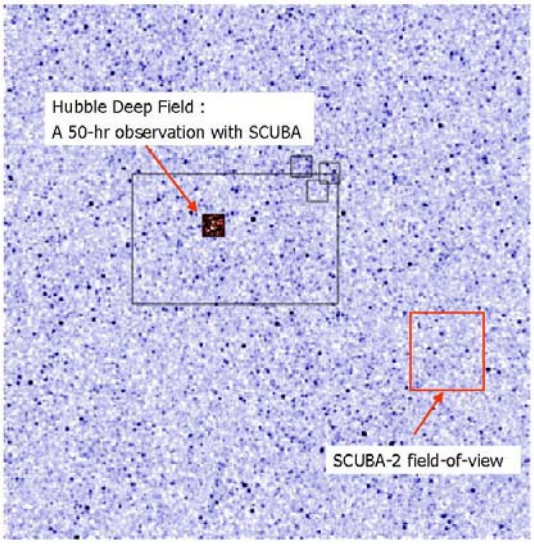


Figure 2: A simulation of what SCUBA-2 will be able to achieve in a deep cosmology survey. The very small central image, labeled Hubble Deep Field, shows the currently best information we have, requiring 50 hours of prime weather using SCUBA (the other small boxes represent other current surveys which are far less deep). The size of the SCUBA-2 field of view is shown at the lower right. SCUBA-2 will be able to map the entire 1 square degree area (the largest box) to the best current depth in only about 20 hours.

Nearby Galaxies

SCUBA-2 will have an enormous impact on the study of individual galaxies. Only a handful of galaxies have been detectable with SCUBA. However even those few objects have shown that previous studies (at other wavelengths) have missed finding the bulk of the dust in nearby galaxies. For example, a SCUBA study of the Andromeda Galaxy, the nearest large spiral galaxy to ours, has revealed an ultra-cold (~9K) dust component with five times the mass previously known. It may be true that most of the dust in all galaxies will lie in cold, extended, low surface brightness clouds. SCUBA-2 will be the most effective way to study these clouds. **SCUBA-2 will enormously increase the number of nearby galaxies that can be studied at submillimetre wavelengths.** Observations of nearby galaxies will have a number of goals including:

- studies of galactic structure (e.g. comparing the distribution of the dust to that of the neutral hydrogen, the molecular gas, and the optical emission) in spiral, irregular, and elliptical galaxies;
- examining star formation in very different environments;
- measuring the ratio of the mass in dust to the mass of gas in environments with different metallicities or UV radiation fields; and
- providing a census on the properties of local samples of galaxy types for comparison to samples at large redshift.

The Milky Way Galaxy

Figure 3 shows a recently produced very large scale SCUBA image of the plane of our Milky Way galaxy in the vicinity of the Galactic Centre. This superb image (made by a team of 14 astronomers from 5 countries including Canada) shows a great deal of structure and will be the object of extensive further study. The observations required to produce this image consumed many days of time using the JCMT and yet this represents approximately 0.01 *percent* of the plane of our Galaxy, and the plane of the Galaxy is only a small fraction of the overall area in the sky. While SCUBA is currently the most powerful instrument of its kind, it is still limited in what it can produce. There is a large international effort underway to image the entire Galactic Plane at other wavelengths, but with current instrumentation **this has not been possible at submillimetre wavelengths. Because of its great mapping speed it will become possible with SCUBA-2.**

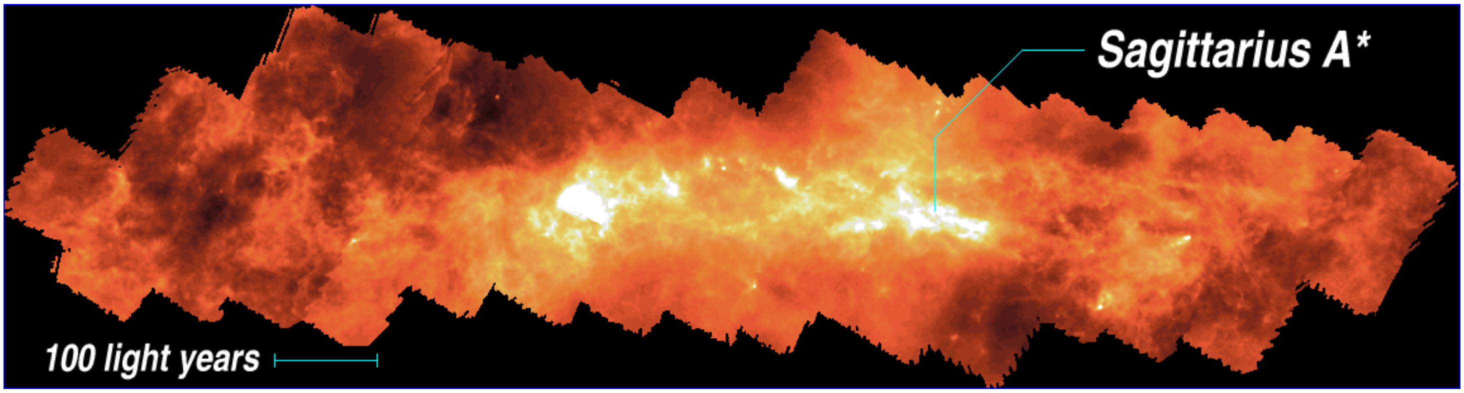


Figure 3: The Plane of our Galaxy towards the Galactic Centre (Sagittarius A)

Star Formation and Nearby Molecular Clouds

The lack of a sophisticated understanding of how giant reservoirs of gas and dust, molecular clouds, produce stars impacts almost all other areas of astrophysics. Most stars that are produced must have less mass than the Sun; however, the rarely formed massive stars will account for the bulk of all radiant energy and are responsible for much of the chemical enrichment of the Universe. Present star formation studies only provide broad hints to the process through which the mass of a star is determined. Stars form deep within molecular clouds where the obscuration of optical light is extreme. This obscuration also shields the local gas and dust from the insterstellar radiation field, providing a very low, <20K, regime where most of the energy that escapes does so at submillimetre wavelengths. Thus, submillimeter observations are key to understanding the physics of star formation, and SCUBA has played a leading role in this endeavour. While it is now known that, within the cloud, precise physical conditions such as, temperature, pressure, and magnetic field strength, are significant factors determining the numbers and masses of stars formed, we lack instruments with the sensitivity and stability to precisely measure these quantities. **SCUBA2 will break this impasse.**

With SCUBA it is possible to produce moderate-area, fraction of a square-degree fields, of nearby molecular clouds (such as the 850 micron image of Orion shown at right in Figure 4). A great deal of structure is found within these maps on all scales, from individual point-sources and moderately resolved clumps of prenatal dust and gas, through clusters of clumped sources, to large-scale filaments, with and without internal fragmentation. These SCUBA maps reveal that the molecular cloud material condenses into individual clumps, with a distribution in masses similar to that of the initial stellar mass spectrum. Yet only some regions of the cloud are able to form these clumps, and the clumps that form appear stable to internal gravitational collapse. On larger scales, details of the filamentary structure within molecular clouds provides evidence for the presence of ordered magnetic fields, which may be dynamically important.

While the SCUBA results are tantalizing, the physical conditions within both the condensed clumps, and the larger molecular cloud, are only inferred from the observations. **With SCUBA-2 this situation will change enormously.** For example, the increased speed of SCUBA-2 allows for orders of magnitude improvement in the size of surveyed molecular clouds, providing a detailed census of entire regions. The increased sensitivity and imaging power of SCUBA-2 will allow for detailed physical studies of individual fields within molecular clouds using both the FTS and the polarimeter. Obtaining low resolution spectra, with the FTS, will allow for investigation into the dust properties, temperature and emissivity, within each individual clump, as well as a quick census of the most important molecular species. These physical parameters are needed in order for theoretical models of the production and collapse of the condensations observed presently with SCUBA. Likewise, polarization orientation observations will provide evidence for the presence and importance of ordered magnetic fields in these regions.

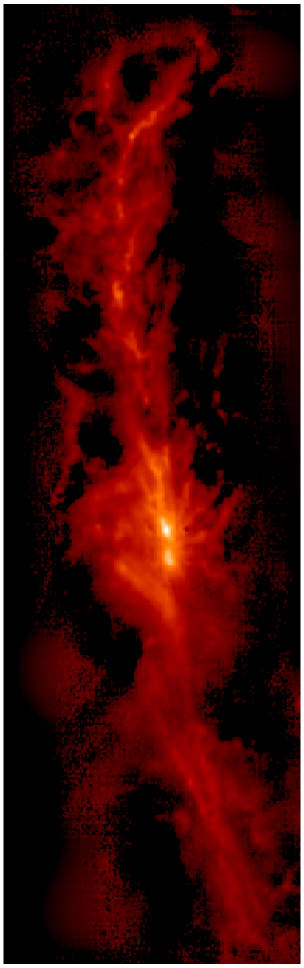


Figure 4: Orion at 850 microns

Signatures of Planets in Nearby Debris Disks

The study of debris disks of cold dust around nearby main sequence stars can give vital clues to the planetary formation process. This dust is thought to arise from material left over from the formation of planets. 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. In the numerical simulation of the ε Eridani dust disk (shown at right of Figure 5) an inner planet (known to exist from radial velocity searches) has cleared the central region (orbit shown as solid circle), whilst an outer planet (dotted circle) causes perturbations in the dust disk. The position of this putative planet can be estimated (large white dot). 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.

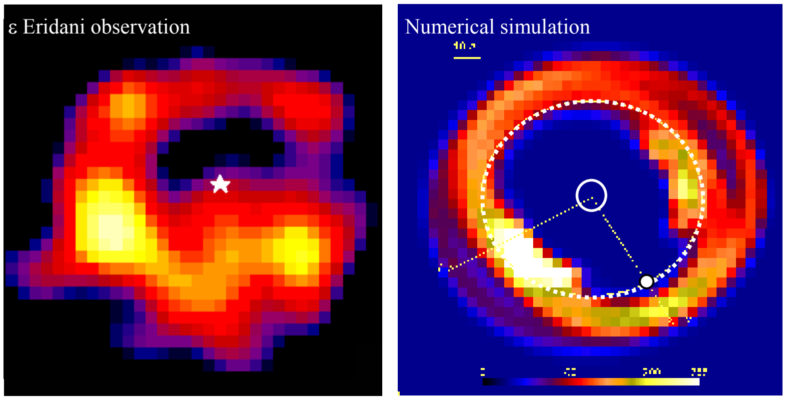


Figure 5: (Left): SCUBA 850 micron observation of the faint dust ring surrounding ε Eridani (Greaves et al. 1998). (Right): numerical simulation of dust trapped in mean motion resonances with a putative planet (Liou, Greaves & Holland 2002, in prep).

Comets

It has long been suspected that large particles may be present in comets, sufficient to dominate the total mass of the coma. Submillimetre observations are vital for studying the properties of these large particles; the data provide an estimate of the total mass, the dust mass production rate as a function of heliocentric distance, and the size of the particles in comparison with those in circumstellar disks. SCUBA-2 will permit the acquisition of "snapshot" images of comets as a function of heliocentric distance. These quick images are invaluable as near-Earth comets often necessitate daytime observing when calibration can be time variable and problematic. The high-dynamic-range images available with **SCUBA-2 will give a first detailed picture** of the time variability of ejection of dust and gas.

Asteroids and Near-Earth Objects (NEOs)

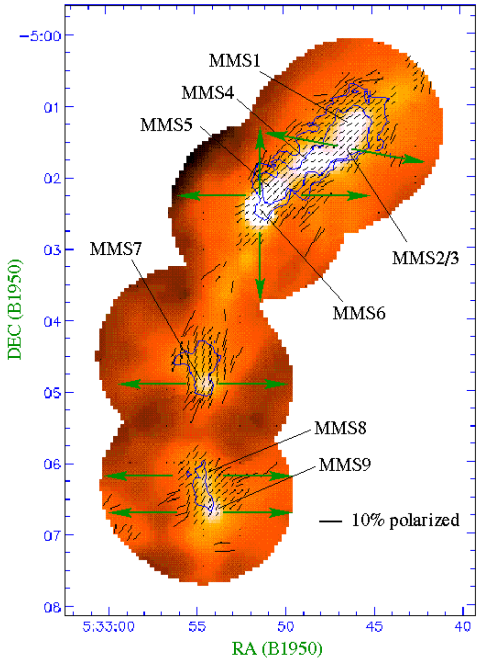
NEOs are scientifically important objects not only because of their proximity but also because they include most of the mineralogical classes of main-belt asteroids. Observations of asteroids and NEOs are challenging, however, because of their intrinsic faintness and their non-sidereal motion across the sky. The faintness problem will be addressed by the enhanced sensitivity of SCUBA-2. The solution traditionally applied to the location problem by optical astronomers is to observe the object with a camera possessing a wide field of view, so that the object is sure to appear somewhere in the image. SCUBA-2 will, for the first time, permit the adoption of the same strategy at submillimetre wavelengths. With SCUBA-2, photometry of faint, rapidly moving NEOs with poorly known orbits should become a straightforward application.

Trans-Neptunian Objects (TNOs)

More than 300 TNOs have been detected since the original discovery in 1991. The history and properties of these bodies are of direct interest for studying both the primordial Solar System and extrasolar analogues of the Kuiper Belt. Observations in the visible do not provide an unambiguous determination of the albedo, from which the size of the TNOs can in principle be determined. Combined visible and submillimetre photometry, however, can resolve the ambiguity and yield a unique solution. SCUBA-2, with its much larger field of view and improved point-source sensitivity, will allow deep and wide surveys of specific regions of the Kuiper Belt.

Polarimetry with SCUBA-2

The study of polarized radiation is the primary means of investigating the geometry of magnetic fields within astronomical sources. These fields are prevalent throughout galaxies, from the largest scales to the small cores that are collapsing to form stars within molecular clouds. Understanding the geometry of these fields, both at a global and a detailed level, is crucial to our understanding of star formation processes and the physics of molecular clouds. Polarimetric maps of dense filamentary clouds in Orion obtained with SCUBA have shown that the magnetic field structure (the many small straight lines in Figure 6) can be explained with a theoretical model of filamentary clouds with a helical magnetic field.



Recently, it has been possible to combine three observational techniques to obtain a 3-D map of the field configuration in the M17 molecular cloud. The strength of the magnetic field along the line of sight is provided by Zeeman measurements, polarimetric measurements give the orientation of the field in the plane of the sky, and the ion-to-neutral molecular line width ratio determines the angle between the magnetic field and the line of sight. SCUBA-2 will provide essential measurements for studying magnetic fields in 3-D in other regions.The SCUBA-2 polarimeter will be the most sensitive instrument for the detection of polarized radiation in the submillimetre regime. It will provide a strong complement to the planned Hale polarimeter on SOFIA (which will operate in the Far-IR). Together they will give the wavelength dependence of polarization that provides constraints on dust grain physics.

The advantages of polarimetry with SCUBA-2 as compared to polarimetry with SCUBA include:

a) the capability to mapping several thousand times faster than SCUBA to comparable sensitivities.
b) the ability to make large-scale polarimetric maps of lower density material in molecular clouds whose emission is too weak to map with SCUBA. This is needed to show how the magnetic field in dense star-forming regions is connected to the field threading the rest of the cloud.
c) eliminating the necessity to chop on and off the field of interest to remove sky noise. Since SCUBA-2 will operate in a fundamentally different manner, we will be able measure polarized emission in regions where it is slowly varying (under current chopping observations, the subtractions yield zero in such areas).
d) With SCUBA, only M82 has been observed. However, the increased sensitivity of SCUBA-2 will make observations of the magnetic field geometry of many external galaxies possible for the first time.

Fourier Transform Spectroscopy

An imaging Fourier transform spectrometer (FTS) will provide simultaneous, intermediate resolution, spectroscopy over the broad 450 and 850 micron spectral bands. The spectral resolution can be instantly adjusted for the scientific problem at hand. Three areas of interest are given below:

Planetary Atmospheres

The submillimetre region is a particularly rich field of study because it is the region of maximum intensity for the rotational lines of many potential atmospheric constitutents. Spectroscopic measurements provide an inventory of molecular species and information on the physical and dynamical processes (e.g. internal heat sources) of the atmosphere. The FTS and small diffraction limited JCMT beam of 7” at 450 micron will allow, for the first time, submillimetre spectral mapping of the Jovian, Saturnian and Martian discs (which have angular sizes of 45”, 19” and 16”, respectively at opposition) and the study of hemispheric, zonal and polar differences and transport effects. Off-source pixels will provide a direct means of cancelling variations in telluric emission without the need for off-source pointing. Spectral mapping of Jupiter will also be practical at longer wavelengths where the diffraction limit reaches 14” at 850 micron.

Interstellar medium

The FTS has the potential to have a broader impact on submillimetre astronomy by allowing direct measurements of the spectral energy distributions (SED) of sources detected at submillimetre wavelengths. Recent measurements obtained with an FTS operating with a single detector at the JCMT have shown that Fourier spectroscopy is capable of differentiating continuum and line emission in complex regions like the Orion molecular cloud. Measurements of the spectral energy distributions (SED) of sources detected at submillimetre wavelengths would allow the determination of the dust contribution to emission seen in SCUBA-2 maps without the uncertainties associated with using complex dust models.

Extragalactic astronomy

One exciting area of interest of the FTS is extragalactic spectroscopy, in particular redshift measurements of high-z galaxies. Submillimetre and FIR surveys by SCUBA-2, SIRTF, Herschel and ALMA should be able to detect large numbers of primeval galaxies, but will not easily be able to measure their redshifts. In many cases there will be no optical counterparts, and one of the promising methods of determining z is to measure two redshifted high-J CO lines, a task well suited to a broadband FTS. Its ability to obtain a spectrum at each point in the image lessens the requirement to know accurately the source position.

Making SCUBA-2

SCUBA-2 will be a revolutionary instrument, and is technologically extremely ambitious. The SCUBA-2 science drivers dictate the following requirements for the instrument design:

- Per-pixel sensitivities dominated by the sky-background photon noise. This requires improvements of a factor of three over the current SCUBA bolometers.
- Utilising the maximum (undistorted) field-of-view allowed by the telescope. This is 64 sq-arcmins (compared to only 4.3 sq-arcmins for SCUBA) – a factor of 16 times larger field.
- Improved image fidelity and map dynamic range. Having fully-sampled image planes and ultra-stable electronics at low (DC) frequencies will significantly improve image quality over that achievable with current submillimetre instrumentation.
- A dichroic beamsplitter to split the short- and long-wave channels onto two separate arrays. Thus, simultaneous observing will be available with two colours.

When SCUBA-2 was first conceived one of the most important design specifications was to cover as much area as possible with detectors. SCUBA-2 has been designed to have the largest square detector array that can be fitted into the JCMT (re-imaged) focal plane. Filling this large area requires a huge number of independent detectors.

Conventional bolometer technology (such as that used in SCUBA) is not practical for the pixel count required for SCUBA-2. Recent advances in superconducting detector technology have demonstrated that large-format arrays of many thousands of pixels are now possible. SCUBA-2 proposes to fill the re-imaged focal plane of the telescope with state-of-the-art transition edge sensors (TES) with the signals being read out using multiplexed SQUID amplifiers. This will realise a two-order of magnitude leap in the number of pixels over SCUBA, using two sets of arrays with some 5120 pixels of identical geometries in each. The arrays will instantaneously sample the sky in a way akin to CCDs or infrared cameras. The pixels will be DC-coupled, which will remove the necessity to sky-chop and give further improvements in efficiency, potentially allowing more large-scale structure to be visible, and more accurate calibration and less image artefacts. These TES detectors have other potential uses, both in other areas of science and in commercial applications. For example, extremely sensitive X-ray detectors have been built with TES detectors. These have been used in particle physics experiments but may also prove useful in medical or industrial X-ray imaging systems.

The fabrication of SCUBA-2 has been divided into a number of distinct workpackages. These are described below following the order followed by an astronomical signal passing through the instrument: first the sub-instruments (the FTS and the polarimeter), then the optics and cryogenic portions of the instrument, then the detector arrays and their associated multiplexed cold electronics, then the warm (room temperature) electronics, and finally the software that converts the signal to a form usable for astronomical research.

Fourier Transform Spectrometer

The imaging Fourier Transform Spectrometer is being made by a team led by Prof. Naylor (U.Lethbridge).

In the simplest type of Fourier spectrometer, the Michelson interferometer, the incoming beam of light (e.g. from the telescope) is divided into two beams of equal intensity by a beamsplitter. After reflection from a fixed and a moving mirror the beams recombine at the beamsplitter and are brought to a focus on the detector. The signal recorded by the detector as a function of the path difference, or delay, between the recombining beams is known as the interferogram. The interferogram represents the autocovariance function of the incident radiation. Fourier transformation of the interferogram yields the spectrum. Thus, while in principle the design of an FTS is quite simple, obtaining the spectrum requires sophisticated mathematical analysis.

To date most astronomical FTSs have used a single detector element to obtain spectral information from one point on the sky. However, the rapid development of imaging detector arrays, which has resulted in such consumer products as hand-held video cameras and high-resolution single-shot cameras, has paved the way for long-wavelength cameras like SCUBA-2. By combining an imaging detector array with a spectrometer it is now possible to obtain, simultaneously, a spectrum from each point on the sky corresponding to individual pixels in the array. An imaging spectrometer therefore opens up a third dimension in astronomical observations by providing spectral information at each point in the object under study. While imaging spectroscopy at visible wavelengths has been conducted for many years using Fabry-Perot and diffraction grating spectrometers, the technology is now ripe for exploiting this technique at submillimetre wavelengths. Although SCUBA-2 will provide unprecedented morphological information on, for example, a galaxy, the composition and physical conditions of the galaxy can only be determined through imaging spectral measurements.

Figure 7: The Mach-Zehnder FTS produced for the JCMT
In December 2001. (JCMT telescope structure in background.)

Following the pioneering work of Maillard in astronomical imaging Fourier transform spectroscopy at near-infrared wavelengths with the Canada France Hawaii Telescope, the rapid development of array detectors and the increased capabilities of modern computers have propelled this field to a mature level. This is evidenced by the imaging FTSs proposed for NASA's James Webb Space Telescope (JWST) and the SPIRE instrument (**S**pectral and **P**hotometric **I**maging **RE**ceiver) of ESA's Herschel mission. An imaging FTS is therefore seen to be an ideal complement to SCUBA-2, providing broadband, intermediate resolution, imaging spectroscopy.

More recently, Dr Naylor’s group at the University of Lethbridge (in collaboration with Prof. Peter Ade’s group at Cardiff University) has completed the development of a novel type of FTS (shown in Figure 7), which is ideally-suited to imaging spectroscopy. This design uses two broadband-intensity beamsplitters in a Mach-Zehnder configuration, which provides access to all four interferometer ports while maintaining maximum throughput and removing any polarization sensitivity. The performance of this design, on which the SPIRE instrument is based, has been demonstrated in the laboratory and recently tested in the field.

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 850 micron 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.

Polarimeter

The SCUBA-2 polarimeter is being made by a team at the Université de Montéal led by Prof. Bastien. Submillimetre polarimetry is a powerful tool for studying magnetic fields in a variety of astrophysical phenomena. As outlined above, an imaging polarimeter for SCUBA-2, taking advantage of the extra sensitivity, imaging speed and improved image fidelity of the new camera, would allow completely new areas of astronomy to be studied. The project scientist for the SCUBA-2 polarimeter will be Pierre Bastien from the Université de Montreal. The polarimeter will be designed and fabricated by an engineer working under the guidance of Prof. Bastien and Prof. Joncas (Université Laval).

The polarimeter for SCUBA-2 will consist of a rotating half-waveplate and a fixed analyser. It is proposed that the polarimeter be located close to the pupil image at the window of the cryostat. To utilise the full field-of-view therefore requires that the polarimeter must have a clear aperture of 180mm in diameter. The most critical component in the design is the waveplate that rotates the plane of polarisation with respect to a fixed axis of the analyser. To work at both 450 and 850 micron with high efficiency requires an achromatic design. Hence, the waveplate will be made to be achromatic by combining 3-5 monochromatic plates (the Pancharatnam design). Anti-reflection coatings will be applied to the plates to minimise signal loss. A thin layer of polypropylene can provide the necessary broadband AR coating required for the wavelength range of SCUBA-2. Figure 8 shows a cross-sectional view of the module assembly attached to a chopper wheel (which may not be needed) on the cryostat window. The waveplates will most likely be made of birefringent quartz, cut to a thickness to retard one-plane of polarisation by half a wavelength relative to the orthogonal one.

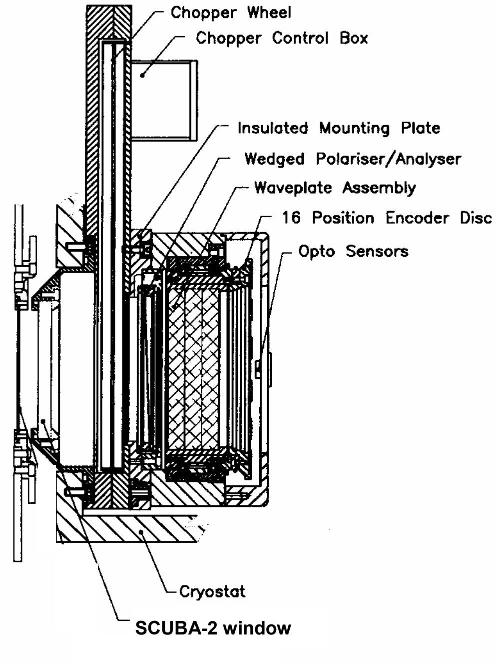


Figure 8: A cross-sectional view of the polarimeter.

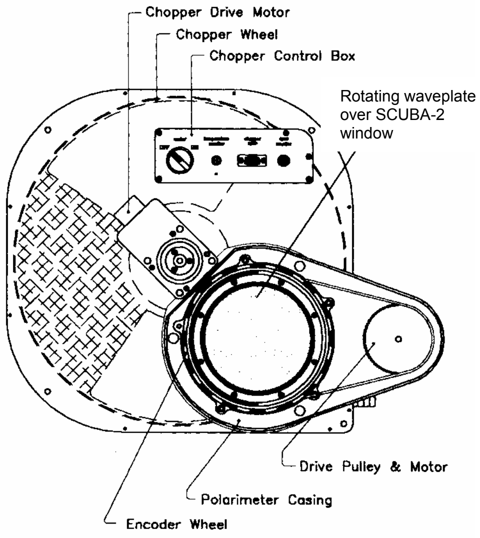


Figure 9: A side view of the polarimeter

The analyser will be a grid of 6 micron spacing, slightly tilted to reflect one plane of polarisation out of the system. It will most likely be made in a similar way to the analyser used by the SCUBA polarimeter i.e. a photolithographically etched grid on a mylar substrate.

Other aspects of the design include the housing module that requires a drive pulley and motor, encoder disk, casing and mounting brackets, and also a control unit (most likely synchronized with the JCMT real-time sequencer). It is envisaged that these components will be very similar to the SCUBA polarimeter (for which the engineering drawings exist) minimising the design effort in this area. Figure 9 shows a face-on view of the module. The window location for the polarimeter means that the instrument will be easily accessible from the mezzanine level location of the cryostat. A reliable and robust mounting method is also needed to ensure the polarimeter can be installed and removed with the minimum of disruption to regular observing.

It is envisaged that there will be two modes of operation. 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.

Optics and Cryogenics

These parts of the SCUBA-2 project are the responsibility of the Astronomy Technology Centre with assistance from the University of Cardiff.

Optics

The optical design matches the telescope field (~8 sq- arcmins) and focal ratio (f/12) to the f ratio (f/2.8) of the detectors. The 2.8 ratio is chosen to give a manageable focal plane size of 90mm square at 100mK, together with greater than wavelength size pixels and full sampling of the diffraction pattern at 850 micron. To minimize losses an all reflective (mirror) system will be used. The optics also has to relay the light from the telescope receiver cabin to the mezzanine floor location for SCUBA-2. To do this the light must pass through the narrow elevation bearing tube. Since the cabin also rotates in elevation with respect to the fixed SCUBA-2 the cabin optics shears against the optics on the telescope structure. These requirements mean a complex design is needed, consisting of 9 aspheric, off-axis mirrors (4 in the cabin, 2 on the telescope structure and 3 inside the cryostat). The left side of Figure 10 shows the optical path following the first telescope structure re-imaging mirror. This feeds, via a narrow beam-waist into the cryostat and eventually into the focal plane box that house the arrays. A successful preliminary design review was held in October 2001 for the optical system. The modeled performance is excellent: completely diffraction-limited with Strehl ratios in excess of 98% and low field distortion (0.3%) at all elevations.

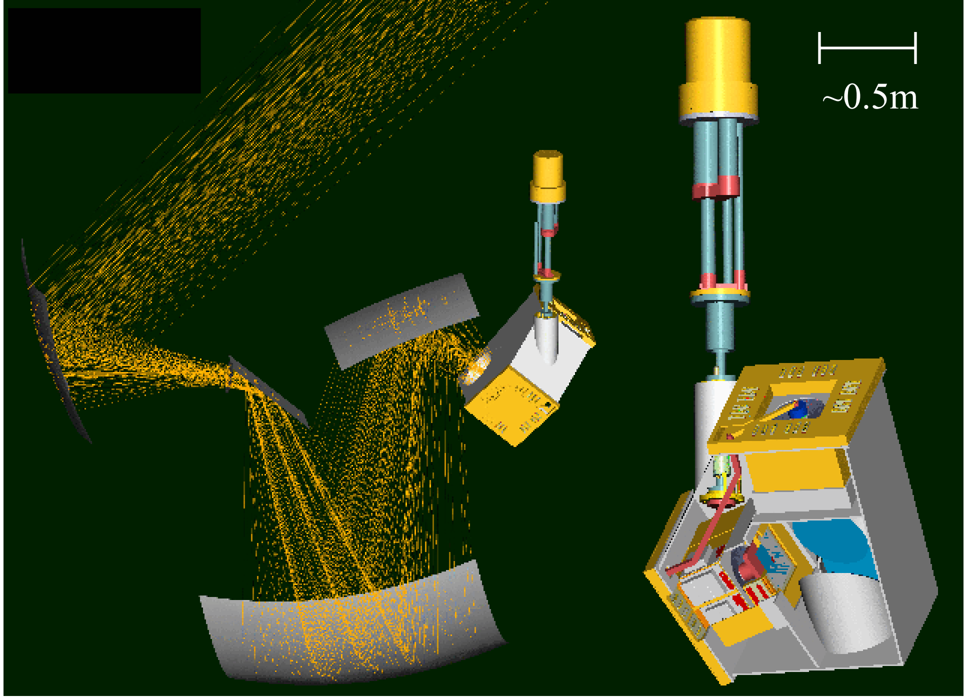


Figure 10: (left) The SCUBA-2 optical path from the first telescope structure mirror on the Nasymth platform. (right) The conceptual layout of the focal plane with dilution refrigerator insert.

Cryogenics

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 will be implemented. The only liquid cryogen needed is 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 from Leiden Cryogenics will provide ~100µW cooling power at 100mK. Leiden will incorporate a 4K pulse tube cooler (PT) from CryoMech 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 serious problem with the current SCUBA) and hence maximizing operation time. The DR is automated using Labview and may be operated and monitored remotely. A second PT will cool the radiation shield (~60K) and cryostat mirrors (4K). The 1K focal plane box (seen on the right in Figure 10) will be cooled by the still of the DR.

Detector Arrays/Cold Electronics

This is the heart of the entire SCUBA-2 instrument: the most challenging component to fabricate. To maximize the sensitivity of SCUBA-2 the detector and the signal readout electronics must be kept at very low temperatures. The detectors are made as a chip with a 40X32 array of extremely sensitive TES devices that must then be attached on top of a readout chip. It is extremely challenging to fabricate these devices and the entire process is at the "cutting-edge" of new technology. **It is this high level of innovation that will give SCUBA-2 its formidable advantage over competing instruments.** The TES devices are being produced at the National Institute of Standards and Technology (NIST) from wafers manufactured at the University of Edinburgh. The readout wafers are produced jointly by the staff at the ATC, NIST, and the University of Waterloo. Testing of the final assembled detector arrays will be performed at the University of Cardiff.

Detector Arrays

TES devices have unique advantages for SCUBA-2. They have low impedance, and thus low sensitivity to microphonics (a problem with the current 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. Each SCUBA-2 array will be composed of four sub-arrays that will be butted together to give the full field-of-view. They will be cooled to 120mK to provide excellent sensitivity and background-limited performance. Most importantly, the existence of a practical cryogenic multiplexing scheme makes it possible to instrument the full field-of-view at both 450 micron and 850 micron with a practical number of wires. Without the multiplex advantage (described below) the six wires that would be required for each TES detector element would lead to 76,800 wires emerging from the detector array – a formidable number that would inevitably lead to great difficulties in construction.

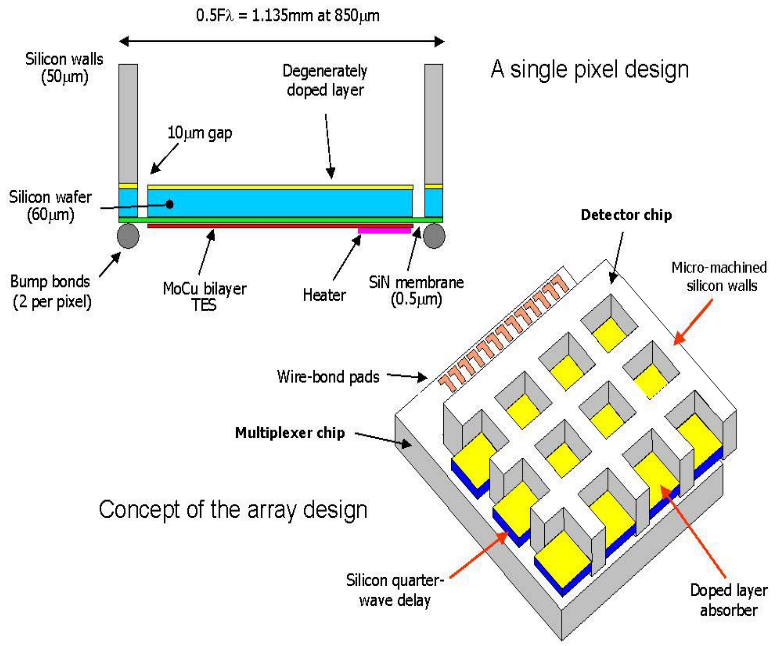


Figure 11: Schematic drawings of single SCUBA-2 pixel and array concept

Figure 11 shows a schematic drawing of the novel SCUBA-2 pixel design, together with 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 at least 90%.

Cold Electronics / Multiplexed signal readouts

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 the 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.

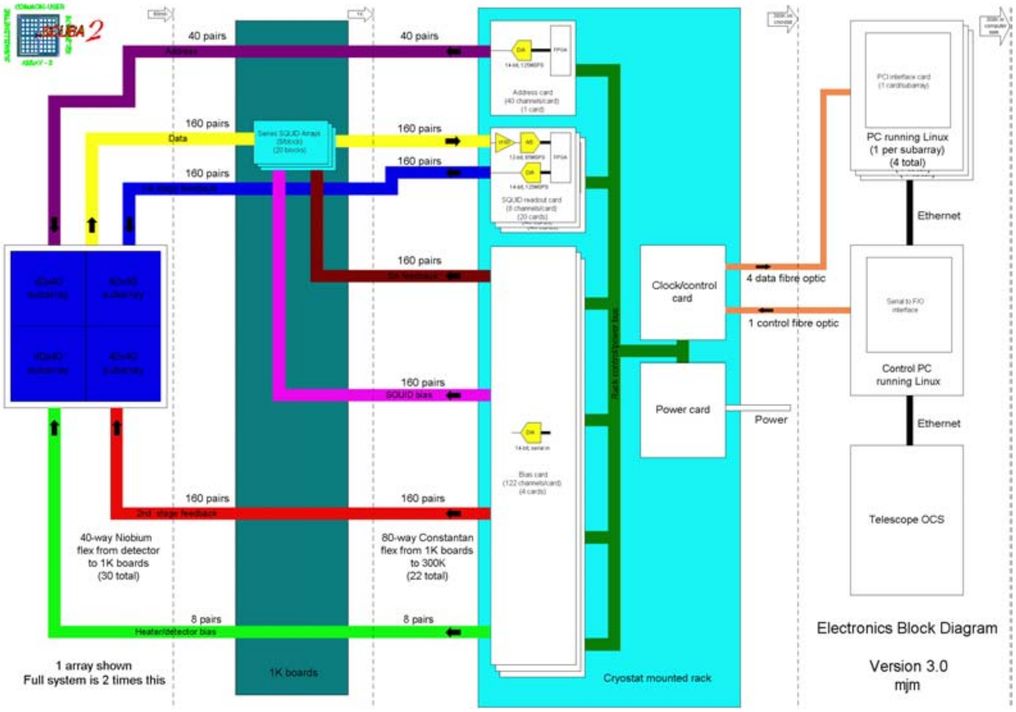
Each pixel requires six wire connections and its own series array. As this is impractical, SCUBA-2 will overcome these problems by employing a multiplexing scheme. This is done by connecting all the SQUIDs in a column in series and then using a set of row select lines to turn on each row of SQUIDs in 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. The hybrid array design means that each pixel has a SQUID amplifier and coupling transformer directly underneath on the MUX chip. The MUX design is critical in that it has to minimise signal crosstalk due to magnetic coupling between adjacent pixels.

Multi-Channel Electronics

This, the largest Canadian Workpackage in the SCUBA-2 project, is led by Prof. Halpern (UBC). Figure 12 shows a block diagram of the electronics design required for one of the two arrays in the SCUBA-2 instrument. The Warm (room temperature) electronics, shown in the box labeled ‘Cryostat mounted rack’, are mounted in racks on or near the cryostat, and are based on repackaged versions of the existing NIST electronics.

There are three main sections in the room temperature electronics: 1) a row select card which is used to address the SQUID multiplexers attached to the detectors, 2) SQUID readout cards which digitise the data from all the pixels in the currently addressed row and provide feedback compensation for the first stage SQUIDs, and 3) bias cards which provide bias voltages for the SQUID multiplexers, series SQUID arrays, pixel heaters and detectors. In addition there is a clock/control card that decodes commands from, and sends data to, the data acquisition computers.

Figure 12: SCUBA-2 electronics block diagram



Data acquisition

The arrays are read out, one row at a time, at a frame rate of ~5kHz. As shown in Figure 12, the data feed a SQUID readout card that contains an A/D converter and a field programmable gate array (FPGA). The FPGAs control the array readout and feedback and perform low-pass filtering and sub-sampling. There are additional FPGA boards with fibre connections for control activities. The current design, as shown in Figure 14 has optical fibres from the readout cards to the processing computers, along which data are transferred at a frame rate of around 200Hz. Each sub-array will most likely have a dual-processor PC (using real-time Linux) performing data capture and processing. A VME-VxWorks system will provide the interface to the JCMT Real-Time Sequencer for control and timing of observations.

Observing and Data Reduction Software

Software to allow astronomers to use SCUBA-2 is being produced by a team led by Prof. Scott (U.B.C.). This software includes real-time data pipelines that produce real-time images taken with the camera, off-line data reduction recipes and post-processing software, and a variety of analysis toolds.