CIRSI

Cambridge Infra Red Survey Instrument

Critical Design Review

June 1996

Abstract

The Institute of Astronomy (IoA) is currently building a panoramic wide field near infrared imaging camera based on 4 Rockwell HgCdTe 1024^2 detectors. The survey instrument will be as scientifically versatile and as easy to use as a large format CCD camera and is expected to be ready for astronomical use by Nov 1997. It will be particularly well-suited for surveys of star-forming regions, low mass stars, distant galaxies, clusters and QSOs The field of view of this camera with 0.15'' pixels is 5.1x5.1 arc minutes and is thus ≈60 times larger the current near-infrared imager on Keck(NIRC). When combined with the MMT 6.5m, the combination is ≈25 times as powerful as the Keck 10.0m, when the apertures are taken into account. The instrument design includes the option of adding wavefront sensing and a tip-tilt facilities at a later date. In addition an option of upgrading the camera into a wide field spectroscopic survey instrument is currently at the design stage.

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1. Introduction

The Institute of Astronomy(IoA) instrumentation group is currently building a panoramic infrared imaging camera. The device, which will consist of a mosaiced array of 4 times HgCdTe 1024^2 detectors, will be used to carry out deep imaging surveys in the near-infrared spectral region. The survey instrument will be as scientifically versatile as a large format CCD camera. It will be particularly well-suited for surveys of star-forming regions, distant galaxies, clusters and QSOs and is clearly well-matched to current IoA scientific interests. It is intended that the camera be ready for astronomical use by Quarter III, 1997.

A NIR f/3.9 wide field corrector has been designed for the Cassegrain focus of the 6.5m MMT, giving a scale of 0.15''/pixel and a field of view of 5.1'x5.1'. The design includes the option of adding wavefront sensing and a tip-tilt facilities at a later date, based on proven techniques developed for the Cambridge Optical Aperture Synthesis Telescope (COAST) by members of the IoA team (i.e. Beckett & Mackay).

The program includes the option of upgrading the camera at a later date to a wide field spectroscopic survey instrument equivalent to an infrared version of the highly-successful Low Dispersion Survey Spectrograph. This multi-object NIR spectrograph would enable powerful cosmological applications particularly on an large-aperture telescope. The spectroscopic upgrade is currently at the design stage with a variety of options including fibre fed capabilities being considered.

2. Scientific Objectives

2.1 Overview

The Institute of Astronomy has a long tradition in survey astronomy and the scientific value of the various galactic and extra-galactic surveys conducted in Cambridge is well-documented. Examples include various quasars surveys and the Southern Sky galaxy catalogue constructed using the Automatic Plate Measuring machine(APM) (designed and operated within the Institute), the ground-based follow-up of X-ray catalogues defining the range of physical properties of clusters of galaxies, and numerous redshift surveys of the local Universe using both optical and infrared-selected samples. These and other ongoing surveys serve to define the population of galaxies, clusters and related objects at various epochs.

Wide field broad band sky surveys represent an important observational tool in astronomy. They can be used to select objects in a quantitative manner for statistical studies or subsequent investigations with a large telescope. They are also useful in the follow-up of sources detected at other frequencies, e.g. radio, Infra-red and X-ray surveys.

This programme is concerned with extending the Institute's survey imaging capability to near-infrared wavelengths. The impact of large format CCDs is clear from the substantial efforts many observatories have invested to secure such devices. For the first time, a similar technological capability is now available at infrared wavelengths via the first 1024^2 HgCdTe arrays. The mosaic camera discussed here consists of 4 times 1024^2 detectors which will fill a significant fraction of the unvignetted focal plane on existing 2-4m class telescopes. Such a device will represent a major leap (≈50-100) in our survey capability at infrared wavelengths. Indeed, a similar jump in capability at modest cost is unlikely to occur again.

The near-infrared wavebands are increasingly important for both galactic and extra-galactic surveys. Distant galaxies are optimally studied at these wavelengths because the k-correction is smaller and less uncertain. For QSOs, a significant increase in redshift coverage (i.e. $z>6$) requires NIR observations since cosmologically distributed HI absorbs away most of the optical waveband. Further physical drivers include minimising dust obscuration at low Galactic latitudes as well as searching for cool sources with temperatures ≈2000 K.

A key program could be the establishment of deep medium angle survey fields which would be the focus of survey programs into the next millennium on the 8m's and future space missions such as AXAF, XMM, SIRTF etc.

The range of scientific programs that can be attempted with a wide field infrared imaging camera is substantial. Below is listed a representative sample.

- Brown dwarf and low mass star.
- Low mass stellar halos around galaxies.
- Very high redshift QSOs.
- Obscured sources and star-forming regions
- High redshift galaxy clusters and lensed sources.
- Narrow band studies.
- XMM/AXAF follow-up
- ISO/SIRTF follow-up
- 2dF or SDSS follow-up
- Gemini preparation, particularly faint galaxies and QSO absorbers.
- Supernovae at intermediate and high redshift.
- Photometric redshift survey (NIR combined with optical bands)
- $W(\theta)$ as a function of magnitude and colour.
- Tully-Fisher in clusters via H band observations.
- Stellar population studies in nearby galaxies e.g. M31, M33, M51, M101
- Serendipity

2.2 More detailed expositions

2.2.1 Basic considerations

Rather than provide detailed scientific and technical cases for the types of program listed earlier we provide some basic information and expand a few cases. In Table 2.2.1a we show a comparison between the Cambridge camera and a variety of other Camera + Telescope combinations normalised against the Keck 10m with NIRC. The comparison is quite illuminating and illustrates the power wide field capabilities. The 2.5m INT telescopes appears quite favourable but the poor spatial sampling and long integration times are the major limitation. It is more suited to a shallow survey to $H\approx20$ as indicated by Figure 2.2.1a . Table 2.2.1b summarises the expected sensitivity of the camera system.

Figure 2.2.1b shows the expected magnitudes for an L* unevolving galaxy as a function of redshift and spectral type. At high redshift there are a number of uncertainties. Evolution generally causes some brightening whereas merging results in fainter individual discrete galaxies at higher redshift. The three horizontal lines show the expected depth for 3 exposure telescope options

i.e. INT 2.5m + 5mins; INT 2.5m + 30mins; MMT 6.5m + 30mins.

One important point is that for an non-evolving population there is no significant difference between the H and K detectabilities. The K band figures assume a fully cryogenic shielded camera. Figure 2.2.1c shows a optical-NIR two colour plot to show the wide range of expected colours. On this diagram, a simple V—H>6 sample isolates ellipticals or a bulge dominated population with z>1. By observing in multiple bands in the optical and NIR the derivation of redshift, spectral-types and even population ages should be possible.

In Figure 2.2.1d is shown the spectral energy distribution of the recently discovered brown dwarf candidate Gl 229B. Note the rather blue spectrum of this star longward of 1μm. The actual J—H, H—K colours are -0.1 and 0.1 respectively unlike normal M stars which are much redder. As a result there is no advantage in using K in surveys for such objects. A simple I—J colour selection or Z—J is required.

2.2.2 Clusters of galaxies with z>1

The evolutionary history of galaxy clusters offers a sensitive test of current theories for the origin of structure (White *et al* 1994). The required data consists of cluster surface densities as a function of contrast and preferably redshift (Couch *et al* 1990, Postman *et al* 1996). Such samples also provide a natural source for distant galaxy studies (Dickinson 1996).

Unfortunately, the major difficulty lies in finding a robust way of finding distant examples. Optical searches have found some examples beyond z≈0.5 but their contrast against the very high field counts renders the method unreliable. Similarly, the X-ray luminosity of the richest examples is surprisingly low (Castander *e tal* 1993, 1995). Yet it is known that structures do exist at high redshift. Dickinson (1995) finds galaxy associations around radio galaxies at z>1 whose contrast factor to modest limits nonetheless implies quite significant richness. Similar systems are being identified in the deepest redshift surveys (LeFevre *et al* 1995).

The slow evolution of cluster ellipticals identified from a variety of studies (Aragon-Salamanca *et al* 1994, Ellis 1995) indicates that the contrast of a z>1 cluster galaxy against the foreground field is considerably greater at near-infrared wavelengths than for the current optical samples. Panoramic infrared surveys for such associations have, to date, been considered prohibitively difficult because of the limited field of view.

Simulations indicate that clusters of Abell richness R>3 can be located with adequate contrast to z≈2 in surveys reaching H=21.5. Even if their volume density is an order of magnitude lower than locally, useful samples can be constructed in a survey of a few degree^2.

2.2.3 Ultra high redshift QSOs

A more ambitious program would be a search for QSOs with redshifts in excess of 7 where Lyman-α lies beyond 1μm. Even a firm upper limit would be of great cosmological interest. Ten years ago, there were no QSOs known beyond z=3.8 (Hazard, McMahon and Sargent 1986). QSO surveys undertaken with the APM have transformed the situation and now around 60 z>4 QSOs are known. The majority of these z>4 quasars have been found using multi-colour surveys with the APM (Irwin, McMahon & Hazard 1991, Warren, Hewett & Osmer 1993). These z>4 QSOs have primarily been selected on the basis of red B-R colours e.g. B-R>3. This approach starts to fail at z≈4.5 since the R band samples the Lyman-α forest absorption. Various optical surveys for QSOs in the redshift range 5 to 6 are currently under way using the same basic principle of red optical colours The principle behind the B-R techniques can be extended to even higher redshifts i.e. z>7 using R-J,J-H colours.

The highest redshift QSO known PC1247+34(z=4.9) (Schneider, Schmidt & Gunn 1991) has J,H and K mags of 18.0, 17.6 and 17.0 (McMahon *et al*, in prep) respectively, whereas the brightest known QSO above z=4.5, BR1202-0725 (z=4.7), has J, H and K mags of 16.9, 16.2 and 15.7 (McMahon *et al*, in prep) respectively. The QSO PC1247+34 was discovered in a survey covering 3 deg^2 so a survey over an area of 20 deg^2, 2-3 magnitudes fainter i.e. H=20 would be in the right ball park. At these redshift objects QSOs dim as $(1+z)^3$ so going from z=5 to z=10 produces 2 magnitudes of dimming in an unabsorbed continuum band.

The uncertainties in the expected numbers of QSOs is large. The aim of any survey program would to determine the space density or set the best limits possible. Ideally one would carry out both shallow and a deeper survey over a smaller area so that one constrains the shape of the QSO luminosity function. A primary motivation for high redshift QSO survey work is the use of such QSOs as probes of intervening absorption systems.

2.3 HST and NICMOS considerations

The forthcoming HST refurbishment mission scheduled for early 1997 will include the installation of the near infrared red camera NICMOS. It will be timely to redefine the area of wide field near IR astronomy on the same timescale that NICMOS opens up a new window in the regime of small field but ultra-deep NIR astronomy. NICMOS is built around 256x256 arrays and has a field of view of a mere 19''x19'' with 0.075'' sampling. A ground based deep wide field NIR survey program should generate ideal targets for HST follow-up with NICMOS.

One exciting possibility would be to devote a substantial amount of time to a NIR equivalent equivalent of the HDF. For example, in 100hrs one on the MMT 6.5m one would reach H=26 (equivalent to K=25 for a typical galaxy with z>1) where most of the detected objects would be at z>2. In a single 5'x5' field one would expect over 1000 galaxies. One caveat is that HST+ NICMOS may be more efficient due the lower sky background although it would require many NICMOS pointings. However, there are still considerable uncertainties about the performance of NICMOS in the background limited regime e.g. the in-orbit read out noise, dark current and thermal background are unknown. We should know on the timescale of a year whether it is practical to use NICMOS for ultra deep survey wide field survey programs. If it is not we shall be poised to take the lead in this important area.

3. Description of the Instrument

3.1 The Wide Field Camera

The camera will be remarkably simple and compact (see Figure 3.1a) It is an extension of current IoA capabilities, e.g. Martin Beckett and Craig Mackay's development of a NICMOS HgCdTe 256^2 device for the IoA/MRAO collaborative programme on the Cambridge-Optical-Aperture-Synthesis-Telescope [1] and does not involve significant technological risk. The prime difficulty in moving in this direction has been the prohibitive cost of the new large arrays. The recent fund-raising successes at Cambridge provides an excellent and timely opportunity to move ahead. The system under construction will represent a major leap (≈50) in our survey capability at infrared wavelengths. A similar jump in capability at modest cost is unlikely to ever occur again.

The camera has a core detector system which consists of 4 Rockwell 1024x1024 HgCdTe arrays. The basic characteristics of these arrays are given in Table 3.1a with comparative figures for the NICMOS-3 devices. Unlike optical CCDs, it is not possible to closely pack the infrared arrays (see Figure 3.1b) and thus a minimum of four exposures is needed to give a 100% fill-factor (at additional cost a contiguous field could be provided using a pyramidal system similar to WFPC2). An advantage of the of the large gaps between the detectors, it will be possible to use small, relatively cheap, filters since we benefit from a multiple order. This will be important for narrow band programs.

The camera system includes a fully integrated auto-guider system (see Figure 3.1c) A small pick-off mirror and some small lenses inside the dewar will be used to send the light from an unused part of the field to a Peltier-cooled CCD on the side of the dewar. The control computer for the CCD will lock on to the brightest star in the field and generate XY correction signals and send them down an RS232 line to the telescope control system. The CCD system will also allow the option of dithering exposures to reduce flat field noise and the effects of dead pixels. The CCD field will be about 4x6 arcmin if the re-imaging lens produces a final image scale of 0.25 arcsec/pixel.

Figure 3.1d shows a schematic of the detector control system with associated computer system. Each detector has 4 quadrants which can be read out independently. A full exposure of the 4 chips requires the capture of 16Mb of data. In the H band the sky is very bright and this dictates how fast the mosaic has to be read out. Assuming a well capacity of 60,000, each pixel saturates in ≈15 seconds for the INT, WHT or WHT which is within the specification of the AstroCam 4100 controller. We propose to commission the new camera initially on the 2.5m Isaac Newton Telescope or the 4.2m William Herschel

[1] http://www.phy.cam.ac.uk/www/research/ra/coast.home.html paper available as ps

Telescope but, thereafter it can be transported to telescopes elsewhere. The overall characteristics and estimated performance on the 2.5m INT, 4.2m WHT and 6.5m MMT (as a guide) is given in Table 3.1b. As part of the work done for this proposal a fully-transmitting field corrector was designed in detail for the Cassegrain focus of the WHT and so we are confident that successful designs for other telescopes can be achieved. In contrast to the INT these typically offer higher resolution with a smaller field of view.

We have also investigated the feasibility of building a fully functional K band system. However, the problems associated with building a thermally isolated and well shielded wide field camera system are prohibitively expensive and it is not clear that the scientific gains warrant this expense.

3.2 Instrument Control System

This is still undergoing definition. It will be a Tk/TCL graphical User Interface (GUI) with user defined scripts. It is envisaged that a series of dithered and interlaced exposures should take place with little user intervention. A typical cycle of 5 dithers and 4 interlaced raster positions should take one hour. If guide star's are necessary it is envisaged that no user intervention will be required whilst moving between raster positions. Single person operation is intended. Data will be written to disk as either IRAF or FITS format files.

3.3 Data rates and pipeline processing

Each exposure will produce 4 images at 2MBytes each. A typical real-time co-add consisting of 10 times 10sec exposures will result in a single 2MByte image. Therefore the maximum data rate is 8MBytes in 100seconds i.e. 288MBytes/hour. Therefore in a typical '10hr night' the data volume is ≈3GBytes. This will fit onto a DDS-2 DAT(4GB capacity). The 'raw' data which will not usually be archived would amount to 30GBytes.

The members of the IoA have considerable experience is the development of pipelines to process optical imaging data e.g. the APM and NAOJ CCD mosaic project. The proposed pipeline will produce astrometric calibrated images and linearised catalogues of detected objects within an IRAF based environment.

3.4 Filters

The current design includes a 8 slot filter wheel so that a wide range of filters can be used. A summary of the filters that one might use are given in Table 3.4 In addition to a set of standard J and H filters a broad band Z filter and a short pass K filter would be useful. In the Z band (0.85 to 1.0 μm), conventional CCDs have effective QEs of ≈20% at 0.85 microns, and very little sensitivity at 1.0 microns whereas the MCT array has a QE of 60%. Therefore Z band may prove useful. The trade off is that conventional CCD Mosaics can cover a larger field with the same sampling. However, contemporaneous observations in a band that overlaps with CCDs may be useful. A short pass K band filter will also be considered. Its characteristics will depend crucially on the thermal background and transmission of the telescope optics.

Narrow band filters choice fall broadly into two categories;

(i) filters that are defined by zero redshift emission lines

(ii) filters that are defined by redshifted emission lines.

In the case of redshifted lines, one should choose windows in the OH in order to minimise the sky contribution e.g. at 1.25μm and 1.66 - 1.25μm. The choice of optimum windows are currently under investigation.

In addition filters that correspond to 'matched' emission lines would be required for blank sky surveys. e.g. a filter at 1.25 μm could be used to search for H-α at a redshift of 0.9 in order to determine the global star formation rate. This filter would also be useful in eliminating low redshift interlopers from a search for $z \approx 5$ Lyman-α emitting galaxies carried out in the optical at 7100Å. Some of this survey work is clearly more ideally suited to 8m class telescopes rather than 2m class telescopes.

4. Potential telescopes

4.1 Commissioning Phase (La Palma)

The camera can be used directly at the prime focus of the 2.5 Isaac Newton Telescope(INT) using the existing triplet corrector which gives excellent performance in the J (1.3μm) and H (1.6μm) bands. The timely upgrade to the INT prime focus assembly and telescope control systems to facilitate a 2x2 thinned Loral CCD mosaic means that integration with the IR camera will be quite easy. The advantage of the INT prime is its very large field of view and well matched pixel scale. Each pixel corresponds to 0.46 arcsec and the total field of view is 0.07 deg^2. A sequence of interleaved images will give a final image of 31.4x31.4 arcmin. This in a total of 16 exposures an area of 1 degree square can be covered.

There are no existing or planned IR instruments for the INT and we expect to be able to obtain 2 to 3 weeks per semester. Within the UK context, we effectively gain an IR telescope to complement our access to UKIRT which will be primarily more useful in the K band and in cases where small field and high image quality is the main driver. In the short term one would expect to follow up objects discovered during the INT phase using UKIRT, potentially pushing COHSI to its limits.

It is not clear that moving the camera to the 4.3m William Herschel Telescope(WHT) has any substantial gains over the INT. The advantage of the WHT is the larger aperture and better image scale which would help in deeper surveys. However the WHT prime focus corrector has a lower throughput in H than the INT by ≈50% and bright time is more oversubscribed on the WHT compared with the INT since its bright time instrument set includes an echelle spectrograph and a J,H and K adaptive optics system built around a 256^2 InSb array. Ideally one would work at the Cassegrain focus of the WHT using a special purpose NIR corrector. This option is currently under investigation but it is likely that for comparable cost one could take the camera to a larger telescope.

4.2 MMT phase

Many of the programs in the list in Section 2 would benefit considerably from larger apertures and finer image scales. In addition if some of the more speculative survey programs are successful one would expect that deeper programs would be a logical next step to either probe deeper in flux at the same redshift or to push to higher redshifts. In addition multi-objects near IR spectroscopy is clearly better suited to the larger aperture.

The basic camera system should be easily transportable to the MMT environment. On a longer term, spectroscopic capability and contiguous field possibly via a pyramidal mirror system similar to the HST Wide Field Camera with the inclusion of tip-tilt adaptive optics is clearly possible. Contiguous field would be a significant gain for programs that want to go deep over smaller areas since the 2x2 interleaving effectively drives one to larger fields than one can follow-up easily with multi-object spectrographs.

4.3 A NIR corrector for the f/5 MMT Cassegrain focus

Fabricant & McLeod ('Optical Specifications for the MMT conversion',1995) describe an f/5.48 wide field corrector optimised in the optical over the wavelength range 3000--10000Å. We have carried out some preliminary optical design work on a NIR wide field triplet corrector for use with the MMT's f/5 secondary to give good images in the wavelength range 1.0-1.8µm over a field of view corresponding to our mosaic. The triplet lens has some power of its own to increase the field of view on the sky and gives a pixel scale with good sampling in excellent seeing. The final f-ratio is f/3.9 and the image scale is 123µm/arcsec or 0.15 arcsec/pixel. This should be compared with the bare f/5.25 scale of 0.11 arcsec/pixel and represents a factor of ≈2 increase in field of view.

The triplet shown in Figure 4.3a uses PK51A and BALF5 glasses to provide correction for chromatic aberrations. The largest element has a clear aperture of 228mm. The back-focal distance is 400mm to allow the possibility of including a tip-tilt mirror. The focal plane is 111mm below the instrument mounting surface.

The image quality is shown in the spot diagrams (Figure 4.3b) and encircled energy plot (Figure 4.3c) for 4 field positions that correspond to the corner of an array near the centre of the mosaic, the corner of the mosaic and 2 other points equi-spaced in between. The imaging performance is not quite diffraction limited but 90% of the energy falls within a circle of 20 radius. The box size for the spot plots is 37µm which is 2x2 pixels.

4.4 Design Study and Case for Wide Field Spectroscopy

The wide field camera system under construction offers a further great opportunity if it can be upgraded to a very wide field deep spectroscopy system for a 6-8m class telescope.

4.5 Scientific rationale

Over the past 5 years, impressive progress has been made in extending redshift surveys to higher redshift providing information on the evolutionary behaviour of galaxies, clusters and quasars. Much of the progress has resulted from surveys made possible via purpose-built instrumentation, e.g. multiple object spectrographs capable of measuring redshifts for many hundreds of faint sources or wide field imaging capabilities.

The cosmic landmark represented by a redshift of one has been a significant barrier for galaxy and cluster work for many years. The apparent magnitude of a typical galaxy at this distance is at the spectroscopic limit of a 4-m telescope. Furthermore, the optical contrast of a rich cluster against the projected field population also falls below a critical detection threshold (2-3σ). Most significantly, the spectral features used so successfully to determine the redshifts of faint galaxies, visible emission lines of [O II], [O III] and H-α, are shifted into the near infrared and thus optical spectrographs are not well-equipped for measuring redshifts beyond 1.

Systematic redshifts surveys with 4-m telescopes have succeeded in determining the spatial distribution of nearby galaxies and the evolutionary behaviour of various classes of galaxies out to redshifts of 1 (Glazebrook *et al* 1995, Lilly *et al* 1995, Ellis *et al* 1996). The recent discovery of an abundant population of star forming galaxies *beyond a redshift 1* from faint object Keck spectroscopy (Cowie *et al* 1995) and, at higher redshift from various lensing studies (Lewis *et al* 1995, Ebbels *et al* 1996) and Lyman-limit-selected surveys (Steidel *et al* 1996) raises the question of how best to search systematically for such objects.

The scientific motivation for extending the earlier studies to higher redshift follows from the implications of the strength of emission seen in the important diagnostic lines of [O II], [O III] and H-α. The limited data currently available indicates a significant fraction of the present stellar mass was being created in the redshift range $z>1$. This may be consistent with the relatively mild evolution seen at later times but places in question the significance of the abundant dwarf population. Only by tracking the mean star-formation rate of well-controlled samples as a function of look-back time can these various issues be resolved.

In addition to quantifying the era during which galaxies formed the bulk of their stars, the spatial distribution of star-forming galaxies at early epochs might be derived if the technical challenge of surveying $\approx$5-10,000 faint galaxies in the redshift range $1<z<3$ could be overcome. The growth of clustering on various scales can be used to constrain models for the evolution of structure which are themselves indicators of the cosmological parameters once the spatial distributions at the present-day and epoch of recombination are well-defined as can be expected in the next few years.

As with the earlier redshift surveys, the key to progress lies in the development of the appropriate instrumentation. The Lyman-limit selection pioneered by Pettini and collaborators remains a promising method for the highest redshift systems. However, follow-up spectroscopy with the largest telescopes is still required to derive precise redshifts and star formation diagnostics. One important limitation with the method is that it cannot be used below a redshift $z_{Ly\infty} \approx 2.8$ without access to space-borne UV facilities. As these currently have very narrow fields of view, they are not well-suited to survey work.

Direct spectroscopy of broad-band selected targets such as is now being conducted on the Keck by Cowie and co-workers is also limited by telescope aperture and the availability of emission line features at optical wavelengths. The success of the sky-limited redshift surveys relies largely on the availability of strong [O II] which disappears from the optical region beyond $z \approx 1.4$. Indeed, without the emission lines, none of Cowie's galaxies would probably have yielded redshifts when examined with Keck's LRIS. A logical solution to this problem is to build a panoramic wide-field spectrograph.

If the primary goal is to determine the star-formation history of normal galaxies and it is assumed (as now seems reasonable) that suitable systems are present in abundance at high redshift, then rather than attempting to measure the redshifts of galaxies selected first using broad-band techniques, it may also be effective to search within narrow spectral bands for objects containing emission lines within selected redshift ranges where the OH contamination is low. As well as being technically advantageous in lowering the line flux limit, this would offer a number of strategic advantages in the derivation of evolutionary conclusions and spatial correlation functions. Spanning 2-D space at a given redshift does not replace the continuing need to probe 3-D in single fields but does illustrate the versatility possible with wide-field instrumentation.

Some earlier narrow-band programmes failed to locate star-forming proto-galaxies at high redshift; these used both optical (Djorgovski *et al* 1995) and infrared techniques (Thompson *et al* 1995, Pahre & Djorgovski 1995). The apparent failure of these programmes is puzzling for two reasons. Firstly, the surface density of $z>3$ galaxies with high star formation rates identified by Steidel *et al*(1995) strongly suggests that obscuring dust does not seriously limit the detectability of high z objects as had been argued. It also confirms suspicions that Lyman-α emission is not a reliable indicator of star formation. These developments may explain the null Lyman-α results. However, recently Hu & McMahon(Nature in press) have detected Lyman-α emitters in the vicinity of QSOs with $z=4.44$. So far as the near-infrared results are concerned, the emission line fluxes directly witnessed by Cowie *et al* already lie well above the lower limits of null detection claimed by Pahre & Djorgovski *despite the fact that the redshift ranges of both observational programmes overlap*. Thus the new Keck spectra give much more promising indications of the merits of surveying for emission line galaxies in the near-infrared spectral window.

How many star-forming galaxies might a particular survey find? Part of the motivation is, of course, to determine the answer. Nonetheless some estimates can be made on the basis of the early Keck results. The key advantage of a spectrograph that can exploit 4 1024^2 arrays is its enormous field of view of $\approx$72 arcmin^2. It potentially can operate in both conventional imaging or multi-slit spectroscopic mode or in a 'narrow band selector mode' whose redshift range, Δz, can be moved in z. The advantage of the latter mode is that it can offer a much fainter line flux limit for various technical reasons. This advantage is offset by an obviously much smaller volume sampled at a chosen redshift of interest. The key to which mode to use will depend on the performance and the surface density of interesting objects.

For the conventional mode where broad-band images are used for multi-slit work within a given redshift range, we can make some estimates from Steidel *et al*'s data. They find a surface density of 0.4 arcmin^{-2} for R<25 galaxies within $3<z<3.5$ giving $\approx$30 per instrument field. Clearly this is a lower limit to the number of distant galaxies amenable for study. The total number of galaxies with R<25 within the field is $\approx$1000 (Metcalfe *et al* 1995). The mean star formation rate Steidel *et al* infer from their UV continua is 4-25M_O

5. Instrument Design

5.1 Detector specification and performance

The contract with Rockwell calls for devices with the following performance:

The 1024X1024 arrays shall be manufactured on a best effort basis to meet the following performance specifications and goals.

	Specification	Goal
Format (pixels)	1024X1024	1024X1024
Pixel pitch (ÿm)	18.5	18.5
Fill Factor	> 95	> 95
Quantum Efficiency (77K)		
@1.2 micron	40%	70%
@ 2.35 micron (or peak)	50%	75%
Long wavelength cut-off (micron)	2.5	2.5
Short wavelength cut-on (micron)	0.85	0.85
Read noise (e- at 77K)	< 20	< 5
Dark current (e-/s at 77K Vb= 0.5V)	< 0.5	< 0.1
Well capacity (e-, Vb= 0.5V)	6E4	6E4
Yield (working pixels)	> 92%	> 97%
Temperature	<77K	<77K

The specifications above apply to mean values. There will be four outputs.

5.2 Operational requirements

5.2.1 Device environment: temperature, background

This camera has relatively simple cryogenic requirements compared to many infrared cameras. The Mercury-Cadmium Telluride (MCT) devices are only sensitive to the J (1.3 µm),H (1.6 µm) and K (2.2 µm) bands and so the thermal background of the instrument has a much smaller effect than with detectors that have a much longer wavelength sensitivity such as InSb devices). The devices have a very low intrinsic dark current at a convenient operating temperature of 77K allowing simple liquid nitrogen cooling. CIRSI is only intended to operate in the H and J bands, although the internal design of the dewar must minimise any radiation out to the long wavelength cut-off of around 2.6 µm.

When used in survey mode the camera must accept a f/3.5 beam from the telescope but the lack of any re-imaging optics means that the detector sees a f/1.4 beam and so detects a large thermal background from the telescope. In the H band the camera will detect approximately 1000 e/s/pixel from this background, this is small compared to the OH emission from the sky which may be up to 4000 e/s/pixel.

5.2.2 Filters: filter specification, blocking

The filter wheel must be cooled because the HAWAII device is sensitive to infrared radiation up to a wavelength of 2.6 µm, although it will not be operated at this wavelength in survey mode. The restricted wavelength response of the MCT devices is a great advantage as the filter doesn't have to provide high blocking at long wavelength. Near infrared filters for InSb based cameras require extra blocking layers to prevent red-leaks which increase the size and cost of the filters and reduce the peak transmission. The specification of the filters ordered is in Appendix 5.2.2.

5.3 Dewar design

The camera will be contained in a simple liquid nitrogen cooled dewar. Internal optics and mechanical components have been minimised to simplify the design. A test dewar is being constructed to operate a single chip, this uses an existing Oxford Instruments MN1815 dewar of the type used for CCD cameras by AstroCam and LPO. The internal structure of the final camera dewar will be very similar to the test dewar, a single cylindrical dewar with a single large filter wheel and no other internal optics apart from the fixed autoguider take-off mirror.

5.3.1 Detector mount

The detector mount emphasis the modular design of the system. The infrared array is fitted in a socket on a circuit board. The detector mount surrounds this circuit board and provides a cold finger, a clamp to hold the detector in place and the socket for the electrical connections. The mount allows 2 edge butting of the device constrained by the size of the socket. This mount can hold either a HAWAII or NICMOS device and is can be used in the test dewar, main camera dewar and COHSI cryogenic spectrograph, it is intended that any future instruments will use the same mount design. The detector mount package can be safely removed from the dewar and stored with the device installed. The detector mounts consist of a single fixed cold finger supporting the back of the detector and a cooled clamp on the front which holds the chip firmly onto the cold finger. The clamp maintains a constant contact pressure onto the cold finger and prevents the chip moving as the dewar orientation changes. The tension in the clamp can be adjusted.

The four detector chips must be position at a common focal plane. The small size of the pixels and the fast f/ratio of the telescope mean that the accuracy of this positioning is a major challenge. The mount contains no built-in movements to adjust the position of the detector surface, this would produce an impossibly complex design and would inevitably reduce the cooling power available. Instead the four detector units will be assembled and the height and tilt of the individual chips measured with a travelling microscope. The mounts will then be individually polished to produce a common focal surface, note that the actual height is un-important as the whole camera assembly can be moved by the telescope focus. The major variation in the position of each chip comes from the layer of epoxy glue used to fix the hybrid detector assembly into the chip carrier ceramic. Appendix 5.3.1 shows the electrical and mechanical design of the detector mount.

5.3.2 Filter wheel

The filter wheel is inside the dewar so the available range of filters can be changed only after warming and partially dismantling the dewar. Because of this a large number of filters are available in the wheel. Initially the system will house up to 8 filter positions although one may be reserved as a blank position to allow testing of the camera in a no-signal state. The design allows for an upgrade with a second filter wheel to fit in front of the first, giving a total of 14 positions.

The HAWAII chip package prevents close packing of the arrays and the camera is designed with a large gap between adjacent chips. This means that it is possible to use four small filters, each 32mm square, rather than a single large element. A cell of four filters can be removed from the filter wheel as a group allowing easy changes of the pattern of loaded filters while reducing the handling risk of individual pieces of glass.

The filter wheel is driven by an external motor connected by a vacuum feed-through. We are using a Ferro-magnetic fluid sealed feed-through. The position of the wheel is measured by a potentiometer on the motor gearbox which allows a measurement of the absolute position of the wheel to within a degree. Although it is necessary to open the dewar to install filters the camera is designed to make access easy. When the radiation shields have been removed the entire filter wheel can be removed or individual filter cells swapped without disturbing the detector mounts.

The small filters are not only cheaper and easier to produce but allow the same filter sets to be used in a range of instruments. This also means that special filters can be produced easily as only one small filter is needed, it is even possible to have different filters can be mounted in front of each of the four chips.

5.3.3 Shielding requirements

The field of view of the camera should ideally be only the sky and cold low emmissivity shielding inside the dewar. But operating at a fast focal ratio with a wide field of view the efficiency of the shielding is compromised to avoid vignetting the image. See the section on background for technical details.

5.3.4 A & G system pick-off mirror

The camera will have its own acquisition and guiding system. This is needed at the INT prime focus as there is no other autoguider available.

The star counts that we expect to encounter in practice have been examined so that we can be sure that the search areas for our autoguider are satisfactory. These are given in Appendix 5.3.4.

The autoguider will use an Peltier cooled CCD camera mounted outside the dewar viewing a fixed mirror mounted inside the dewar near the focal plane. A re-imaging system will produce an image on the camera at the correct scale. The pick-off mirror can be large enough to fill the autoguider CCD re-imaged with a scale of 2:1, i.e. 0.45 arcsec/pixel.

5.3.5 Electrical connections

The detector mount module contains a 25 way micro-D connector carrying all the electrical connections to a single chip. These are then connected to two 55 way Amphenol connectors mounted in the dewar wall. The internal dewar connections are made with 36 AWG Manganin wire with Formvar insulation (from Lakeshore Cryonics). The Manganin wire has a thermal conductivity only 2% that of pure Copper and this arrangement gives a heat load of 70μW / connection. Even with the 100 connections needed for the camera the heat load due to the wire is much smaller than the radiation load.

5.3.6 LN hold time

The dewar design is not yet finalised and so only approximate estimates of the hold time can be made. By simply scaling the test dewar to the size needed for the final camera and assuming that the construction is the same, we have a capacity of 12 litres and a hold time of over 60 hours. This is easily enough for the camera's normal operation but means that some extra system is needed to allow the nitrogen to be poured out and the dewar warmed to allow changes of internal components in a reasonable time.

5.3.7 Shipping constraints

The camera is likely to be a single cylindrical dewar of 0.5 metre diameter and less than 0.5m long with a mass of 50 Kg. The associated controller electronics is a small case 30x25x20 cm and is accompanied by a normal desktop PC. The system could be contained in small flight cases and transported as checked-baggage on a scheduled flight. The mechanical telescope interface is much larger. Using the same design as the RGO CCD mosaic for the INT would require a metal disc around 1m in diameter. It may be possible to reduce the size and weight of the interface at the expense of greater complexity by using a construction framework system such as the ALUSET used for the COHSI shell. The telescope interface is obviously different for each telescope and it is likely that on the first run at a particular observatory the interface and the camera would be shipped out in advance along with a few of the group to supervise the integration. On subsequent runs the camera alone would be taken, it would then be convenient if the system could be carried along with the observers. Depending on the number of telescopes used it may be better to produce an adaptable telescope interface framework which can fit a number of telescopes.

5.4 Detector output multiplexor

The Rockwell HAWAII array, like the earlier NICMOS array, is arranged as four identical separate quadrants produced on the same integrated circuit. Each quadrant has independent power supplies, addressing functions and output amplifiers. The CIRSI camera will use four arrays each with four outputs but with a single camera controller and signal processing chain. An output multiplexor circuit mounted immediately outside the dewar allows addressing functions to be routed to any quadrant of any chip and connects any of the outputs to the signal processing chain.

The schematic design of the multiplexor circuit has been completed.

5.4.1 Detailed design - electrical

The signal from the HAWAII output amplifier is switched with relays, ensuring a reliable and noise free signal path. The unused outputs are connected to ground which both protects against electro-static damage and removes power from the on-chip amplifier. While the camera is integrating all the output amplifiers can be powered off which reduces light emission from the on-chip circuits.

A very flexible addressing scheme has been implemented. A single set of addressing clocks is generated by the camera controller, these are fed to the camera through a multiplexor which allows signals to only reach the selected set of quadrants.

The pattern of selected quadrants and chips is loaded into the multiplexor and a clock sequence generated by the controller. This can be repeated with a different clock sequence for each pattern of chips, allowing any pattern of quadrants to be reset or read. Additionally the whole camera can be reset in the time it takes to address one quadrant. Any pattern of sub-arrays on any of the quadrants can be defined and read independently, the only limitation imposed by the HAWAII on-chip circuitry is that a full row of 512 pixels is reset at a time.

The multiplexor PCB also contains the circuits which generate the bias levels for the HAWAII array. Only one of the levels is generally adjustable, VRESET which controls the well capacity. This level will be adjustable by a trimmer on the circuit and will not normally be changed initial after testing.

A detailed electrical schematic is at Appendix 5.4.1.

5.4.2 Detailed design - mechanical

The multiplexor is contained on a single circuit board is approximately 200mm square which is mounted in a screened metal box immediately outside the dewar. The camera controller is mounted approximately 1m away and is connected by a single 60way flat cable which carries all the power supplies and clock levels, and a co-axial cable which carries the output signal.

A detailed electrical schematic is at Appendix 5.4.1.

5.5 Controller

5.5.1 Overview

The controller to be used for CIRSI is an AstroCam 4100 high-speed CCD controller, modified in-house to allow it to work well with the HAWAII infra-red arrays.
The controller has been in production by AstroCam for over four years. Many have been sold for all sorts of application, including, for example, one for use as the JOSE optical seeing monitor on the William Herschel Telescope on La Palma. As a commercial product (AstroCam is fully ISO9000 accredited) it is well documented and has a good track record for reliability.
The controller has at its heart a programmable sequencer IC (called a SAM, made by Altera Inc., USA) that generates patterns of digital signals at 24MHz. These data patterns are used with CCDs to control the clock waveforms, the signal processing chain and the analogue to digital conversions. With CCD use, the internally generated electronic noise referred to the output of the detector is approximately 4 µvolts at a pixel rate of 500 KHz, corresponding to about 1 electron of noise from the HAWAII devices, and higher at higher pixel rates. The controller is capable of working at a maximum of 8 MHz pixel rate, and at 5.5 MHz pixel rate with full double correlated sampling. In practice the HAWAII arrays are limited to a maximum pixel rate of 1 MHz, with a rate not in excess of 300 KHz if optimum performance is to be achieved, so only pixel rates at the lower end of the 4100 controllers range are likely to be used. The fast clocking will permit rapid skipping through unwanted pixels when sub-array read-out is needed.

The 4100 controller can manage a single output channel at once. With the HAWAII arrays, each device has four independent channels, and there are four devices. The single channel 4100 controller will use a separate multiplexor box to allow one out of the sixteen quadrants to be addressed and read out at a time. With 4 million pixels, and a peak read rate of 300 KHz, the read-out time will be in excess of 10 seconds.

The SAM will be entirely reprogrammed to allow the 4100 controller to generate the necessary waveforms to clock the signal from the HAWAII array quadrants, and to process the output analogue signals appropriately. The 4100 controller is normally used with a buffer card close to the detector head that provides clock level control and a small amount of output signal pre-amplification. With the HAWAII arrays this buffer card will not be needed since the arrays accept digital TTL (5 volt) logic levels directly. There will need to be a separate multiplexor box to allow the analogue channels to be enabled and buffered separately. The multiplexor box will also provide some impedance matching to allow the output from the HAWAII channels to be made to look like a CCD output for convenience.

The 4100 controller is operated under the overall control of a simple Transputer microprocessor device. The role of this Transputer is to manage the operation of the SAM by triggering it to carry out one out of a number of functions which are requested with a number of parameters passed with each command. The SAM generates the instruction data patterns, and the data are passed directly to a parallel port (NOT via the Transputer, which is much too slow to handle these data rates), buffered (RS422, with over 100 metre driving range) and so passed back to the host computer.

5.5.2 SAM Code

The SAM code is developed with software provided by the SAM manufacturer. It allows the device to be programmed with a simple assembly-type language that is easy to follow and modify. As a guide and aid to learning the language, AstroCam have agreed to loan a standard CCD head (with a Kodak KAF-0400 CCD), a frame grabber card (an Imaging Technology VFG card), cabling and high-level software. This will allow us to modify the CCD read-out procedures as we gain familiarity with the code and allow us to go on to programming the HAWAII control patterns with more confidence.
An example of the SAM code is attached in Appendix 5.5.1

5.5.3 Transputer

The INMOS Transputer is programmed in Occam. We do not, however, expect to need to make any changes to the Occam code supplied by AstroCam. This code (of which the source has been supplied by AstroCam) allows all the functions of the SAM to be utilised fully so we will retain its format so that the calling programme thinks it is dealing with a CCD. Only the SAM will know better. This allows the calling software and driver software in the host computer to remain unchanged, saving a great deal of work. Should minor modifications be necessary, AstroCam has agreed to assist.

The control of the Transputer microprocessor may be handled via a Transputer link or via a fast RS-232 interface. We intend only to use the RS-232 interface for simplicity and to allow the option of using non-PC control computers in the future.

5.5.4 Data Output Format

The data are output in an industry standard format used by many manufacturers of image frame grabbers. It consists of 16 data lines, with pixel, line and frame pulses. All data are buffered for RS-422 twisted pair drivers that are capable of operating over a cable of over 100 metres length (about 80 metres are used on the WHT routinely at present).

5.6 Computer Interface

The faster data rates that are possible with the HAWAII arrays are faster than may be handled by the IBM/PC ISA bus. For this reason we intend to use a PCI bus interface card that AstroCam are integrating. The card is being procured from a small Tucson based company (Spectral Instruments). A beta unit has already been received and works well. A production version is expected in June, with quantities (and one for this project) in July.
In order to speed the development of the SAM code, AstroCam have loaned the project an existing frame grabber (Imaging Technology VFG board) that already works with the calling software until the PCI board is ready and fully integrated with the same software package to make it call compatible.

5.7 Software

The camera control and data taking software is a major part of the project. The software system must support all the features needed for engineering tests and observing at the telescope, it must be reliable and robust enough not to waste observing time and be useable by observers without a large support effort.
The development of the software must proceed at the same time as the camera construction and so it is important that the camera testing is not delayed by a lack of control software. Initially AstroCam supplied CCD camera software will be used in the lab for device testing and the astronomical software integrated in as packages are finished.
There are a number of separate components all of which must all work together. They include:

1. The SAM code, hardware microcode that is held in electrically programmable sequencer integrated circuit (an Altera SAM chip). This generate the individual clock and signal processing waveforms for the HAWAII device. SAM software has never been written for an X-Y addressable CMOS device before.

2. The controller contains an INMOS Transputer IC for system control and a variety of useful housekeeping purposes. We intend not to modify this code in any way, but we will need to get a good understanding of what it does.

3. The controller is connected to the IBM/PC compatible computer by an interface that is supplied by AstroCam Ltd. They have loaned one of their existing frame grabber boards which will let us do a great deal of the development work. They are at present working on a PCI interface board that will have a lot of advantages including simplicity, speed and cost over the existing frame grabbers. This PCI interface is being purchased from a small company in Tucson, Arizona. The first version of the board has been tried successfully. The next version is expected at AstroCam in 3-4 weeks,

and this board is expected to be essentially complete. AstroCam will then complete the device driver work to integrate it closely with the controller and make it compatible with the existing higher level software that controls the system. This higher level product is called the 41 User Interface (or 41UI).

4. The 41UI is essentially a C-callable subroutine library, also available in DLL form for Windows 3.11/Windows 95 use. It has no graphical user interface of its own. AstroCam have a variety of options that provide comprehensive imaging support and will provide suitable environments for developing the system in the laboratory. Different software will be required for use at the telescope, and the way it is interfaced to the 41UI, the developmental Windows based package and to IRAF is still being discussed.

5.7.1 Microcode

The programs which generate the clock patterns to operate the arrays are written in a hardware specific low-level language. The programs are generally downloaded and executed in computers embedded in the controller hardware, the mode and format of the readout is selected by downloading a different program or passing parameters to the program. In the NICMOS system this is an assembly language for a custom RISC microprocessor in the HAWAII system a programmable micro-sequencer (SAM) is used. The SAM is unusual in that all the available programs are burnt into the device during development and cannot be changed at the telescope. The parameters of the read such as exposure time, pixel rate or sub-windows can be changed before each exposure.

5.7.2 Image kernel

The centre of the software system is a number of separate packages which each control an area of operation such as image handling, camera control or file handling. Using object-orientated programming techniques it is possible to produce a reliable and robust system with access to the components of the data available through a strictly controlled interface. This methodology allows enhancements and upgrades to the packages without breaking existing code. This code is written in C++ and is designed to operate seamlessly across PC and workstation architectures.

5.7.3 Command language

The versatility of the camera system in its wide range of operating modes demands of requires a very flexible software system. It is impossible to predict all the requirements of astronomical and engineering users and so a highly adaptable system is needed, this takes the form of a command and scripting language. The command language is based on TCL an embeddable command shell produced by Sun but available on a range of operating systems. The language is similar to the Unix shell or Perl and is familiar to any Unix user so extra commands may be added by the camera packages to provide support for the camera features. An integral part of TCL is TK. This a windows toolkit which allows graphical user interfaces to be written in TCL with a few simple script commands.

5.7.4 Observing commands

The observing software is based on the Unix / IRAF model of providing a number of simple commands which can be built up into complete packages rather than large difficult to modify programs.
Different sets of commands will be needed for engineering tests and observing at the telescope, and observations in different modes by different astronomers but they are all based on the same basic commands.

5.7.5 Data analysis

Astronomical data analysis packages usually expand out of control to meet all the requirements of all possible users. The model for this system is to produce image data in a standard format and pass this data to an existing astronomical analysis system, such as IRAF. The mechanism for this can be as simple as saving the data in FITS files to a shared directory and have a copy of IRAF being used by another observer to reduce the data, or it may be possible to pass the data transparently to IRAF and have the answers returned and presented to the user.
Analysis features in the camera software will be limited to those needed for engineering tests which are not commonly available in astronomical packages together with some simple on-line statistics to monitor camera operation.

5.7.6 Other software components

5.7.6.1 Network environment

All the programs written in TCL/TK can be moved across platforms unchanged. In addition TCL provides a network transparent data and command transport, TCL programs running on one machine can pass data easily to TCL programs running on networked machines with a different operating system.

5.7.6.2 File formats + archiving

The camera will store all it's data in FITS format, although the software has the ability to import and export data in a number of other formats for compatibility with AstroCam systems. On a Unix system supporting IRAF it is also possible to write data in IRAF image format, however this format is not machine independent and is not available as a separate standard on non-IRAF platforms.
The typical data from a full night observing is less than 1.5Gb and can easily be stored on DAT tape. We may also record data on write-able CD-ROM directly.

5.7.6.3 Device drivers

The camera controller is interfaced to the computer through a serial line for downloading commands and configuration and a high speed parallel data bus to receive image data. The data is handled by a frame-grabber card mounted on the host computer's bus, this can be an SDV board from EDT in a Sun/SPARC or a PCDI board from Spectral Instruments on a PC's PCI bus. The frame-grabber is supplied with a device driver which allows incoming data to be transferred directly into the computer's memory. The PC card is supplied with drivers for Windows95 and Linux. We will use an older ISA frame-grabber card loaned by AstroCam until the PCI card is available.

5.7.6.4 Displays

The TK toolkit provides a simple image display tool but this lacks the colour table and image scaling facilities usually available in astronomical display packages. The system will pipe image data to SAOImage, on Unix based systems, or an AstroCam supplied display utility on Windows systems.
As the camera will be read-out continually during a long integration it is possible to display the image in real-time as it is integrated. The entire image contains too many pixels to easily display the entire image but a single quadrant, or a number of selected sub-windows, could be displayed and updated continually.

5.7.6.5 Telescope Interface

It is important that the camera system is well integrated with the telescope control system. With multiple exposures at different positions to build up a mosaic image the camera must be able to efficiently reposition the telescope. The system becomes more complicated as it must support a range of telescopes with different control systems. The current plan at the INT is for a server application to run on the telescope workstation which can communicate with the telescope control system (by DRAMA) and to the camera and autoguider computers. This will run through the sequence of exposures, moving the telescope between positions, co-ordinating the autoguider link and telling the camera when to start an exposure.

6. Development Programme

6.1 Overview

Section 5 covered the detailed considerations that had to be looked at for each aspect of the design of CIRSI. These requirements have been translated into a series of work packages that lead from the project through to a complete system that will meet the overall requirements that have been set.

The project has been organised with Microsoft's Project for Windows. The detailed Project Schedule including a GANTT chart is in section 6.3. In order to make it more understandable, each task has been listed below together with a short description where appropriate of the work that is to be undertaken to complete it. In reviewing the details of the information listed below and on the GANTT chart it is important to understand the assumptions that have been used to construct this project programme.

Each task has associated a number of man-days that are predicted for the project to take to complete the task. Project tasks are shown to follow one after another. In practice the most efficient scheduling will be for a number of tasks to be in progress at any one time so that on average across the project we see that the total time to completion is unchanged despite the fact that some tasks will appear to be late and some will appear to be early. On average equal tasks should be early and late.

The information provided for this Critical Design Review are taken from a revised Project Plan that was constructed in late May, 1996, while the project actually started in early February 1996. The currently predicted completion of the Project has slipped by only three days. This implies good progress with the Project but it is important to appreciate that there are some real uncertainties in the plan, and we have not tried to do the hardest parts which are getting the detector to run properly. Any problems here could give much larger delays overall.

6.2 Detailed Task List

The format here follows that shown on the GANTT chart. Each task has a title within the major subdivision of the tasks. Under the title are shown the number of man-days for the task to be carried out with the start and finish dates. Following the dates are the predecessor tasks (those that must be completed before the current one is started, and the initials of the individuals who are presently assigned to carry out these tasks.

6.2.1 Project Reassessment Start Date

1d 21/05/96 21/05/96
This is the base time relative to which all activities are scheduled.

6.2.2 Science Program

35d 22/05/96 09/07/96
The overall science programme needs to be fully established and articulated so that the design of the instrument may be tailored as closely as possible to the goals of the programme. It is achieved by a series of meetings with special interest groups within the IoA as well as from outside.

6.2.3 Telescope target 1 identify

5d 22/05/96 28/05/96 1 rse,rgm
The science programme can only be carried out on suitable telescopes. The plan calls for two such telescopes to be identified, the contacts made with their keepers so that access may be negotiated in good time. The first telescope will be one that is easy to access and to interface to, and is likely to be the Isaac Newton Telescope (2.5 metres) on La Palma.

6.2.4 Overall instrument concept

1d 22/05/96 22/05/96 1 rse,rgm
The science programme is translated into a general instrument concept as a guide to the instrumentalists who are developing the system.

6.2.4.1 Consultation in department

20d 23/05/96 19/06/96 4 rse,rgm
This involves discussions with interested parties within and outside the IoA.

6.2.5 First draft programme

5d 20/06/96 26/06/96 5,3 rse,rgm
This section calls for a first pass at a typical observing programme or programmes so that the model observing sequences may be developed. This is an important guide to the kinds of facilities that are needed for on-line data reduction and analysis at the telescope, the quantities of data that are to be archived and displayed, and the level of completeness of reduction that are needed.

6.2.6 Telescope target 2 identify

20d 29/05/96 25/06/96 3 rse,rgm

As with the first telescope a second telescope needs to be identified that is a suitable location for the camera to carry out longer term survey work. Possibilities include the refurbished MMT, telescopes in Arizona such as the Steward 90 inch, the Mexican telescope near Nogales, or one of the telescopes on Hawaii.

6.2.7 Final science programme

10d 26/06/96 09/07/96 7 rse,rgm

The programme calls for a final science programme to be produced that folds into the equation the characteristics of the actual telescopes to be used and the way that this might affect the overall programmes.

6.2.8 Observing Procedure Design

36d 23/05/96 11/07/96

This task calls for a detailed analysis of all reduction and analysis facilities, and all the facilities such as A&G, telescope control and system management facilities that are to be provided at the telescope for the full range of observing programmes.

6.2.9 Facilities required specification

2d 23/05/96 24/05/96 1,4 cdm

This tasks calls for all hardware and interface requirements to be specified in order to provide the facilities requested to be provided.

6.2.10 Operational modes definition

2d 27/06/96 28/06/96 10,6 cdm

Here is a task that will establish the principal operating regimes for the camera and A&G system so that we are sure that data rates can be handled, and that frequently used procedures are made as slick and easy to use as possible.

6.2.11 System controls needed spec

2d 01/07/96 02/07/96 11 cdm

We need to determine the type and level of control procedures we need to manage the telescope and instrumentation systems.

6.2.12 Software facilities needed spec

2d 03/07/96 04/07/96 12 cdm
Detailed specification of the software facilities we need at the telescope for efficient operation.

6.2.13 A&G facilities needed

2d 05/07/96 08/07/96 13 cdm
Define the level and detailed A&G procedures that we need to provide at the telescope.

6.2.14 Telescope interfaces needed

3d 09/07/96 11/07/96 14 cdm
Define the hardware and software interfaces to the telescopes that we will need to make a clean connection to the telescope and its telescope control system.

6.2.15 Hardware Procurement

186d 21/05/96 04/02/97
Much of the main hardware items have already been procured. There are a few remaining items that are still outstanding, in particular the HAWAII infra-red arrays themselves. The Engineering grade device was received on 22 May, 1996, four months ahead of schedule.

6.2.16 Receive Engineering grade device

1d 21/05/96 21/05/96 rockwell
Already received.

6.2.17 Receive device #1

120d 22/05/96 05/11/96 17 rockwell
The date of receipt of the device is the second one listed here.

6.2.18 Receive device #2

20d 06/11/96 03/12/96 18 rockwell

The date of receipt of the device is the second one listed here.

6.2.19 Receive device #3

25d 04/12/96 07/01/97 19 rockwell
The date of receipt of the device is the second one listed here.

6.2.20 Receive device #4

20d 08/01/97 04/02/97 20 rockwell
The date of receipt of the device is the second one listed here.

6.2.21 Test Camera Construction

116d 22/05/96 30/10/96
The programme calls for the construction of a fully functional test camera that may be used to run the dummy HAWAII model chip (a device with all the read-out electronics working, but without any of the IR sensitive element attached. This will also be used to test the individual science grade devices as they arrive and before they are installed in the main science dewar. It will in fact provide a fully working single device camera that could be used independently of the main camera.

6.2.22 Construct multiplexor box

2d 16/08/96 19/08/96 1 mgb
The HAWAII devices have four independent outputs. Four devices give sixteen device outputs. We intend to read these in sequence, and we use a multiplexor box to allow easy switching under computer control from one sector to the next. The system will allow any combination of quadrants and devices to be read out to handle problems such as a device that is not working properly, or a special format for a particular scientific observing programme. This task covers the construction of this box which is already well advanced. Help has been contracted from Hugh Gibson (MRAO).

6.2.23 Test multiplexor box

2d 20/08/96 21/08/96 23 mgb
Testing of the box to be carried out after its construction.

6.2.24 Manufacture test dewar internals

10d 22/05/96 04/06/96 1 workshop

The internals of the test dewar are designed and were passed to the Engineering Dept workshops for manufacture in mid-May. They are expected by the end of May.

6.2.25 Assemble test dewar

2d 06/06/96 07/06/96 25 mgb

Once the parts are received, the test dewar has to be assembled by mgb and jp (see next task).

6.2.26 Assemble test dewar

3d 10/06/96 12/06/96 26 jp

See previous task.

6.2.27 Install IR detector model, thermal tests

5d 24/06/96 28/06/96 17,27 mgb

Once the test dewar is complete, the bare (non-IR sensitive) device is to be installed into the dewar so that electrical and thermal tests may be carried out. There are concerns as to how close to 77K we will be able to get since we know that this is important for faint signal work where the background must be low.

6.2.28 Multiplexor Electrical tests

10d 22/08/96 04/09/96 24,28,40 mgb

The bare electrical sample must be operated to demonstrate that all is well and that the engineering grade device may be safely installed. The bare device is in fact sensitive to visible light and so some imaging tests may be done. However, the properties of the device (impedances, noise levels etc.>) are greatly affected by the absence of the IR sensitive layer that only limited tests may be carried out at this stage.

6.2.29 Install engineering grade detector and test

10d 12/09/96 25/09/96 29,41 mgb

Next the full IR sensitive engineering grade HAWAII device (already received) is to be installed in the test dewar for the first full tests. This is the point at which we will have a working IR imaging system for the first time. This and the full system test that follow (see next task) will be one of the major milestones since this is when we are to do more new things and learn from our mistakes more than at any other time in the programme.

6.2.30 Full system tests

15d 10/10/96 30/10/96 30,42 mgb

This is a continuation of the previous task that involves the software systems as well as the IR detector specific components of the system.

6.2.31 Software for controller (AstroCam 4100)

102d 21/05/96 09/10/96

This section covers the development of the various components of the software needed for the whole system. There are a number of separate components all of which must all work together. They include:

1. The SAM code, hardware microcode that is held in electrically programmable sequencer integrated circuit (an Altera SAM chip). This generate the individual clock and signal processing waveforms for the HAWAII device. SAM software has never been written for an X-Y addressable CMOS device before.

2. The controller contains an INMOS Transputer IC for system control and a variety of useful housekeeping purposes. We intend not to modify this code in any way, but we will need to get a good understanding of what it does.

3. The controller is connected to the IBM/PC compatible computer by an interface that is supplied by AstroCam Ltd. They have loaned one of their existing frame grabber boards which will let us do a great deal of the development work. They are at present working on a PCI interface board that will have a lot of advantages including simplicity, speed and cost over the existing frame grabbers. This PCI interface is being purchased from a small company in Tucson, Arizona. The first version of the board has been tried successfully. The next version is expected at AstroCam in 3-4 weeks, and this board is expected to be essentially complete. AstroCam will then complete the device driver work to integrate it closely with the controller and make it compatible with the existing higher level software that controls the system. This higher level product is called the 41 User Interface (or 41UI).

4. The 41UI is essentially a C-callable subroutine library, also available in DLL form for Windows 3.11/95 use. It has no graphical user interface of its own. AstroCam have a variety of options that

provide comprehensive imaging support and will provide suitable environments for developing the system in the laboratory. Different software will be required for use at the telescope, and the way it is interfaced to the 41UI, the developmental Windows based package and to IRAF is still being discussed.

6.2.32 Software functional specification

2d 21/05/96 22/05/96 mgb,cdm

This task has already had a considerable amount of time spent on it. A detailed functional specification of each of the components (1-4) above is needed to guide the work and its prioritising.

6.2.33 Review SAM/Transputer/41UI code

2d 23/05/96 24/05/96 33 mgb

The existing code that we have from AstroCam for the SAM and the Transputer code and the 41UI code is an extremely valuable resource that will be an important guide to how we should structure our own work.

6.2.34 Conceptual design of camera software

3d 03/06/96 05/06/96 34 mgb

Again this is part of the planning of the facilities that we need to be able to develop the camera system efficiently in the laboratory.

6.2.35 Tests with 4100 standard system

5d 27/05/96 31/05/96 33 mgb

The 4100 camera system is a complete, working CCD system (or at least we have been able to borrow the bits that we need to let us use our controller, etc. with a CCD camera and frame grabber). This will allow us to operate it properly and get insight into what it does and how it does it. It will also allow us to try out some of the basic ideas that we have on a working system.

6.2.36 Design SAM code

10d 10/06/96 21/06/96 35,36 mgb

The SAM code needed to allow us to drive the HAWAII devices needs to be written and tested (see next task).

6.2.37 Test SAM code

10d 08/07/96 19/07/96 37 mgb
See previous task.

6.2.38 Modify 41UI code

8d 26/07/96 06/08/96 38 mgb
The 41UI code expects the system to behave as a CCD whereas the device we have is an X-Y addressable multiplexor format. Despite these differences it will be helpful if the 41 UI is modified so that the top level system requests sub-array read-out (or full array) of different devices, and the 41UI returns them in a way entirely compatible with what happens for CCDs. This ensures that we may use the great variety of programmes and other software packages that are available from AstroCam which they have already interfaced to.

6.2.39 Test 41UI code changes

5d 07/08/96 13/08/96 39 mgb
The 41UI changes need testing fully.

6.2.40 Integrate in display/diagnostic package

5d 05/09/96 11/09/96 40 mgb
The modified 41UI needs integrating and testing with the selected front end programme.

6.2.41 Full code tests

10d 26/09/96 09/10/96 41 mgb
This stage covers a full test of the entire integrated software system as a whole.

6.2.42 CRITICAL DESIGN REVIEW

1d 10/07/96 10/07/96 8,10,35 ALL
The date scheduled for this is not critical. Rather it is the first significant milestone in the Project.

6.2.43 Main System Construction

240d 01/07/96 30/05/97

The above work has been dedicated to developing a complete single-device imaging system that is fully working with all the facilities to operate the device in any or all of the modes deemed important for our scientific programme. The performance of the test system should be in no way inferior to that expected from the main system which is the custom dewar containing four HAWAII devices. The Main System Construction relates to the full four-device dewar, the devices in it, the A&G sub-system and all the ancillary equipment, software and hardware.

6.2.44 Conceptual design of system

5d 01/07/96 05/07/96 28 mgb,cdm,rgm

This covers an outline plan of what the main system should comprise.

6.2.45 Design of dewar

2d 22/07/96 23/07/96 15,45 mgb

This task is to provide an outline plan for the dewar design to reflect some of the experience with the thermal tests of the test dewar. The design and manufacture of this unit will be carried out by Oxford Instruments, following the work they did in providing the dewar for the WHT prime focus CCD array instrument that is due to be commissioned in the near future.

6.2.46 Design of dewar

20d 24/07/96 20/08/96 46 jr

See previous task details.

6.2.47 Manufacture of dewar

90d 21/08/96 24/12/96 47 Oxford Inst

The manufacture may by done at Oxford Instruments or may be done by the Engineering Dept workshops, overseen by John Rogers.

6.2.48 Design of filter wheel, shielding, etc.

2d 24/07/96 25/07/96 46 mgb

The filter wheel is complicated because it is large and must be kept really cold to minimise thermal background. It has to be kept cold over its entire diameter so that filter changes do not need to be followed by a delay while the filters cool to their operational temperature. In addition, the design of the pick-off mirror required to feed the A&G system is included here. The A&G detector system itself will be optically coupled with a simple relay lens to the focus of the telescope, allowing the A&G detector to be located outside the main dewar.

6.2.49 Design of filter wheel, shielding, etc.

8d 29/07/96 07/08/96 49 jp

This covers the mechanical detailing by Jim Pritchard.

6.2.50 Design of detector mounts

2d 14/08/96 15/08/96 50 mgb

The detectors need to be kept as close to 77K as possible. We already have a suitable PCB design for mounting the HAWAII devices in a close-packed array. This task includes all the associated mounting hardware inside the dewar to allow the devices to be mounted and cooled while providing reasonably easy access.

6.2.51 Design of detector mounts

8d 16/08/96 27/08/96 51 jp

This covers the mechanical detailing by Jim Pritchard.

6.2.52 Manufacture of dewar internals

30d 28/08/96 08/10/96 52 workshop

The dewar internals will be manufactured by the Engineering Department workshops.

6.2.53 Assembly of dewar internals

2d 26/12/96 27/12/96 31,42,48,53 mgb

Some of this assembly will be done by mgb, some by jp (see next task).

6.2.54 Assembly of dewar internals

3d 30/12/96 01/01/97 54 jp

See previous task.

6.2.55 Testing with multiplexor device

5d 27/01/97 31/01/97 55 mgb

The first steps towards getting the main system dewar operating the HAWAII devices is to check each of the four device locations with the non-IR sensitive device.

6.2.56 Design of A&G system (manual)

5d 28/04/97 02/05/97 14,46 mgb

The initial design of the A&G system is for it to be used open loop to control telescope pointing. If time allows, the software to process the A&G data and pass it over to the Telescope Control System for direct guiding will be implemented. However this is not on the first-pass baseline design.

6.2.57 Design of A&G system (manual)

10d 05/05/97 16/05/97 57 jp

This covers the mechanical detailing by Jim Pritchard.

6.2.58 Order A&G camera

0d 02/05/97 02/05/97 57,43,46 mgb

The A&G camera is presently planned to be an uncooled CCD camera using the Kodak KAF-1600 CCD (1536 x 1024 pixels of 9 µm each), installed in an UltraPix camera system from AstroCam Ltd.

6.2.59 Receive A&G camera

20d 05/05/97 30/05/97 59 astrocam

Assumes 1 month delivery.

6.2.60 Order A&G computer

0d 10/07/96 10/07/96 43 mgb

The A&G system uses its own dedicated computer system. This needs only to be a relatively low performance and specification system. However it is likely to be identical to the main computer so that it can provide a backup for the main system computer.

6.2.61 Receive A&G computer

10d 11/07/96 24/07/96 61 World of Comps
Delivery times only.

6.2.62 Install and test A&G system

5d 05/05/97 09/05/97 57 mgb
The A&G camera is mounted on a pick-off port outside the main system dewar.

6.2.63 Test main dewar with engineering grade device

10d 03/02/97 14/02/97 17,42,56 mgb
The next step towards getting the main system dewar operating the HAWAII devices is to check each of the four device locations with the IR sensitive engineering grade device.

6.2.64 Install and test device #1

5d 17/02/97 21/02/97 18,64 mgb
Installation of device #1 in the main system dewar and testing it fully.

6.2.65 Install and test device #2

5d 24/02/97 28/02/97 19,65 mgb
Installation of device #2 in the main system dewar and testing it fully.

6.2.66 Install and test device #3

5d 03/03/97 07/03/97 20,66 mgb
Installation of device #3 in the main system dewar and testing it fully.

6.2.67 Install and test device #4

5d 10/03/97 14/03/97 21,67 mgb
Installation of device #4 in the main system dewar and testing it fully.

6.2.68 Full system tests

30d 17/03/97 25/04/97 68 mgb

This task covers a comprehensive test programme for the now complete main system, including all software and hardware systems.

6.2.69 Telescope #1 Interface hardware

243d 26/06/96 30/05/97

The telescope interface has to be completed so that the first observing run can proceed with the minimum fuss.

6.2.70 Procure interface drawings

1d 26/06/96 26/06/96 3FS+20d rgm

Procurement from observatory including discussions on details of interfacing. May involve a trip to the site if there are concerns about the vintage of the drawings supplied.

6.2.71 Design mount hardware

3d 24/07/96 26/07/96 46,71 cdm,jp

Design in detail the system mounting hardware and any other interface requirements that need to be addressed at this stage.

6.2.72 Manufacture mount hardware

30d 29/07/96 06/09/96 72 workshop

The manufacturing may need to be done by the Engineering Dept workshops as some of these parts may be rather large.

6.2.73 Install on Main dewar

2d 19/05/97 20/05/97 73,48,63 jp

The main system and the mounting hardware for telescope #1 need to be checked in Cambridge before shipping to the telescope.

6.2.74 Test full system

5d 26/05/97 30/05/97 69,74 mgb

Final sanity test of complete system before shipping to the telescope.

6.2.75 Software for Data Taking/Observing

147d 31/10/96 23/05/97

The requirements for software that the observers want/would like to have available at the telescope need to be addressed. We already have had a lot of ideas about this and the requirements are for full operability from IRAF. They also require that the data may be substantially reduced in real time so that data may be taken from the telescope with all instrumental artefacts removed so that astronomical analysis may proceed without any further calibration or processing. Some of this work will involve mgb, but it is hoped that much of the work will be done by astronomers who hope to use and benefit from the use of the system.

6.2.76 Specification of data taking software

5d 31/10/96 06/11/96 8,15,45 rgm,cdm,mgb

A full specification of what is desired with assigned priorities must be produced.

6.2.77 Design of software for observing

5d 07/11/96 13/11/96 77 mgb,cdm

A detailed design of what is needed is covered here.

6.2.78 Writing of observing software

30d 14/11/96 25/12/96 78 mgb

This is a major piece of work (six man weeks). We have assumed that mgb will do this but it will be much better if astronomers are involved in the lions share of this work.

6.2.79 Testing of observing software

20d 30/12/96 24/01/97 79 mgb

Testing of the product of the above task. The same considerations apply in not having mgb carry out this work.

6.2.80 Documentation of observing software

10d 12/05/97 23/05/97 80 mgb

As for 79 and 80. Good on-line documentation is essential if the system is to be useable by people other that the inventors of the software and camera systems.

6.2.81 Corrector Design and Manufacture

140d 10/07/96 21/01/97

The use of CIRSI on the INT will be with the current corrector at prime focus. On any other telescope it is almost certain that a corrector and/or focal reducer will be required to give the optimal scale for the instrument. This section covers the construction of this unit.

6.2.82 Corrector design study

15d 10/07/96 30/07/96 8 irp,fp

This has been started by irp/fp, and by Roderick Willstrop on the assumption that the MMT is the target telescope #2.

6.2.83 Full corrector design

15d 31/07/96 20/08/96 46,83 fp

The design will be carried out on Zemax.

6.2.84 Manufacturing of corrector

90d 21/08/96 24/12/96 84 optics

6.2.85 Assembly of corrector

10d 25/12/96 07/01/97 85 irp,fp

6.2.86 Testing of corrector

10d 08/01/97 21/01/97 86 irp,fp

6.2.87 Telescope #2 Interface hardware

240d 10/07/96 10/06/97

This section is simply a duplicate of the section 70, and tasks numbers 89-93 follow 71-75 precisely.

6.2.88 Procure interface drawings

1d 10/07/96 10/07/96 8,3FS+20d rgm

6.2.89 Design mount hardware

3d 28/08/96 30/08/96 84,89 cdm,jp

6.2.90 Manufacture mount hardware

30d 02/09/96 11/10/96 90 workshop

6.2.91 Install on Main dewar

2d 02/06/97 03/06/97 69,75,91 jp

6.2.92 Test full system

5d 04/06/97 10/06/97 92 jp

7. Costings

The project costings have not changed greatly since the start of the project approximately three months ago. This is because the costs are dominated by the array costs (which could be affected by a change in the £/US$ exchange rate), and manpower. The ancillary equipment costs are generally coming a little under budget, and nothing has happened yet to suggest that unexpected additional expenditure will arise.

7.1 Detailed Estimates

The detailed budgets that we are using are given in the attached spreadsheet. We are approximately on budget (actually slightly under by about 2.5 percent), but this is well into the noise at this fairly early stage of the project.

7.1.1 Hardware Purchases

These have been dominated by the Rockwell array stage payments. One payment (for the start-up, multiplexor and engineering grade device) has already been made. It has been possible to import them under the Inward Processing Relief scheme. This requires the dutiable devices to be exported from the UK eventually.

Other hardware purchases have included the AstroCam 4100 controller, SAM development hardware, system computer, and a liquid nitrogen storage vessel. One area where there are still considerable uncertainties is in the area of the Cassegrain corrector for the (as yet unspecified) second telescope. The constraints of whatever telescope we eventually select could be significant.

7.1.2 Manpower

We have not yet appointed the technician, although this is now being negotiated with the University. Otherwise the predicted costs are being achieved here.

7.1.3 Consumables, Miscellaneous

No unexpected surprises here, although there is a concern that the travel allowances may not be enough to mount more than the commissioning trips.

7.2 Cost to Completion

The project is on schedule and within budget to the level of accuracy that we should expect at this stage of the project.

7.3 Contingency

The budgets shown above do not include any significant contingency allowance. The total of funds that are available to the Institute of Astronomy include a large contingency that may be used for other things as well. It is worth noting that the major cost items are unlikely to be overspent (Manpower, fixed by University regulation and the contracts already awarded), and the Rockwell arrays (for which we have a fixed price contract already agreed). Once these two items are excluded (£360K out of a total of £422K4), even a fairly large miscalculation (of which there is no evidence yet), will give a relatively modest change in the cost to completion. The biggest potential source of overspend is in the manpower budget. This runs at a total of about £25K per annum so the main cost risks are with a schedule over-run (i.e. the project runs late). At present we are still on the original schedule created in February, 1996.

8. Risk Assessment

The risks to the project may be considered to be external (due to events outside our control) and internal (due to our error or inability to achieve the scheduled plan). In detail these are:

8.1 The Arrays are Late

The Arrays are the most technically sophisticated part of this project. Rockwell have so far made very few of them. They are in the middle of a major expansion of their IR array manufacturing facility, and this can cause problems when they find that they cannot get the quality (usually in terms of yield) that is needed.

The specification of the devices we have ordered is below that of their top grade devices, since that is all we could afford. If there is a small drop in quality we are likely to get ours before other customers. A more likely scenario is that they are simply late in effecting their delivery.

We have constructed a project schedule that allows the devices to be very late. Virtually all of the testing and system development work can be done with the engineering grade device that we have already received, and which looks to be an excellent device in all respects except that it is cosmetically poorer that their best (it does in fact meet our specification for the science grade devices already). The development can be continued using the engineering grade device and the multiplexor (dummy device) until a later date. We would start to be significantly impacted if the science grade devices did not come through by mid-April 1997 for the first one, and late May, 1997 for the last one. This would correspond to a delay from their quoted deliveries of an additional six months. It would entail essentially completing all the development, and plugging the devices in and expecting them to run with relatively little development effort afterwards.

8.2 The Arrays prove to be Hard to Get Working

Not at all impossible. The contingency here is that the schedule has Martin Beckett responsible for all the software that is needed for data taking including the IRAF related software. He is scheduled to take 10 weeks on these work packages (see sections to of this CDR document). In practice it is expected that about two weeks of his time will be needed, but we hope to be able to call on the extensive software expertise in these areas that exists within the Institute to carry this out (Richard McMahon and collaborators, such as all the post-docs and students that hope to use CIRSI). This gives an additional 8 working weeks of schedule contingency.

8.3 The Cryogenic Aspects of the Project may be more than we Expected

Quite possible. We are however, using the extensive experience of the Mullard Radio Astronomy Group (and John Rogers in particular) to help us with the design work. We will also use Oxford Instruments to carry out the work of building the dewar, so we believe we are well covered here.

8.4 Too much work for our workshops

We are already contracting out a lot of instrumental development work associated with this and other projects, particularly to the Engineering department's excellent workshops, and we will continue with this.

8.5 Critical Staff Illness

This is still a small department instrumentally. We are at risk from single point people failures, and there is probably little we can do about this. We are trying to ensure that no knowledge is solely held by a single individual as far as is possible, but there is no doubt that we are risk in this area.

8.6 Completion Targets

The project schedule shows the work being completed in the third quarter of 1997. The project has now run for three months out of the 17 scheduled, and we are still targeting the same completion date and cost to completion that we started with. As a result of the considerable progress that has been made in these three months we are more confident that we will be able to keep to the costs and time-scales that we originally estimated.