Chapter 2
UKIRT – The Project and the Early Years

Terry Lee

Abstract This is a personal overview of the early years of UKIRT, from its inception to the first observing years, showing how many of the decisions taken have turned out to be crucial in giving UKIRT such a high scientific profile. The theme of a common-user facility in terms of the user-experience was novel for the time but set the scene for the next generation of 8 m telescopes many years later. I also pay tribute to the many people who have made UKIRT such a tremendous success.

Introduction

Thirty five years ago I was on a bus in Geneva. I heard a strong baritone voice a few rows behind say "So the UK is going to build an infrared telescope on MK. No one in the UK has done much IR except Aitken and Jones". Well Eric Becklin, who was to become a dear friend, was right, especially if you exclude those Brits who had spent time at Caltech such as Mike Penston – who he was addressing at the time. Nonetheless, many of us had recognized the potential of that part of the electromagnetic spectrum. Indeed, the proposal for a major UK IR facility was first made in 1968. At that time astronomers in the USA were reporting observations using lead sulphide (PbS) detectors (e.g.: stellar photometry by Harold Johnson, a 2 μm sky survey by Leighton and Neugebauer), while for work at longer wavelengths Frank Low was using the gallium doped-germanium bolometer, his invention (sadly, Frank died this summer).

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Jim Ring, Professor at ICST, was interested both in infrared astronomy and telescope design. In particular, he wanted to explore the limits of passive designs for seeing-limited telescopes as the primary diameter increases. [At that time one arcsec was assumed to be the seeing-limit from the ground.] He also sought to challenge the cost-diameter relation for their construction: the cost of building a telescope of traditional design increased as the third power of the primary diameter or faster. By replacing the primary mirror of 6–1 diameter-to-thickness ratio with a thinner one supported by a sufficient number of air-filled pads, the mass of mirror plus cell would be significantly reduced. In turn, the mass of steel and concrete needed to support the optics would be less. Constructing a telescope with this type of design would not pose a risk to observations that do not need seeing-limited images. At the time the argument was that because the internal noise in the PbS detectors was greater than the thermal noise from the sky and telescope for apertures of several arcsec, photometric measurements did not require good image quality.

As a first step the Science and Research Council (SRC) funded a 1.5 m precursor, ‘the IR flux collector’ that was installed at Izañia on the Island of Tenerife in 1972. This instrument was mainly used by UK and Spanish astronomers, many of us learning how to set up instruments and observe in the infrared for the first time. Researchers who had gained experience in the USA were also able to use it to continue their work. It also indicated that the design concepts for a thin-mirror telescope were sound.

In 1973 Jim Ring and Gordon Carpenter, the senior engineer at ROE, made a proposal for a fully functional, major IR flux collector; either a 3.8 m instrument to be sited alongside the 1.5 m at Izañia or a 3 m instrument on Mauna Kea, a much higher and drier site in Hawaii. In the event the Astronomy Committee led by its chairman, Professor Walter Stibbs, forwarded a proposal for the 3.8 m version on Mauna Kea! This was approved in June 1974. Gordon Carpenter was appointed as Project Manager and the ‘3.8 m Flux Collector Steering Committee was formed, drawing members from the active infrared groups in the UK. The first task was to study the draft specification and recommend changes, especially in the light of recent developments.

There are significant differences between the design of telescopes used for infrared observations and optical telescopes, the break-point being around 2 μm, longward of which thermal emission from the sky and the telescope dominates the background radiation. For photographic work in the optical stray-light baffles were generally placed around the primary and secondary mirrors and inside the central hole of the primary. Effectively these have a thermal emissivity close to unity. However, for the infrared, any structure in the light path must be minimised. Furthermore, sky emission and gradients must be subtracted from the object and for the single detector instruments of the time, chopping and nodding techniques were used. The subtraction of gradients is more accurate the closer in time that the measurements in the two beams are made. In addition, nodding placed requirements on the dynamic performance of telescope.

Key Elements of the Design

- Lightweight primary supported by 80 pneumatic pistons
- Fast primary ($f/2.5$) to keep tube short
- Clean structure thermally
- Light structure, no central box thermal and cost considerations
- Large diameter gears quick movement
- Position control loop closed in computer
- No control system independent of computer
- Keyboard input supplemented by a few buttons

Specification:

- Primary diameter 3.8 m
- $f/9$ Cassegrain, $f/20$ coudé
- Primary image quality 98 % EED 2.4″
- Short nod time (2s)
- Tracking (5 arcsec per hour)
- Pointing 30 arcsec circle rms
- Dome building to be as small as possible (to contain costs and maximize slit to volume ratio to work against dome seeing)

The principal amendments to the spec as recommended by the steering committee were the following: (1) increase the maximum payload on the instrument rotator from 100 to 200 kg. [At that time a complete photometer might weigh 25 kg and the possibility of mounting multiple instruments and indeed some increase in size was anticipated (though the like of CGS4 was clearly not)]; (ii) a modest increase in the dome size would enable a chopping secondary to be accommodated; (3) the possibility of including an option for improving image quality to 90 % in 1 arcsec should be explored.

The proposed optical and mechanical design was based on such primary mirror blanks as were immediately available – Owens-Illinois Cer-Vit. Where practicable British suppliers and contractors were chosen for building and telescope, and Grubb-Parsons of Newcastle on Tyne for grinding and polishing the optics (having recently done a fine job with the AAT mirrors). The contract contained a provision for continuing to figure the primary mirror beyond the initial specification if testing and evaluation at that stage indicated that it was possible to do so and a price could be agreed. Hadfields of Sheffield was the contractor for the telescope structure and drives. The telescope columns carrying the north and south bearings are tied together, their bases rest on concrete piers via steel thrust-races which allow movement between the piers and telescope structure. Normally horizontal movement is constrained by pins between the steel bases and the piers; these shear to protect the instrument during significant earthquakes. The estimate for the mirror mass was 7 tons as opposed to 15 for a conventional one and the rotating mass was estimated to be 60 tons as opposed to about 250 tons.

A novel feature of the project was to give the tasks of slewing and tracking to a digital computer rather than a set of hard-wired electronics. The user interface was a keyboard and text display, while the RA and Dec axis encoders and sidereal and UT clocks were interfaced via CAMAC, the standard interface for high energy physics at the time. A DEC PDP11 was chosen as the real-time computer running RT11 in 28K words of 16 bit memory. By today's standards this seems very pedestrian, but remember Moore's Law: 30 years worth is a factor of more than a million! Design and programming of the real-time software was done at ICST. A computer was needed to calculate corrections due to atmospheric refraction and uncompensated mechanical movement. Giving it the additional task of closing the position loop saved on the cost of building the digital and analogue circuits and panels. In practice it provided the bonus of an easy upgrade path both to interface and control aspects.

Early Project Developments

The project as originally funded was for the telescope alone, which fell short of what was required for observational astronomy. Clearly there were a number of ways in which the efficiency and effectiveness of the facility could be assured.

1. The addition of a chopping secondary, which experience in the U.S. showed can yield a given photometric observation in a much shorter time than with a focal plane chopper.
2. A detector test and development programme. High purity InSb detectors had become available that were much more sensitive than earlier versions and the standard PbS device of the time. Indeed, developments led to detector noise becoming smaller and smaller through the late 1970s and it had become vital to understand how to get the best out of detectors and to match the optical and cryogenic performances of instruments to suit their needs.
3. The provision of common-user instruments to allow and indeed encourage investigators without infrared equipment or experience to make infrared observations.
4. The setting up of a computer system to control instruments and to log and reduce data in real-time. This enables the astronomer to assess the content and quality of data and to modify the programme accordingly; it also lessens fatigue and the tendency to make mistakes at altitude.
5. The use of intensified TV acquisition and guiding facilities to make target identification easier, to reduce the total duration of an observation (and hence increase efficiency), and to take the guide telescope out of the astrometric loop.
6. The construction of a central Telescope Simulation Facility where investigators can bring their instruments to ensure compatibility with the telescope and test elements of performance (Fig. 2.1).

The content of a possible development programme was discussed at a number of meetings of the Steering Committee leading to a formal proposal by the Royal

Fig. 2.1 Picture of simulation rigs – forerunners of two more generations now at ROE

Observatory Edinburgh to the Science Research Council. During this time I visited several of the labs in the US and the groups in the UK interested in active involvement. In the summer of 1976 a working group met to define details of the first phase of common-user instruments.

The Common-User Instrumentation Plan

- Focal plane choppers for *f*/9 (1 ROE 1 ICST).
- Photometers for *f*/9 Cassegrain: two cryostats using InSb detectors with bandpass filters and CVFs covering 1–5.6 μm.
- Photometers for *f*/35 Cass: two cryostats with bandpass filters and CVFs covering 1–5.6 μm
- Cryostat with bolometer detector and filters covering 3.8–40 μm
- Cryostat with bolometer or doped Si detector with bandpass filters covering 8–40 μm, and a CVF from 8 to 14 μm
- Polarimeter insert (in collaboration with Hatfield Polytechnic)
- Fast photometer
- Visible photometer (UBVRI)
- Cooled grating spectrometer

One of the crucial decisions to be made was the configuration of the instruments at the Cassegrain focus. Infrared detectors must be cooled to their optimum working

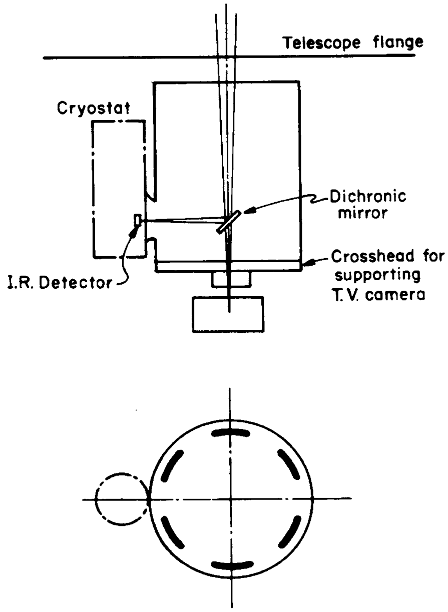

Fig. 2.2 The side-looking configuration

temperatures, which is 77K or lower for near-IR and 4K or lower for longer wavelengths. Cryogenic engineering constraints meant that normal practice was to build the cryostat so that the work surface is the bottom face of a cryogen tank. This configuration is optimal for cryogenic performance and also works well for mounting the detector and optical components with the light beam entering radially, i.e. a bent Cassegrain configuration requiring a tertiary mirror outside the cryostat. This warm mirror is not best suited for thermal infrared work. Some US astronomers were using upward-looking cryostats that were optically efficient (doing away with the reflecting mirror). However, these were more complicated to build, had relatively short hold-times and needed to be demounted from the telescope to fill. The side - looking configuration had the particular advantage that if the tertiary mirror is also a dichroic, the visible light passing through it can be used for acquisition and guiding. This was an important consideration for a new telescope of new design where acquisition, tracking and offsetting properties were not predictable. Furthermore, if this tertiary is mounted on a hollow bearing concentric with the telescope axis then several instruments can be mounted on the telescope at any one time providing backup in the case of problems, or choice. Longer hold-times allow refill operations to become a routine daytime task. So the choice was made. We bought six cryostats from Oxford instruments to a jointly developed design. These featured a long hold-time, flats on the outer casing for mounting motors and windows along with fittings for pumping on the inner vessel (see Fig. 2.2).

InSb detectors were sourced from SBRC or Cincinnati Electronics in the USA. Interference filters were purchased from OCLI Europe in Scotland. We specified

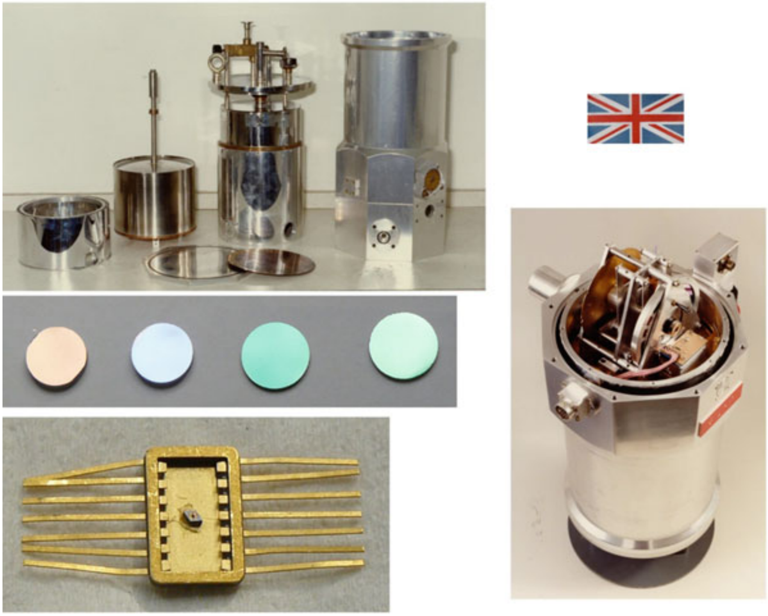

Fig. 2.3 Photometer cryostat with components

filters to match the atmospheric windows (rather than hunting for closest available from surplus catalogs). To limit cost to the project we ordered 50 sets and sold about half to IR groups around the world (Fig. 2.3).

Telescope Realisation

The first landmark in the manufacture of the telescope occurred when David Brown of Grubb Parsons informed us that the specification for the primary figure had been achieved. Furthermore, we were told that it could be improved to a quality of 95 % encircled energy in 1 arcsec for a payment of £20,000. When the proposal was put to the steering committee the decision to accept was made in record time. This subsequently turned out to be a first-class value-for-money decision in the scientific productivity of UKIRT.

The structure and optics were shipped to Hawaii at the end of 1977, and the telescope was assembled in the dome, which had been completed on Mauna Kea early in 1978. Interestingly it was as part of the shipping process that the '3.8 m Flux Collector' became known as UKIRT, analogous to the recently arrived IRTF and CFHT. This gave us an obvious identity and a place on the map locally in Hawaii.

Fig. 2.4 A model demonstrating the design of the telescope was part of the British Genius Exhibition of 1977 in Battersea Park in celebration of the Queen's Silver Jubilee

In 1977 as the project was well underway, two contrasting events happened in close unison: Her Majesty the Queen visited the Silver Jubilee exhibition on May 27th (see Fig. 2.4) and tragically, Gordon Carpenter died on June 1. I was in Sheffield at Hadfields at the time. Following Gordon's death, management of the project was taken on by Colin Humphries. Colin was already part of the project as manager of the optics.

First Light

First light was obtained at 03:23 am on July 31st 1977. Alpha Peg images appeared circular and about 2 arcsec in size. Testing various aspects of the telescope in its $f/9$ configuration continued through 1978. The optical image quality was investigated using a Hartman screen and plate photography, knife-edge tests and examination of out-of-focus images. Two effects were shown to deteriorate the basic image quality much of the time: dome seeing due to warm air in the building, and oscillation in RA (of up to 5 arcsec) due to the nature of the position encoder.

The good news was that the mirrors and supports behaved within specification. Later, in early 1979, when there was a TV camera mounted and differential air temperatures were low, from time to time images appeared to be smaller than 1 arcsec in diameter. Jim Ring's telescope concept was demonstrated. A telescope with excellent image quality had been built for a modest cost.

Other results from these shakedown tests were:

- Pointing within spec (30 arcsec rms).
- Tracking was strictly within spec but the oscillation was not acceptable for observing.
- Nod performance was poor, typically about 5 s for small nods.
- Guide telescope flexed too much with respect to the main structure.
- Crosshead for the autoguider had drives errors.
- Dome drive was marginal even in moderate wind.
- *Dome crane was not safe to lift top end.*

This last was to cause a major delay as strengthening work had to be carried out through the summer of 1979. After strengthening of the dome the dome drive continued to be unsatisfactory and it was some years after the replacement of the track, bogies and drive that reliable automatic dome following of the telescope was achieved.

By the end of 1978, the main testing was completed; mounting of the $f/35$ was rescheduled until after dome work completion. Hadfields were to return to do this and try to improve dynamic performance of the telescope. The telescope became available to the operations team to install wiring and piping through the structure to the Cassegrain area to enable the instruments to be installed. The tasks were then to improve pointing and tracking and to commission the infrared photometers.

Early in January 1979 Dave Beattie prepared and I mounted UKT1 on the telescope. At dinner Eric Becklin said "I hear you guys are going to get first IR, can I come and watch?". We agreed. At the telescope the conversation went something like this:

Eric: "What size aperture do you have"
Dave: "5 arcsec",
Eric: "Do you have a bigger one"
Dave: "Yes"
Eric "Are you going to use it?"
Lee and Beattie in unison: "No"

Back in the control room we set the telescope on the target, centred it on the TV and immediately we had signal. Even Eric was a little impressed. PATT-allocated operation started with the last quarter of 1979. The ICST group took the first slot (Fig. 2.5).

Fig. 2.5 Terry Lee with the first photometer on UKIRT

Dedication

On the 10th October 1979 the Duke of Gloucester opened the facility, now officially called UKIRT, with a ceremony in the dome. Among the dignitaries were Vince Reddish (director ROE), Geoff Allen, (Chairman of SRC), other telescope directors, Harry Atkinson (SRC director of science), University of Hawaii Chancellor, those involved in constructing the facility and many others. Sadly, not Jim Ring who, perhaps wisely, had a fear of flying (Fig. 2.6).

This was followed by an evening dinner in Hilo. Round about 3 am myself, Gareth Wynn-Williams and others finally persuaded a relaxed Harry Atkinson to divulge who was to succeed Vincent Reddish as Director ROE. The answer was of course Malcolm Longair. For me this was an unknown quantity and the changeover was nearly a year away. I had my own Observatory to run and a year's worth of users to serve. Since it was a low-cost telescope we were expected by certain quarters to operate it in proportion cost – but users would expect good service!

It's worth recalling that in those days, long distance communication was a completely different picture from today. There was no internet; written communication was by letter or TELEX (110 b/s). It was not possible to direct dial an international phone call from Hawaii. Summit phones were via a low capacity microwave link able to support voice only. These realities, combined with the time difference between Hawaii and the UK, meant that volume and frequency of communication were not great. We worked rather independently. We were only a dozen or so from the UK at the time and added staff recruited locally.

Fig. 2.6 Vincent Reddish (Astronomer royal for Scotland) and Duke of Gloucester. *Top*: Geoff Allen (Chairman SERC), Min Lee, Des Hickinson (of Hadfields). *Bottom*: Colin Humphries, Terry Lee, Duke of Gloucester

How We Observed

Before we could take on scheduled observing there were issues that had to be addressed. There was no secondary chopper yet, therefore the only choice was to work at *f*/9. For acquisition, no intensified TV camera was yet available, and the combination of the lower sensitivity of the silicon target camera and the restricted field-of-view of the *f*/9 photometer was inadequate for finding guide stars. Guide telescope issues meant that pursuing its use was not fruitful.

The solution was to convert the *f*/35 gold dustbin to *f*/9 use by mounting a focal plane chopper on the end of an arm fixed in one of the six ports. The TV was mounted on the X-Y stage at *f*/9. This gave an offset field of + or-13 arcmin which was very useable. However image motion while tracking was still up to 5 arcsec due to the fine code error of the encoder. This was too big for most projects. I remembered that I had lent a constant voltage source to the telescope project team for factory tests of the telescope drives. It was therefore possible to inject small signals to the RA and Dec amplifiers to drive the telescope in fine motions. After acquisition the computer controlled tracking could be switched off and the analog box switched into the circuit. Inside the analog box was essentially a battery with a few resistors, a couple of potentiometers and a connector for an Atari joystick.

Fig. 2.7 David Beattie at the original UKIRT controls with the PDP11

The size of the observing team would depend on the scientific programme but might need:

- One person to operate telescope and guider
- One to operate instrument
- One to review data and check the dome position
- One to compute guide star and guider offsets
- At times one quality control, backup, make coffee.

Over time and with very skilful software engineering of the limited computing capacity more functions were put into the computer. Later, an autoguider was fashioned by fixing a quadrant photodiode to the TV monitor and feeding signals into an analog box. The *f*/35 secondary and InSb photometer cryostats (designed by John Harris) arrived in 1980 (Figs. 2.7 and 2.8).

The Longair Effect

Malcolm Longair arrived on the scene in Hawaii even before he was in post. It became clear that we would be seeing him in Hawaii both as Director and telescope user; and in time that he expected us to become a world beating facility. The deal would be that we had to get the results and he would find the resources. Failure was not on the agenda – action was. He moved to regenerate and re-energize our connection to Edinburgh, directly to himself as Director and to the instrument work there. As a first action item the next instrument to be built would be CGS1: a 1–5 μm spectrometer with Richard Wade as project scientist. Tim Hawarden was appointed

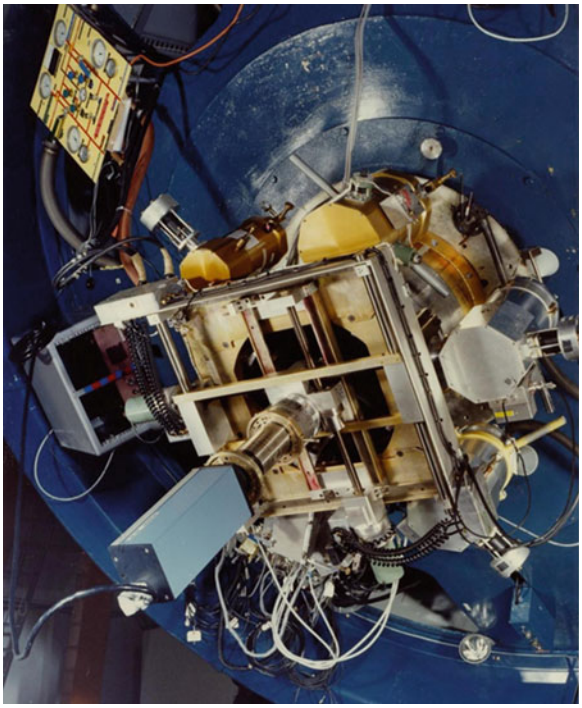

Fig. 2.8 The f/35 instrument cluster

as scientific liaison generally and to the UKIRT user committee in particular. A decade later Tim thought out and carried through an upgrades programme to yield images of superb quality (see contribution by T Hawarden).

Users

The Agreement with the UH allowed them 15 % of telescope time as site rent. The rest was allocated by PATT including Dutch time of about 5 %, part of the agreement on IRAS. Users fell into broad categories. There were those who brought their own instruments, experienced observers who used common-user instruments and observers new to the infrared. In the very early years we did not have telescope operators since user interfaces and instrument systems were not stable enough. So the staff astronomer allocated to each observing team acted as telescope operator and where appropriate instrument operator and sometimes tutor. Prominent among those who brought their own instruments were far infrared observers and heterodyne spectroscopists. Most of the groups in existence worldwide using these techniques came to take advantage of the large aperture of UKIRT and the atmosphere of Mauna Kea. Observers new to the IR came from the UK, Netherlands and Japan. Experienced observers came from UK, Hawaii, US, Japan and Australia.

Examples of Observing Programmes

In general, observing programmes were designed to benefit from the greater sensitivity of the large aperture and the drier, more transparent and more stable atmosphere of Mauna Kea. This enabled more effective mapping, faster time resolution photometry, and more secure polarimetry and spectroscopy. Early examples included:

- Mapping star-formation regions to search for embedded objects
- Photometry of Variable stars at 1-s intervals
- mm/submm photometry and line searches, maps of higher molecular transitions
- Diffraction limited mapping at 12, 20, 30 μm
- Spectroscopy of IR masers, planetary nebulae
- Galactic centre, mapping, spectroscopy
- Detection of Dust features in other galaxies

Extragalactic observations became a reality. At high redshifts the peak of starlight is redshifted into the 2.2 μm window. For example Simon Lilly and Malcolm Longair came for several heroic observing runs plugging away for hours at a time to get a K magnitude detection of high redshift galaxies. Infrared photometry was shown to be a major tool for cosmology.

Mauna Kea had had a mixed reputation as an observing site. The effects of altitude on people and the difficult logistics relative to US mainland sites were cited as impediments to good science. Observations from UKIRT, the IRTF and CFHT in their first years of operation quickly dispelled these myths. Each of these large telescopes demonstrated the unparalleled quality of the mountain. Data published from UKIRT observations began to establish the telescope as a force and the UK as a major player in infrared astronomy.

Evolution

Although UKIRT was a low budget telescope, the expectation of some users was a performance and service on a par with other large telescope facilities. This was quite a challenge.

In parallel with observing support there was a continual programme of improvements. Pointing accuracy increased to 4 arcsec rms. Nod-time was reduced by running control feedback through computer-enabled dynamic tuning. Other shortcomings were diagnosed and solutions found or components replaced (e.g. 24 bit encoders in place of the original 20 bit). For guiding, intensified cameras and their postprocessors were utilised.

The user interface was improved with the incorporation of online catalogues and routines for calculating and commanding guider offsets. Communications between instrument and the telescope computer were enhanced and a ‘list-processing’ system for standard observing sequences was introduced. Phone capacity at the summit greatly increased so we could network from the Hilo Base to the summit and also back to Edinburgh. This opened up the possibility of remote observing, which Malcolm Stewart first demonstrated. Later a remote observing room was set up in Edinburgh using a dedicated phone line. Subsequently this was extended within the UK via the networks. UKIRT set the stage for today's practices at large observatories.

Spectroscopy

CGS1 arrived in 1982, adding a new dimension to our capabilities. Even with just one detector it enabled significant observations to be made. It was soon put to good use in mapping shocked molecular hydrogen in the Galactic Centre region. Molecular hydrogen is what had brought me to astronomy. After the galactic centre work I was keen to see if I could make a detection in M17. My attempts in evening twilight around this time of year did not succeed though it was evident that something was there. We concluded that the hydrogen was so extended that we could not chop off it, so we came up with the idea of chopping in wavenumber space, which was implemented for the following year. Simply put, the solution was to mount a Fabry-Perot etalon in the beam feeding a photometric cryostat and measure the flux at selected spacings. Luckily there was a source of FPs that could be commanded by computer (Queensgate Instruments). We made an extensive map using an 18 arcsec beam.

Parallel Developments – Buildings

The minimum-sized dome turned out to be too minimal. An extension was added to house instrument preparation equipment and allow much of the computing and other noise and heat generating equipment to be moved from the control room (Fig. 2.9).

In the beginning we operated from a warehouse building near Hilo airport. This soon became cramped. At the time of negotiations for the mountain-top site and in the course of discussions on collaboration with CFHT, there was a gentleman's agreement at Head Office level that both would site their low level base in Waimea. We bought adjacent plots of land there in 1979. It became clear in the course of the first year or so that from many considerations, including the lives of most of the staff, remaining in Hilo was preferable. The University of Hawaii was keen to open a new section of the Hilo campus to accommodate astronomy facilities. In 1982 the decision was made to design and construct a permanent base for UKIRT there. Ground was broken in 1983. The facility was opened in 1985.

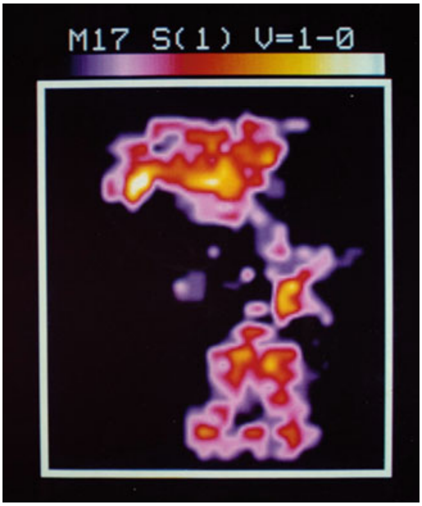

Fig. 2.9 Emission from rotation vibration transitions of shocked molecular hydrogen in M17

The huts at Hale Pohaku will remain long in the memories of older observers for days of interrupted sleep and limited privacy. We participated in the design details for the mid-level facilities which were completed later in the 1980s. With the mid-level facility came a power-line extending all the way to the summit to replace the diesel generators (Fig. 2.10).

Signs of Success

First early signs of success were that observing time was well oversubscribed, people wanted to come back. They published observations and made convincing cases. Later came independent signs external to the UK. The Japanese National Observatory had been impressed by UKIRT as an observatory that provided both telescope and instruments to the observing community. In Mitaka they sought in-depth advice on how to emulate us for a 6 m plus project. We also set up a collaboration between the two countries on UKIRT and the new Nobeyama mm telescope. After many years of selling single pixel detectors the Santa Barbara Research Corporation had come up with a plan to provide two-dimensional detectors for astronomy. As pilot project they chose UKIRT as one of their two IR array partners; the other was NOAO. It was indeed unusual for a US company to engage in this way with a foreign agency. Their assessment of our overall capability must have been high indeed. Ian McLean will tell all about this in his paper.

Fig. 2.10 Building projects

Tribute

Of the scores of people who contributed to the project and its early years, two stand out:

Jim Ring was a brilliant instrument scientist and a charming sincere person who brought and held the infrared community together. He convinced committees and attracted excellent researchers and students, many of whom still contribute to astronomy in key roles.

David Beattie brought us at UKIRT through some difficult times. As my deputy he was there when I was not and much more. With his great drive, enthusiasm, energy and sense of humour (at times macabre) he moved things along on the mountain and in Hilo. On any day or night he might take on the role of staff astronomer, instrument specialist, day work supervisor, contract negotiator, building design coordinator . . . He was my partner for 10 years in a great adventure.

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