SCUBA-2
A Submillimetre Bolometer Array Camera for the JCMT

A Status Review for the Long Range Plan Mid-Term Review Panel

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Summary

SCUBA-2 will be a replacement for SCUBA, the very successful bolometer array camera currently in use at the JCMT. The design goal for SCUBA-2 is that it should be at least one hundred times faster, and preferably one thousand times faster than the original SCUBA camera. SCUBA-2 is being built by a consortium of institutions in Canada, the United Kingdom, and the USA. Funding for SCUBA-2 is provided by the JCMT Development Fund, the Particle Physics and Astronomy Research Council (UK), and the Canada Foundation for Innovation (CFI). First science operations are due to begin in May 2006. An intermediate resolution imaging spectrometer (an FTS) and a polarimeter will also be delivered with SCUBA-2.

SCUBA-2 was not included in the Canadian Long Range Plan for Astronomy as the project was in too early a stage of development at the time the Plan was created. Fortunately CFI created a funding program that was a very good "fit" to this project at exactly the time that we needed it.

Background

The JCMT began operation in 1987 with a sensitive single channel bolometer (UKT14, borrowed from UKIRT). To make an image required such a laborious process of scanning this one pixel across the sky that only a few modestly-sized images were ever made.

A first generation of "Common User" instruments was built over the next ten years. 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 UKT14.

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. Some of these, and other SCUBA discoveries are highlighted in the sections below.

Disks around Stars

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 Figure 1 a SCUBA image of a nearby system is shown beside a computer model. In the numerical simulation of the ε Eridani dust disk (shown at right of Figure 1) 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).

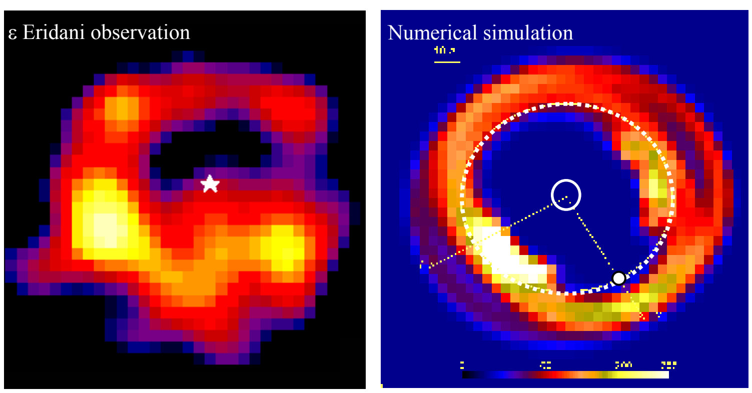

Figure 1: (Left): SCUBA 850 micron observation of the faint dust ring surrounding ε Eridani (Greaves et al. 1998). (Right): numerical simulation of dust trapped in mean motion resonances with a putative planet (Liou, Greaves & Holland 2003).

The Centre of our Galaxy

Figure 2 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.

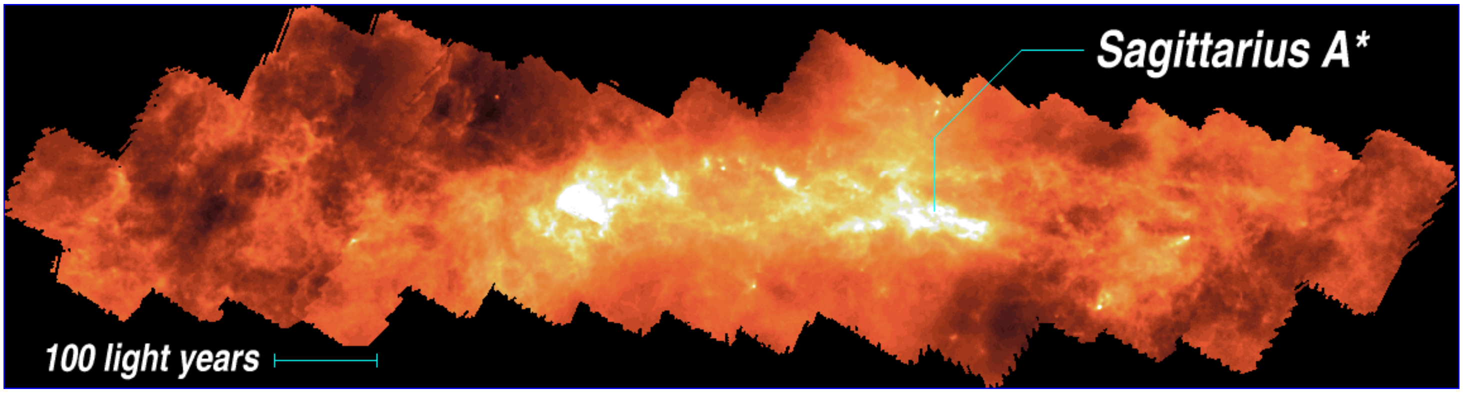

Figure 2: The Plane of our Galaxy towards the Galactic Centre (Sagittarius A)

Star Formation

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 below in Figure 3). 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.

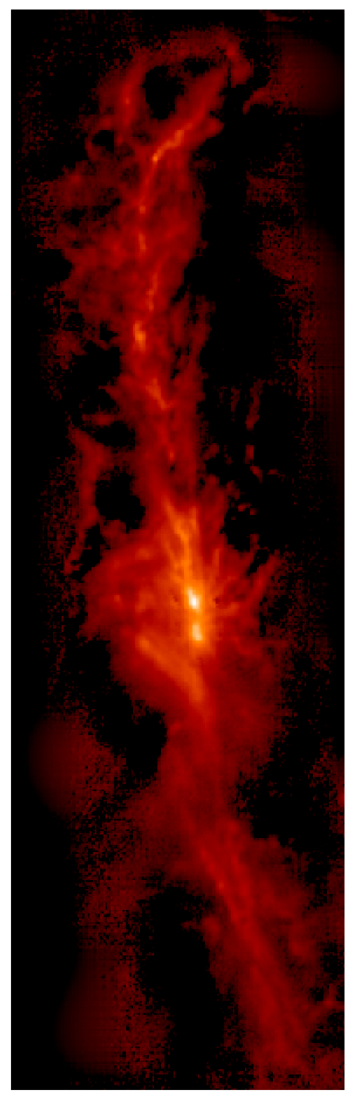

Figure 3: Orion at 850 microns

Polarimetry

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 (Figure 4) 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.

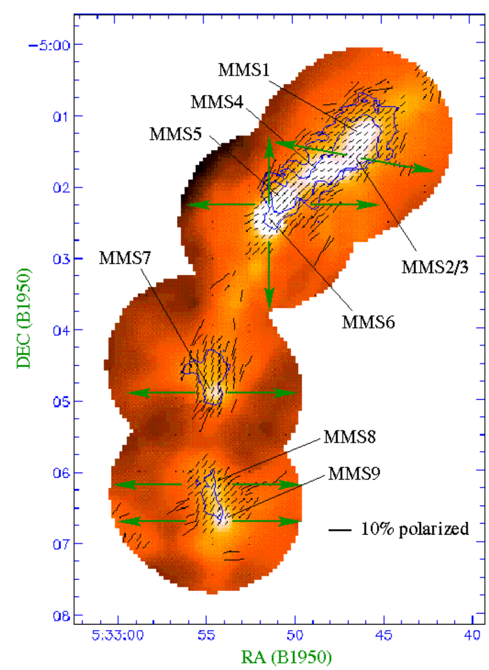

Figure 4: Polarization Observations of the Orion Molecular Cloud

Cosmology: The Formation of Galaxies

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. 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. (see Figure 5 for an illustration of this!)

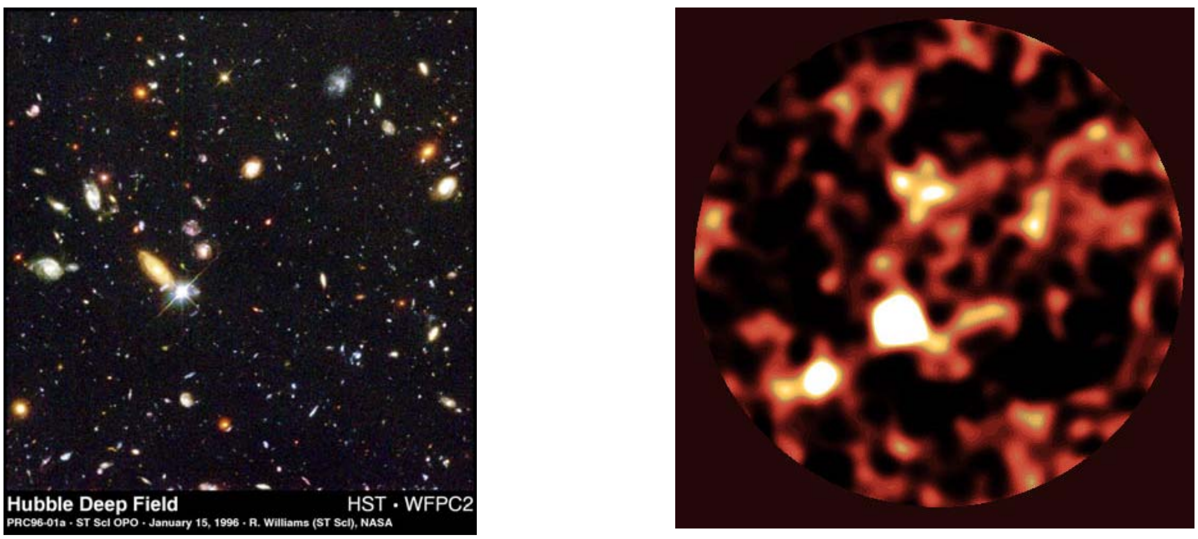

Figure 5: (Left) a very long exposure of a small part of the sky with the Hubble Space Telescope. Virtually every object in this picture is a galaxy. (Right) A very "deep" exposure of the same part of the sky with SCUBA. Everything shown is a real source of submillimetre light (i.e. there is no "noise" in this image). Essentially every object seen in the submillimetre image is not detected in the visible image.

Cosmology: The Formation of the First Stars

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.**

SCUBA-2

The SCUBA-2 project is a unique opportunity to exploit emerging new technology to produce the world's most advanced camera for astronomical research in the poorly explored submillimetre region of the spectrum. SCUBA-2 will replace the original SCUBA camera in mid-2006. SCUBA-2 is being built by a large team of researchers with members from various universities and research institutions in the UK and Canada, with the detectors being fabricated under contract by the US National Institute of Standards and Technology (NIST). The lead UK institution in the project is the Astronomy Technology Centre (UK ATC) at the Royal Observatory, Edinburgh, and the lead Canadian institution is the University of Waterloo.

The Canadian SCUBA-2 consortium consists of eight Canadian universities (in addition to University of Waterloo these are: Saint Mary’s University, Université Laval, Université de Montreal, University of Lethbridge, University of Calgary, University of British Columbia, and University of Victoria). The international SCUBA-2 team includes the Canadian Consortium plus a number of other groups, including the group at NIST in Boulder, Colorado, the Astronomy Instrumentation Group at the University of Cardiff, and the Scottish Microelectronics Centre at the University of Edinburgh.

To achieve the scientific potential of SCUBA-2, with a mapping speed that is at least 100 times that of SCUBA (this is the design goal), SCUBA-2 will have focal planes operating at two wavelengths simultaneously (450 and 850μm) that utilize most of the usable field of view of the telescope. This requires ~10,000 pixels - a pixel count on the order of 100 times greater than any existing camera for this wavelength region. Since existing technology is not scalable to such pixel counts, it has been necessary to develop a new approach incorporating superconducting Transition-Edge Sensors (TES) linked to multiplexed SQUID (Superconducting Quantum Interference Device) amplifiers. Such innovative new technology has applications for future astronomical missions as well as a range of industrial, security, and medical applications (e.g. X-ray spectrometers for diagnosing contaminants in silicon chip fabrication lines and detectors for medical imaging).

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. The design for a typical pixel is shown in Figure 6 while Figure 7 shows the lay-out for several pixels in a regular grid.

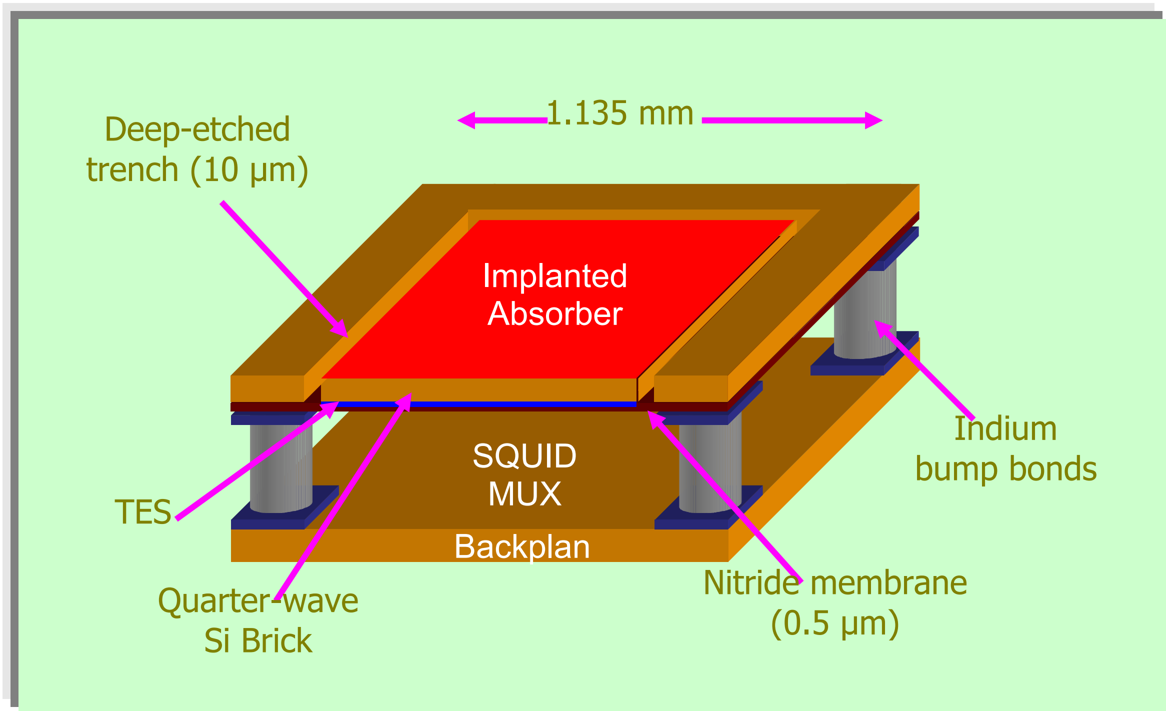

Figure 6: A single SCUBA-2 pixel. Submillimetre light enters the instrument from above and is absorbed, heating up the absorber. The TES "measures" the temperature increase and the temperature is read out by the SQUID MUX (multiplexor).

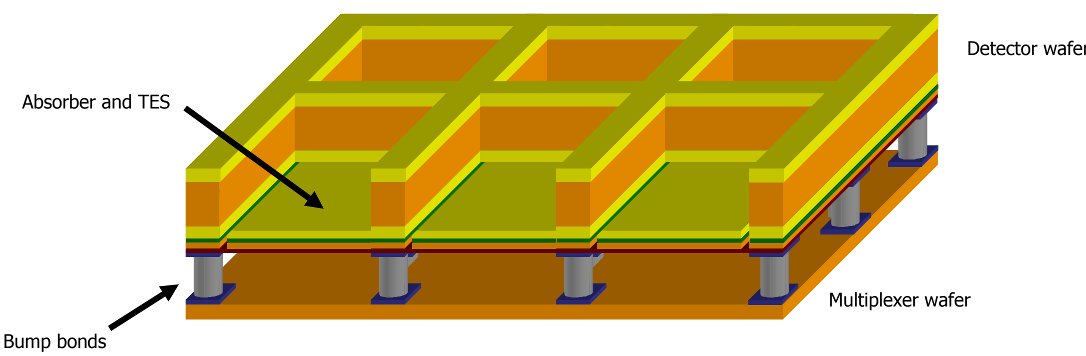

Figure 7: Several pixels laid out in a rectangular grid. Note that there are two wafers, a detector wafer and a multiplexor wafer, and these are connected together by "bump bonds", a very high technology technique.

Due to the physical size of the pixels and limitations on the fabrication of an individual wafer SCUBA-2 will use four sub-arrays of 40 by 32 pixels at each wavelength, fitted together as shown in Figure 8. These sub-arrays will come very close to filling the focal plane of the JCMT.

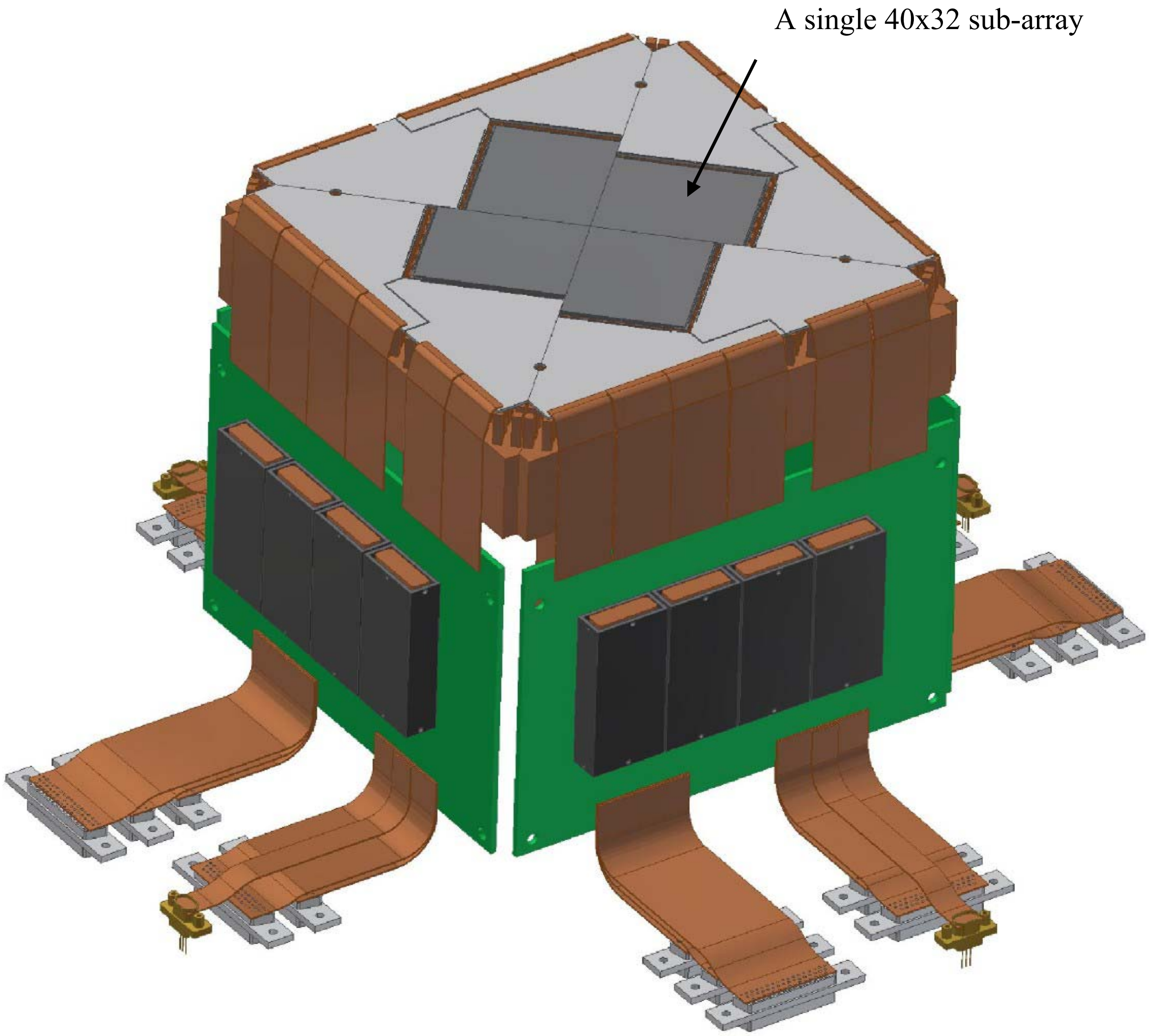

Figure 8: The focal plane assembly for 850 microns showing four sub-arrays fitted together (at the top). The wide copper bands coming out at the bottom on each side are the cables that connect the detectors to the electronics that controls the camera and reads out the data.

SCUBA-2 is scheduled to have the first prototype arrays completed in early 2004, and the plans will have the camera ready for installation in late 2005 with first science operations in May 2006 after extensive commissioning and testing of the instrument on the telescope. In the year following the first science usage of the SCUBA-2 the camera will be augmented with “ancillary” instruments, a polarimeter (to be made at Université de Montréal) and a spectrometer (to be made a the University of Lethbridge).