Demonstration of the TIRGO compact 800 to 900GHz heterodyne receiver on UKIRT

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ABSTRACT

A compact sub-millimetre wavelength Nb superconducting tunnel junction receiver (TIRGO) has been installed on the UKIRT facility, Hawaii. The receiver, used in combination with an acousto-optic spectrometer, exhibited excellent noise performance, achieving a best noise equivalent temperature of 280K (DSB) at 808GHz. Despite unfavourable observing conditions, spectral observations of a variety of astronomical sources were made that effectively verified the sensitivity and usefulness of the instrument for astronomical research. The design, construction and performance of the receiver system are described and some of the astronomical data acquired during the observation period briefly presented.

Keywords: TIRGO, SIS, heterodyne, UKIRT, sub-millimetre

1. Introduction: The 'TIRGO' project

The purpose of this project was to design and fabricate a compact, portable receiver capable of working in the 800-900GHz frequency band for use on a variety of telescopes, in particular, small infrared telescopes that provide excellent beam quality in the sub-millimetre wavelength region. It was also foreseen that this receiver would make an excellent testbed for novel new high frequency devices, for example, NbTiN superconducting tunnel junction (SIS) [1] and Nb superconducting hot electron bolometer (SHEB) devices [2].

Several technical goals needed to be achieved:

(i) The overall size of the receiver to be small so that it could be mounted on a variety of telescopes.

(ii) Adapting the receiver for use on different telescopes to be simple.

(iii) A hybrid cryogenic design required to ensure a long liquid helium hold time.

(iv) The receiver to carry its own internal calibration sources.

These aims have been successfully achieved and the receiver has been initially tested on the 1.5m TIRGO (Telescopio InfraRosso del GOrnergrat) telescope on the Gornergrat (altitude 3170 metres) and from whence the receiver obtains its name. Unfortunately, weather conditions at the Gornergrat site were found to be far from optimum and so poor that, during allocated observing periods, astronomical observations proved to be impossible.

As the receiver is intended to be used on both small and large telescopes and since it is a small, compact, unit (overall height 1.2m, weight 70kg), its design was easily re-configured for use on the United Kingdom Infrared Telescope (UKIRT), Hawaii, where more favourable weather conditions were anticipated. The use of a compact and portable acousto-optic spectrometer (AOS) for spectral analysis also permits use at alternative telescope locations and, in combination with the receiver front-end, provides a complete high resolution spectrometer capability (~ 1MHz resolution bandwidth).

This paper describes the rationale behind the TIRGO receiver, a description of its hardware, performance results and preliminary successful observations made from the UKIRT observatory. Results are only presented for the 800-810 GHz range as this is the range of the Gunn and frequency multiplier local oscillator combination. The receiver, mixer block and junction, however, were all designed to work in the 800-900GHz range allowing future enhancement of the instrument capability though provision of a broader frequency range local oscillator (LO).

2. Scientific rationale

Very little work has been carried out in the 800-900GHz band owing to the shortage of telescopes and receivers capable of observing it effectively and the necessity to work in good weather conditions with Perceptible Water Vapour (PWV) levels of ≤ 2mm.

On Mauna Kea the atmospheric transparency in the 800-900GHz window is expected to be slightly better than that of the 500GHz window, allowing useful 800GHz observations to be performed approximately 30% of the time [3]; on the Gornergrat this proportion is expected to be 50% in December and January [4], though the latter was not realised during our observation period. Out intention was to exploit the UKIRT /TIRGO infrared telescopes by making mapping observations with good resolution (23 arcsec - 60 arcsec), and a high efficiency beam (expected η_{mb} = 0.5) resulting from the high quality optical surface. There is also in principle plenty of observing time available as observations can be performed well into the morning.

There are several complementary scientific programmes to which this strategy will be applied. These include observations of extended neutral carbon (CI) fine structure lines [5], [6], probing of photo-dissociation regions [7], [8], [9], observations of molecular lines, new spectral lines, and line observations of external galaxies [10], [11]. Species with important bright high excitation molecular lines in the 800 - 900 GHz band include HCN, HCO+, CO, CI 3p2_3PI, 13CI, 3P2_3pl, CO+, CS, CI8O, 13CO, C170.

3. Receiver configuration

This section gives a brief, overall description of the receiver and then a more detailed description of each of the receiver sub-systems. Figure 1 is a schematic layout illustrating each of the major components.

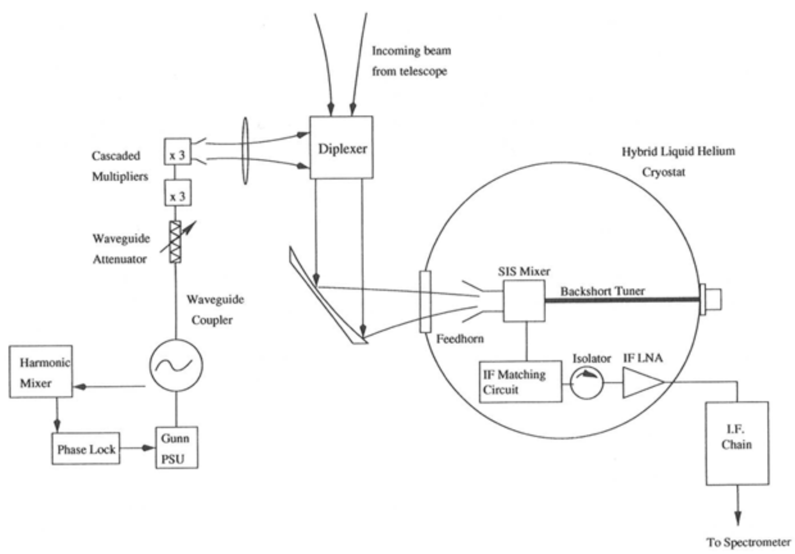

Figure 1: Schematic layout of the TIRGO receiver

The incoming beam from the telescope and LO are coupled into the SIS mixer block via a simple Melanex diplexer (<10µm thick). The SIS junction and substrate are mounted in a channel cut across a half-height rectangular waveguide, fed by a corrugated feedhorn. Tuning is accomplished via a H-plane (non-contacting) sliding backshort tuner. Undesirable Josephson effects are suppressed by a magnetic field supplied by a superconducting magnet (omitted from Figure 1 for the sake of clarity). An intermediate frequency (IF) matching circuit is incorporated into the mixer block to transform the mixer output impedance to the isolator and low-noise first stage IF amplifier. The centre frequency of the IF is 1.5GHz, with an instantaneous bandwidth of 500MHz, defined by the bandwidth of the low noise amplifier which is mounted on the 15K shield. The IF signal is then passed into a room temperature IF amplifier chain before final presentation to the back-end spectrometer, the latter being an acousto-optic device developed by the Istituto Nazionale di Astrofisica, Florence, Italy. Each of the major components of the receiver will now be discussed in more detail.

3.1. Cryostat and optics

The receiver cooling system is based on a hybrid cryostat that uses a closed cycle CTI 350 Gifford-McMahon cooler and a toroidal liquid helium vessel (shown in Figure 2). The closed cycle cooler stages provide sufficient heat lift for cooling radiation shields and ancillary receiver components to approximately 55K and 12K. The helium vessel cools the SIS mixer and superconducting magnet assembly to 4.2K.

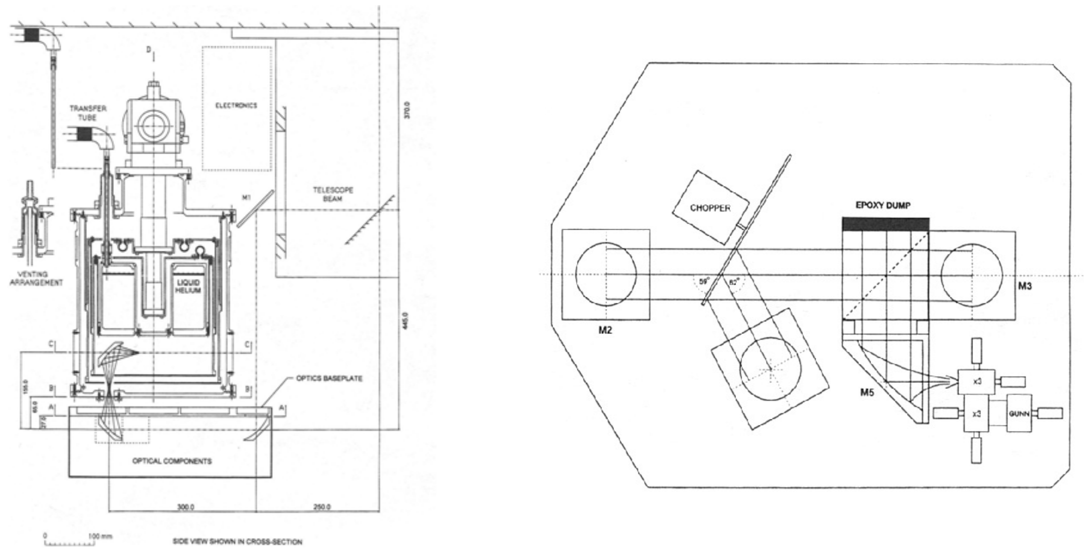

Figure 2:Engineering drawings of the cryostat and optical plate

Apart from a planar downward projecting mirror mounted on the front of the cryostat, the optical components are attached to an optics plate underneath the cryostat (see Figure 2). Appropriate dowelling ensures that the optics are correctly located upon the optics plate, and the entire plate is dowelled to the cryostat. Palatine bellows are used as an anti-vibration buffer between the mixer and the cold head. The measured boil-off rate is approximately 150cc/min resulting in a hold time in excess of 10 days. Figure 3 is a picture of the cryostat, associated electronics and optics plate, mounted on the UKIRT facility. The chopper, LO-signal beam diplexer, and entrance aperture to the mixer are hidden from view.

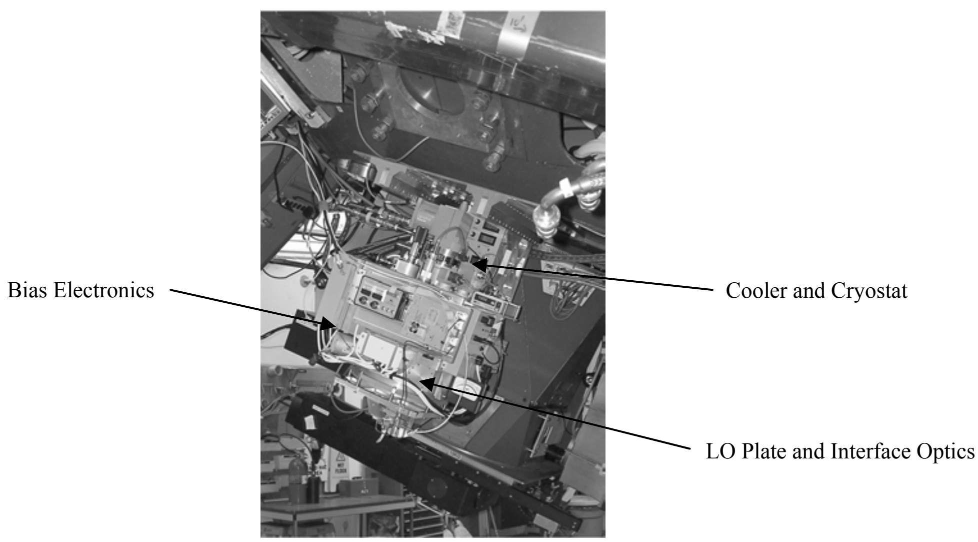

Figure 3: TIRGO receiver mounted on the UKIRT facility

The optical design incorporates four mirrors on the signal path (see Figure 2).

(i) Ml: Flat input mirror, this mirror is oversized and mounted on the cryostat.

(ii) M2: Long-focus mirror to produce parallel beam through the diplexer.

(iii) M3: MPI mirror to produce focused beam waist entering cryostat.

(iv) M4: Mixer mirror (inside cryostat) to produce final required beamwaist at the mixer feedhorn.

Mirrors M2, M3, M4 are all 90 degree off-axis ellipsoidal mirrors, a fifth mirror (M5) focuses the LO signal onto the diplexer. For the purposes of calibration, a pyramidal piece of cast, carbon-loaded epoxy is mounted on the outer radiation shield (typically 55K physical temperature) to act as a cold load. Radiation from the load passes through a vacuum window to a sixth ellipsoidal mirror, used to produce a near-parallel beam. A mirror on one segment of the chopper wheel can be used to direct radiation from the cold load into the mixer beam. All the components mounted on the optics plate are positioned by dead-reckoning using dowels to an accuracy of ±10 microns; their alignment to the input beam has been verified using a laser. A picture of the liquid helium plate is given in Figure 4 and shows the input mirror (M4), mixer block and back-short drive mechanism. The isolator and first stage low-noise IF amplifier are visible at the top left of the picture. All IF connections are made via RG405 semi-rigid co-axial cable.

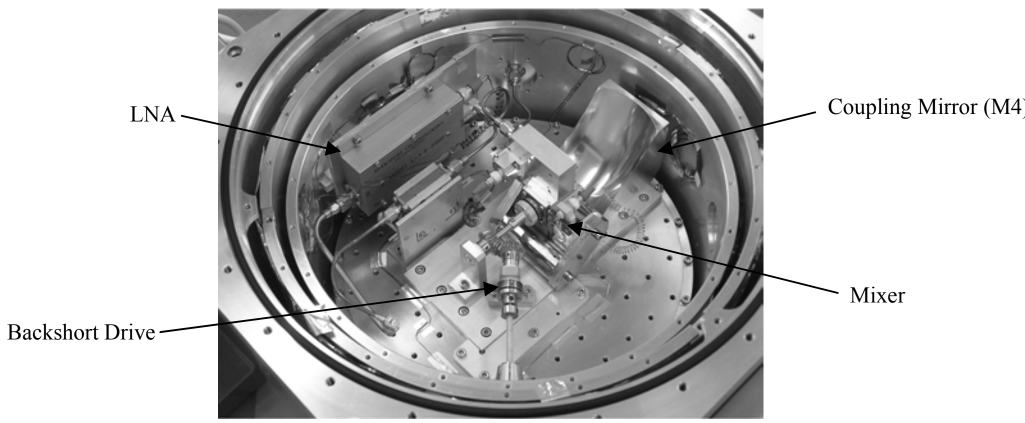

Figure 4: Picture of the mixer block element inside the cryostat

The vacuum window and internal infrared blocking filters of the cryostat comprise a multi-wave TPX (polymethylpentene) window on the cryostat baseplate and a half-wave PTFE infrared filter on the 12K shield. The vacuum window (370μm thick) was optimised for mechanical strength and maximum transmission at 825GHz. This will allow future extension of the receiver operational frequency to 850GHz. An additional half-wave thick fluorogold infrared filter on the 77K shield was shown to be lossy and removed. Although the resulting liquid helium boil-off was higher, this was considered an acceptable compromise. Removal of the 12K PTFE infrared filter resulted in a factor of two reduction in hold-time (to approximately 5 days) and introduced a bolometric type phenomenon whereby placing a hot and cold load into the beam changed the junction resistance without any LO present. It was therefore decided to retain the 12K PTFE infrared filter.

3.2. Mixer, horn and backshort

The mixer mount uses a half-reduced-height waveguide, 280μm by 70μm, with a choke channel 90μm by 90μm, for a junction mounted on a fused quartz substrate 60μm thick and 80μm wide. A single E-plane, quarterwave non-contacting backshort is used to tune the mixer.

The backshort is constructed from gold-plated beryllium-copper foil and machined to a size of 275μm by 65μm so as to be non-contacting within the backshort waveguide. The ability of the backshort to tune out the incident LO power on the junction can give an indication of the 'quality' of the backshort. With perfect backshort tuning we should be able to tune out all of the LO power and restore the junction I-V characteristic to its unpumped state. If this can be achieved we can be confident that the intrinsic parasitic capacitance of the junction can also be tuned out.

An approximate method for estimating the effective backshort VSWR is obtained by moving the backshort from a position of maximum LO power at the junction to a position of minimum power, as measured using changes in the junction DC characteristic to detect the LO power [12].

Then if:

$$F = \frac{(I_{max} - I_o)}{(I_{min} - I_o)}$$

where, I_{max} is the maximum junction current, I_{min} is the minimum junction current (with LO present) and I_o is the junction current with no LO present, the backshort VSWR is given by:

$$VSWR_{808.30GHz} \approx 0.8 \times (2\sqrt{F} - 1)$$

Substituting the best values obtained gives:

$$F_{808.3GHz} = \frac{8.1 - 2.6}{2.7 - 2.6} = 55$$

and

$$VSWR_{808.30GHz} \approx 11$$

This is much worse than the result reported by Ellison et al [12], who obtained a VSWR equal to 96 at 345GHz. Our result is indicative of extra losses at 800GHz, possibly due to operation above the energy gap of niobium and the greater effect of manufacturing errors at the higher frequency. This would reduce the gain by perhaps 3dB compared to a backshort with Q ~ 90 [13].

3.3. SIS Junction

The junction used as the mixer element in the receiver is a NbTiN junction with an area of < 1μm^2, as measured under an optical microscope, and a room temperature impedance of 200 ohms. The substrate material is 40 micron thick fused quartz. The parasitic capacitance of the junction is estimated to be ~80fF [14].

3.4. LO chain

The local oscillator chain employs two triplers in cascade to multiply the signal from 89GHz to 801GHz. The LO was supplied by Radiometer Physics GmbH, Germany to our specifications. It supplies 60 to 125µWatts over a range from 800 to 810GHz. The Gunn oscillator is phase-locked with a commercial system (model 800A/801 supplied by XL Microwave, Oakland, California).

3.5. IF amplification

The isolator and first IF cryogenic amplifier (supplied by Berkshire Technologies Inc., Oakland, California) have a centre frequency of 1.5GHz and a bandwidth of 500MHz, which defines the current maximum bandwidth of the system. It was expected that, for a junction normal state resistance of 50 ohms, the IF output impedance would be ~200 ohms [15], so a microstrip impedance transformer using a microstrip parallel stub and radial quarter wave matching section from 200 to 50 ohms was inserted between the junction and the isolator. The output signal is then further amplified and filtered before presentation to the spectrometer.

3.6. Acousto-optic Spectrometer (AOS)

The acousto-optic spectrometer is a compact and portable system [16]. It operates with an input frequency of 1.5GHz and has 1750 channels covering an IF bandwidth of ~ 750MHz. The noise bandwidth of the AOS results in a frequency resolution of ~ 1MHz. An internal generator can be used to create signals at a comb of frequencies, with a separation of 100MHz, for test purposes and to calibrate spectra. The AOS is controlled from a dedicated laptop computer that can be positioned in the control room of the telescope for ease of use.

3.7. Beam profile

The beam profile of the receiver was measured at a distance of z=500mm, using small linear and circular pieces of ambient temperature AN72 Ecosorb against a 77K background formed of AN72 conical Ecosorb immersed in a bucket of liquid nitrogen.

Both methods of beam measurement, using the circular and linear pieces, yielded vertical and horizontal beam profiles. Deconvolving these data using the method given by Padman et al [17] yielded a 1/e2 beam radius (ωz) extremely close to the predicted value, with ωz = 23mm.

4. Receiver noise performance

Double-sideband (DSB) receiver noise temperatures were measured using the standard Y-factor method. The hot load consisted of a cast piece of carbon-loaded epoxy mounted on the calibration chopper wheel at ambient temperature; the cold load was an external sheet of Eccosorb AN72, dipped in liquid nitrogen and held in the beam of the receiver. The effective temperature of the sheet AN72 was established with reference to a piece of Eccosorb CV-3 absorber immersed in a bucket of liquid nitrogen. The latter was assumed to radiate as a black-body at liquid nitrogen temperature with a small additional contribution due to reflections from the ambient environment. The AN72 was found to have an "effective" physical temperature of 89.5K. The load temperatures were corrected for zero-point quantum noise using the method proposed by Kerr [18] (following Callen and Welton [19]).

Figure 5 shows the DSB receiver noise temperatures of the receiver, measured both in the laboratory (at sea level) and at UKIRT (altitude 4194m). Measurements were made using a dielectric beamsplitter made from 6 µm thick Melanex film. At sea level, the corrected noise temperatures of the hot and cold loads were 293K and 91K respectively. DSB noise temperatures of 334K ± 8K were measured, averaged over an instantaneous IF bandwidth of 500MHz at an IF of 1.5GHz. At UKIRT, the hot and cold loads had corrected noise temperatures of 278K and 87K respectively. A DSB noise temperature of 280K was measured at an LO frequency of 808GHz.

The effective noise temperature of the internal cold load mounted on the radiation shield was established through comparison with the external, liquid nitrogen cooled, AN72 and CV-3 Eccosorb loads. The effective noise temperature of the internal cold load, again corrected for zero-point quantum noise, was found to be ~ 90K.

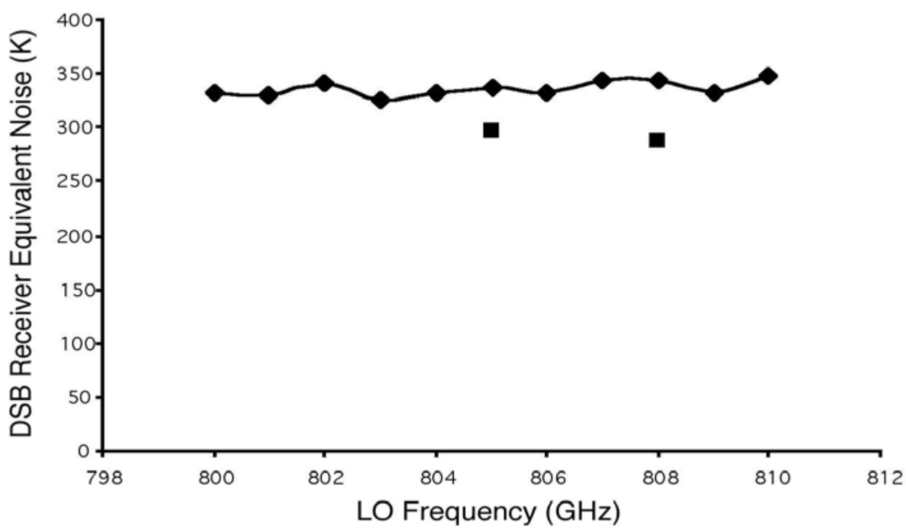

Figure 5: DSB receiver noise temperature measured at sea level (♦) and at UKIRT (■)

5. Observational Results

Observations were made with the 3.8m UKIRT facility in Hawaii. The data shown were obtained through an atmospheric transmission ~ 20 percent on October 17th 2003. The telescope antenna temperature was measured to be 57K, and the beam width was 23 arc seconds. The receiver double sideband noise temperature was typically <350K during the run, and <280K being recorded when tuning was optimised for 801GHz. The measured beam map is shown below in Figure 6.

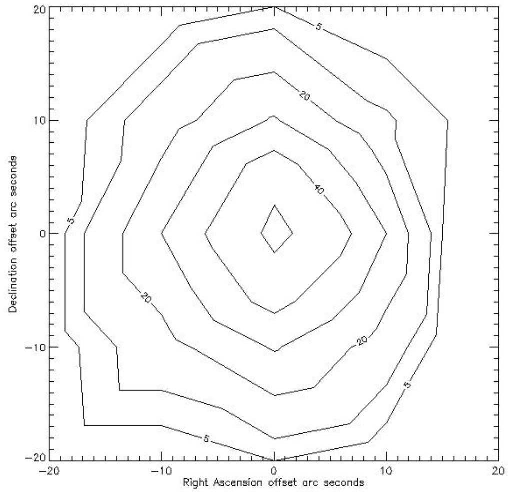

Figure 6. Beam map of the receiver measured from observations of Saturn

The spectra (Figure7) show the CO J=7-6 line at 806.652GHz, and the $^3P_2$ – $^3P_1$ transition of atomic carbon at 809.345GHz. Because of the favourable IF frequency, both lines are simultaneously observed within the same pass band.

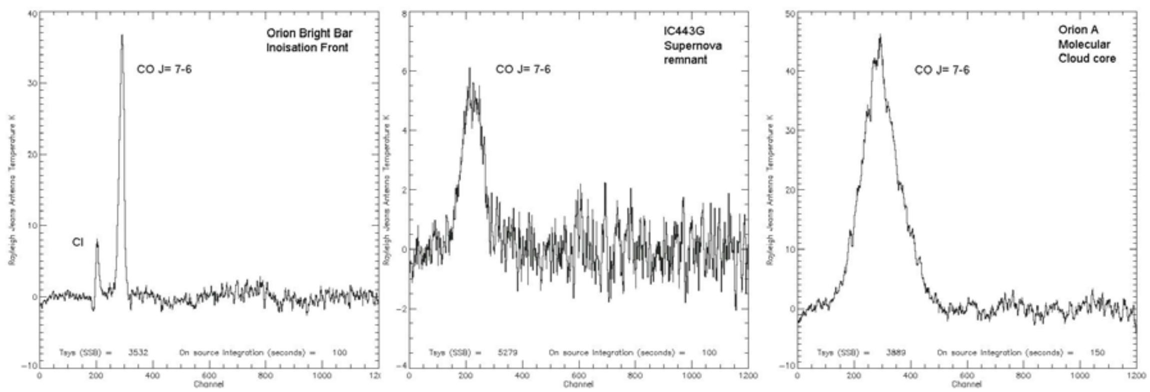

Figure 7. Spectra observed with the UKIRT telescope towards several sources. The spectra were obtained in position switching mode, with on-source integration times ~ 100 seconds. The Orion Bright Bar observations show the simultaneous detection of the CO and atomic carbon, CI lines. For the other sources, the broad line-width resulted in both lines overlapping.

The Orion Bright Bar spectrum was obtained as part of a strip crossing the Orion Bright Bar ionisation front. This molecular cloud interacts with the intense ionising radiation field from several nearby OB stars, leading to the strong CI emission that is observed. The IC443G observations show the shock excited molecular gas lying at the edge of an old supernova remnant, As the supernova blast wave passes into surrounding molecular material, it collisionally excites the gas. The Orion A observations are of the core of the Orion Nebula, our closest high mass star formation region. The broad lines trace gas that has been accelerated outwards at several hundred kilometres per second as part of the star formation process.

6. Conclusions

We have constructed and tested a compact 800-900GHz receiver or astronomical spectral line observations. Its compact and modular design means it is well suited for operation at many different sites requiring the minimum amount of reconfiguration.

The system was successfully deployed at the UKIRT facility in Hawaii during October 2003, and first astronomical data obtained. The best receiver noise performance was 280K (DSB) with ~350K(DSB) typically achieved across the observational frequency range.

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