Pre-launch calibration of the HIRDLS instrument

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ABSTRACT

The High Resolution Dynamics Limb Sounder (HIRDLS) instrument is being built jointly by the UK and USA, and is scheduled for launch on the NASA EOS Chem satellite in 2002. HIRDLS will measure the concentration of trace species and aerosol, and temperature and pressure variations in the Earth's atmosphere between about 8 and 100 km altitude. It is an infrared limb emission sounder, and a primary aim is that it should measure to much finer spatial resolution than has previously been achieved, with simultaneous 1 km vertical and 500 km horizontal resolutions, globally, every 12 hours. Achieving these objectives will depend upon very precise pre-launch calibration. This will be undertaken at Oxford University in a test laboratory that is currently being constructed specifically for the task. The instrument will be surrounded by cryogenically cooled walls, and mounted together with the test equipment on an optical table contained in a vacuum chamber. The table will be mounted independently of the chamber, on an inertial mass supported on pneumatic isolators. Test equipment is being manufactured to measure (i) the radiometric response (with an absolute accuracy equivalent to 70 mK) using full aperture black body targets, (ii) the spectral response of each of the filter channels using a grating monochromator, (iii) the spatial response of the instrument field of view, including low level out-of-field contributions, to 10 μrad accuracy using a monochromator. The methods and equipment used are described together with the principal requirements.

Keywords: calibration, limb-viewing, infrared, remote-sounding, HIRDLS

1. BRIEF DESCRIPTION OF THE HIRDLS INSTRUMENT

HIRDLS is a multi-channel, infrared radiometer[1] to be flown the NASA EOS Chem platform. The instrument measures radiated thermal emissions from the atmospheric limb at a range of azimuth and elevation angles, at various spectral intervals between 6 and 18 μm, chosen to correspond to specific gases and atmospheric 'windows'. The final output will be a set of global 3-D fields of atmospheric temperature, aerosol and several minor constituents in the $8-100$ km height range and horizontal gradients of geopotential height[2].

A single fixed array of 21 detectors is placed in the 18.3 mrad square focal plane of a non-obscuring reflecting telescope of 165 mm diameter entrance aperture. Each detector element corresponds to an atmospheric field of 3.3 mrad (10 km at the tangent point in the atmosphere) horizontal by 0.33 mrad (1 km) vertical. The detector array will be cooled to about 65 K by a Stirling cycle mechanical cooler. A tooth-disc mirror placed at an intermediate focus of the telescope chops the incoming radiation against a cold reference view to space. The telescope views the atmosphere via a two-axis tilting mirror which provides the necessary altitude and azimuth scanning. A multi-axis gyroscope module mounted on the optical bench will provide relative pointing knowledge with the accuracy necessary for the determination of geopotential height gradients.

In-flight radiance calibration information is obtained frequently by tilting the scan mirror to view cold space (just above the atmospheric limb), and by viewing an internal black body reference cavity of known temperature. Normal instrument functions, including scanning, in-flight calibration, thermostat heaters and a moveable sun-baffle will be controlled by stored routines in an on-board microprocessor.

2. REQUIREMENTS FOR PRE-LAUNCH INSTRUMENT CALIBRATION

Retrieval of data products will depend not only upon the instrument being manufactured within specification, but also upon knowledge of its responses to radiation to much finer tolerances. Hence very careful pre-launch characterisation and calibration are essential for the success of the Programme. Following thermal vacuum testing at the Lockheed-Martin Palo Alto and Sunnyvale plants, the HIRDLS Engineering and Protoflight Models will undergo calibration in the test facility at Oxford University which is being upgraded for HIRDLS testing. This section outlines the requirements for the calibration and characterisation.

The instrument measures spectral radiance $\bar{L}$ (power per unit area per unit spectral bandwidth per unit solid angle) emitted by the atmosphere, averaged over the spectral bandwidth and field of view (FOV) of the relevant HIRDLS channel:

$$\bar{L} = \int F(\nu, \mathbf{n}) \, L(\nu, \mathbf{n}) \, d\nu \, d\Omega, \tag{1}$$

where $F(\nu, \mathbf{n})$ is the radiometer averaging function, ν being the frequency, $\mathbf{n}$ the viewing direction, and Ω the solid angle of view, and $L(\nu, \mathbf{n})$ is the scene radiance. The relative form of F can normally be assumed to be separable into components that describe the *spectral response* and the *geometric response*; the absolute scaling of F (further scaled by instrument parameters) then represents the *radiometric response*.

2.1 RADIOMETRIC RESPONSE

The radiometric primary calibration will be performed in flight by making measurements during views of (a) space just above the atmospheric limb as part of each elevation scan cycle (typically every 10 sec), (b) an internal black cavity (typically once every 66 sec). The cavity temperature will be measured using several carefully calibrated sensors (Rosemount 118MK2000C platinum resistance sensors) and an a.c. inductive bridge, to an absolute accuracy of better than 70 mK over the life of the mission. By these means a two point calibration will be obtained with individual measurements of the 'offset' or 'space zero' term for each profile (which will be very close to the low signals received from weakly emitted atmospheric species), together with frequent measurements of the 'gain' or radiometric scaling. The instrument will be by design very nearly linear in its radiometric response (the detectors are the main potential non-linear component), hence the internal calibration will provide nearly all of the information required for radiometric calibration.

The telemetry count S from each channel, is related to $\bar{L}$ by

$$\bar{L} - \bar{L}_2 - \bar{L}_3 = \frac{S - C_1}{G}\Big(1 + \check{k}(S - C_1)\Big), \tag{2}$$

where C_1 is a known digital offset, added on board to ensure that S is positive, $\bar{L}_2$ is a small offset due to any cross-talk and pick-up effects, and $\bar{L}_3$ is a radiometric offset due to chopped instrument emission. These offsets cannot easily be separated by measurement, but as explained above, a combined offset together with the gain G will be determined routinely in flight. Nonlinearity coefficient $\check{k}$ is included to

allow for any nonlinear effects, which must be known e.g. from pre-launch calibration. The equation can then be used for atmospheric views to obtain the atmospheric radiance given the measured signal.

Various small corrections are necessary because the atmosphere is not viewed through precisely the same optical arrangement as the radiometric calibration target:

i) The cavity will be viewed through a parabolic mirror dedicated to the purpose, and both will be maintained at the same temperature (about 300 K) which will be close to the temperature of the scan mirror and the optical enclosure. This will minimise the effects of imperfect or angle-dependent mirror reflectivity, but corrections requiring knowledge of the mirror emissivities will be required to allow for any measured temperature differences between the components. These emissivities will be measurable to some extent in flight by commanding temperature differences in special tests.

ii) Although a space zero measurement will be made for each atmospheric radiance profile at the same azimuth angle, the measurement will be at a slightly different elevation angle, in order to be above the limb. Hence any angular dependence of reflectivity will need to be allowed for, probably by measuring the elevation dependence of space-view signal just above the limb as part of each space viewing sequence, and during special spacecraft manoeuvres when the satellite is pitched to cause the entire elevation range to view space.

During pre-launch testing the radiometric calibration will be performed in the same manner, using a cold external cavity to simulate the view to space. Pre-launch radiometric calibration will then serve the following purposes:

i) to measure any deviations from linearity (i.e. $\tilde{k}$) by means of a variable temperature black body target;

ii) verification of the in-flight cavity temperature sensor calibration, which will already have been calibrated against secondary standards at subsystem level.

iii) an end-to-end verification that the onboard radiometric systems are functioning correctly to the very accurate levels required.

2.2 SPECTRAL RESPONSE

The spectral (i.e. wavelength dependent) response of a channel is determined by the product of the transmissions of several instrument components, primarily its warm band-determining interference filter, but also its cold interference filter (on the focal plane), the anti-reflection coatings, and the transmissive optics material, plus the detector spectral response. These contribute to give a pass band full width at half height of 14–$120\,\mathrm{cm}^{-1}$ or 1–8% depending on the channel. The components will be measured individually and the overall response calculated, but knowledge of the overall response is so crucial to correct interpretation of the data that extensive measurements will be made on the complete instrument. No calibration is possible in flight, hence accurate knowledge depends upon pre-launch characterisation together with stable instrument characteristics.

The problem separates into:

i) *in-band* spectral response - the shape and spectral placement of the pass band is required for modelling the atmospheric radiance; even small displacements or errors in shape can have a large effect because the structure of the atmospheric spectrum varies rapidly with wavelength.

ii) *out-of-band* response ('blocking characteristics') - the channel pass bands are so narrow that a small response outside the pass band integrated over the whole spectrum could contribute a significant radiance error if not accounted for, particularly for atmospheric altitudes where the target species has a much lower concentration or weaker spectral bands than other species. The optical filters have been designed to give negligible signal outside a certain pass band, but ideally this should be verified at instrument level.

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This has led to the following pre-launch measurement requirements in terms of various relative response points (RRP) where the response is a given percentage of the peak response:

- Between the 1% RRP: to within $\pm 0.5\%$ of the peak response, with a spectral resolution of $1\,\mathrm{cm}^{-1}$ and absolute spectral accuracy of $0.6\,\mathrm{cm}^{-1}$ (3σ).
- Between the 0.2% RRP but outside the 1% RRP: to within a factor 2 of the measured amplitude, with a spectral resolution of $2\,\mathrm{cm}^{-1}$ or better, and an absolute spectral accuracy of $1\,\mathrm{cm}^{-1}$ or better.
- By measurement over the spectral range $400-2500\,\mathrm{cm}^{-1}$ but outside the 0.2% RRP: with sufficient sensitivity to detect an out-of-band spectral 'leak' having an amplitude greater than 0.1% of the peak in-band response, with a spectral resolution of 5% or better, and with an absolute spectral accuracy of the larger of $10\,\mathrm{cm}^{-1}$ or 1%.
- Measurements to be performed at various combinations of warm filter and focal plane temperatures.
- The beam used to illuminate the instrument entrance pupil during these measurements shall be uniform in intensity to within $\pm 10\%$ or better.

Although the atmospheric scene is believed to be unpolarised, the instrument and the monochromator both have polarising components, and when used in combination they could produce misleading results. Consequently the polarisation sensitivity will need to be investigated, and if necessary the unpolarised spectral response constructed from measurements at two different polarisations.

2.3 GEOMETRIC RESPONSE

The geometric response divides into two components:

i) *Field of view* which describes $F(\nu, \mathbf{n} - \mathbf{n}_r)$ for each channel where $\mathbf{n}_r$ is some reference direction on the steerable field of view common to all channels. The focal plane will include a 1420–1540 cm^{-1} quadrant detector which will be operable during calibration, and it is likely that this will define $\mathbf{n}_r$. $F(\mathbf{n} - \mathbf{n}_r)$ must be particularly well known in the elevation direction since the atmospheric scene radiance can vary by tens of percent over the nominal 1 km field of view.

ii) *Pointing* which describes how well the nominal view direction $\mathbf{n}_r$ is known; this depends primarily on calibration of the scan mirror angular sensors and the instrument gyroscopes, but also upon any temperature variation of optical system alignment.

There is no possibility to perform in-flight geometric calibration (although views of the Moon, stars or planets might provide some information). Field of view (i) will be measured during pre-launch calibration at instrument level, but pointing (ii) will rely upon calibration of individual subsystems.

This has led to requirements for field of view characterisation in terms of the geometric RRP (response relative to peak response for that channel) of:

- Within the 1% RRP: in amplitude, to within $\pm 0.5\%$ of the peak response and with an angular resolution of 20 μrad or the diffraction-limited spot size (whichever is larger); in angle, to within ± 5 μrad relative to the common datum $\mathbf{n}_r$.
- In the 'wings' between the 1% and 0.2% RRP: to within a factor 2 of the measured amplitude, with an angular resolution of 0.25 of the nominal vertical field of view (332 μrad).
- Over the whole angular range of the overall instrument field beyond the 0.2% RRP: with sufficient sensitivity to verify that the integrated response outside ± 1.3 mrad is less than 0.4% of the total.
- Similar characterisation for the horizontal field of each channel but with required accuracy and resolution relaxed by a factor 5.

3. CALIBRATION FACILITY AND TEST EQUIPMENT

Three issues dominate the requirements for instrument-level calibration and characterisation:

i) The need to perform the tests under vacuum in the correct thermal environment to properly represent the operating conditions; apart from other considerations, vacuum operation is the only viable means to operate the different parts of the instrument at representative in-flight temperatures.

ii) The standards of cleanliness required are particularly high with limb sounders because of the several orders of magnitude contrast between the atmospheric radiance and the nearby Earth's disk. Any particulate contamination on the mirror surfaces will cause scattering. This requires that most of the calibration be performed in a very clean chamber under vacuum, since even a high quality clean room will not allow operation of the instrument with the optical apertures uncovered for more than a few days.

iii) The stability of the instrument and geometric calibration test equipment are particularly demanding. Limb sounders are particularly vulnerable to angular errors at the μrad level, and since HIRDLS is aiming for a substantially better vertical resolution than previous such instruments, the geometrical calibration requirements are correspondingly more difficult to achieve.

3.1 VACUUM CHAMBER, OPTICAL TABLE AND SEISMIC MASS

Experience with calibrating previous limb sounding instruments, e.g. UARS ISAMS[3,4], has shown that the conventional arrangement used for instrument thermal-vacuum testing whereby the instrument and test equipment are hard mounted into a vacuum chamber gives excessive levels of vibration due to:
- low frequency disturbances in the environment beyond our control (due to vehicles, plant, etc);
- noise generated on the chamber (e.g. cooling fluids passing through "environment" walls);
- noise generated by essential support systems such as pumps (even with anti-vibration mounts);
- acoustic waves and air flow turbulence picked up by the chamber;
- resonances in the chamber and environment excited by the instrument.

This had led to a design in which the instrument and test equipment are mounted on a thermostatted optical bench which is mounted on a seismic mass suspended in a floor cavity on pneumatic isolators. The vacuum chamber is mounted separately on to the floor with pillars to the optical table passing through flexible diaphragm seals to avoid transmitting vibration. The instrument will be surrounded by "environment" walls suspended from the chamber. All electrical and fluid connections to the bench will be of low compliance or mechanically decoupled from the chamber walls. This arrangement is shown in Figure 1.
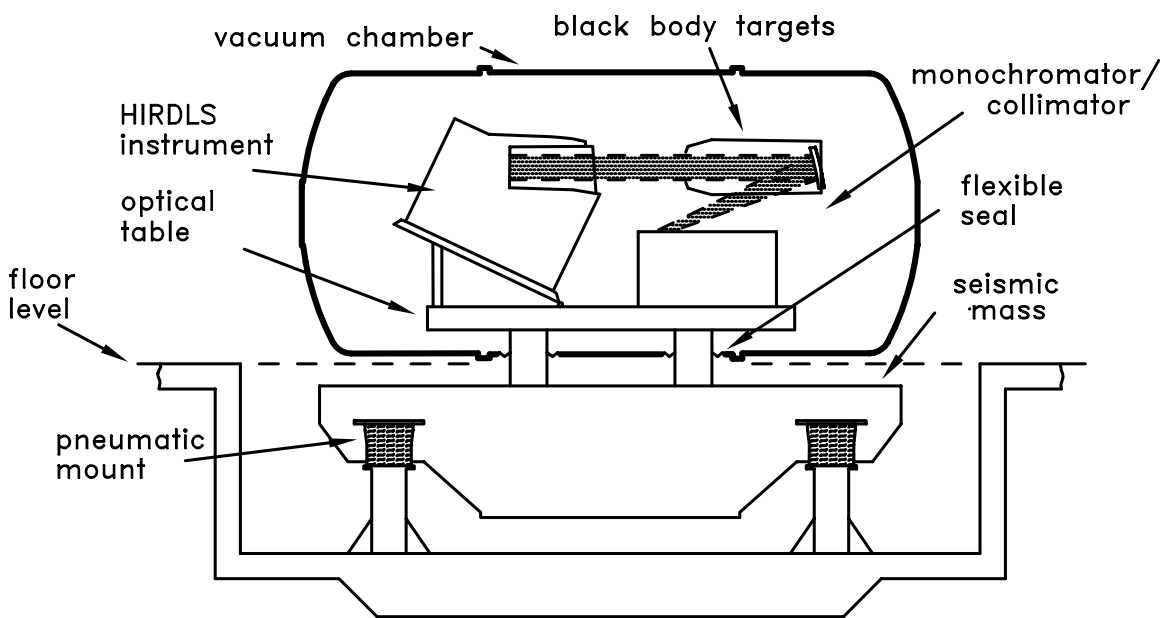

Figure 1. Overall arrangement of the instrument and test equipment in the vacuum chamber on the seismic mount. The chamber supports are not shown.

The vacuum chamber is 5.0 m long by 2.3 m internal diameter, and has a 2 m centre section mounted permanently on 4 feet. The end sections will be mounted on castors which allow them to be easily moved away for access. The optical table is manufactured in stainless steel, with four 100×200 mm hollow sections running longitudinally forming the main bed to which equipment is mounted. A single heating wire will be run down the middle of each tube to provide radiative heating should this be necessary. The instrument baseplate will be tilted by 25° to give an approximately horizontal view direction. This is achieved with a pivoted table machined from cast aluminium alloy to which the instrument isostatic mounts will be attached. The table will be elevated before the chamber is closed with a powered jack.

The optical table, seismic mass and support arrangements were carefully designed using extensive finite element modal analysis to achieve maximum rigidity and to avoid critical instrument frequencies. The mass has a steel reinforced core, and was cast by Taywood Engineering Ltd (Teddington, UK) from a concrete mix developed for the Project to be of high elastic modulus (47−53 GPa). To avoid cracking during curing, the temperature rise was modelled and verified with a full cross section size test casting. The block is suspended on four Barry Controls AL133-12 350 mm air mounts which have vertical and horizontal resonant frequencies of 1.7 and 3.5 Hz respectively. These act on steel outriggers bolted to the sides of the block such that the centre of gravity of the suspended mass (including the instrument) will be in the elastic plane of the mounts. The mass itself weighs approximately 10 tons, and the outriggers, optical table, test equipment and instrument will bring the total suspended mass to 12 tons. The isolators stand on columns mounted on a 500 mm thick reinforced concrete slab foundation which extends over an area of 6x4 m and which is tied into the floor cavity walls and floor of the room. The block is isolated from the clean room overpressure (>20 Pa) by enclosing the service pit and other ducts with floor tiles.

The table support columns are 300 mm in diameter and pass through flexible Dacron reinforced Viton rolling diaphragm seals of effective diameter 380 mm manufactured by Fabreeka International. The pneumatic mounts are servoed to a constant level (which can be disabled during sensitive tests) to ensure that the seals are not displaced vertically by more than a few mm; this is particularly important during pump-down when the load on the mounts will reduce by about 3 tons.

The instrument will be surrounded on 5 sides by 4 independent "environment" walls (not shown) at temperatures controlled between 88 and 328 K mounted on the chamber centre section. Thermal models with the instrument in this configuration have been run by Matra Marconi Space UK (who are responsible for the HIRDLS thermal design) to assist with the panel designs.

The installation is sited inside a 10 × 10 m area which is clean to Class 1000, but with local tented areas provided for disassembly of the instrument to maintain cleanliness of critical surfaces to MIL-STD-1246, Level 280B. The air flow was modelled numerically to help locate the filter banks and vacuum chamber to avoid stagnant areas.

The laboratory has extensive support facilities, including a dedicated control room, a 6000 litre dedicated liquid nitrogen storage (it is expected that several hundred tons will be used during HIRDLS calibration), workshops, computing facilities, an adjacent Class 100 clean room for storage, and other smaller vacuum chambers.

3.2 MONOCHROMATOR AND COLLIMATOR

Spectral and geometrical measurements will be made with a monochromator and collimator utilising a common optical system shown in Figure 2. The option selected will be determined by the position of a plane switching mirror (M2), so that either the output slit of the monochromator or the aperture of the collimator hot source will be at the focus of the large offset paraboloid (M1). Thus a collimated beam will be generated in a fixed direction approximately along the nominal instrument input axis. The instrument scanning mechanism will be used to select the input direction of the radiation relative to the FOV of each channel in both azimuth and elevation. The scanner's requirements for atmospheric scanning mean that

it will have more than adequate performance to fulfill the calibration requirements. The mirror M1 is surrounded by a black temperature-controlled annulus which is sufficiently large that when the beam is directed to any point in the field of view, all other points see either this annulus or the source assembly reflected by M1. This is necessary to enable the effects of any multiple reflections behind the instrument chopper (e.g. in the refractive components) or any electrical crosstalk between detector elements (the most likely causes of any distant response in $F(\mathbf{n} - \mathbf{n}_r)$) to be detected and quantified.
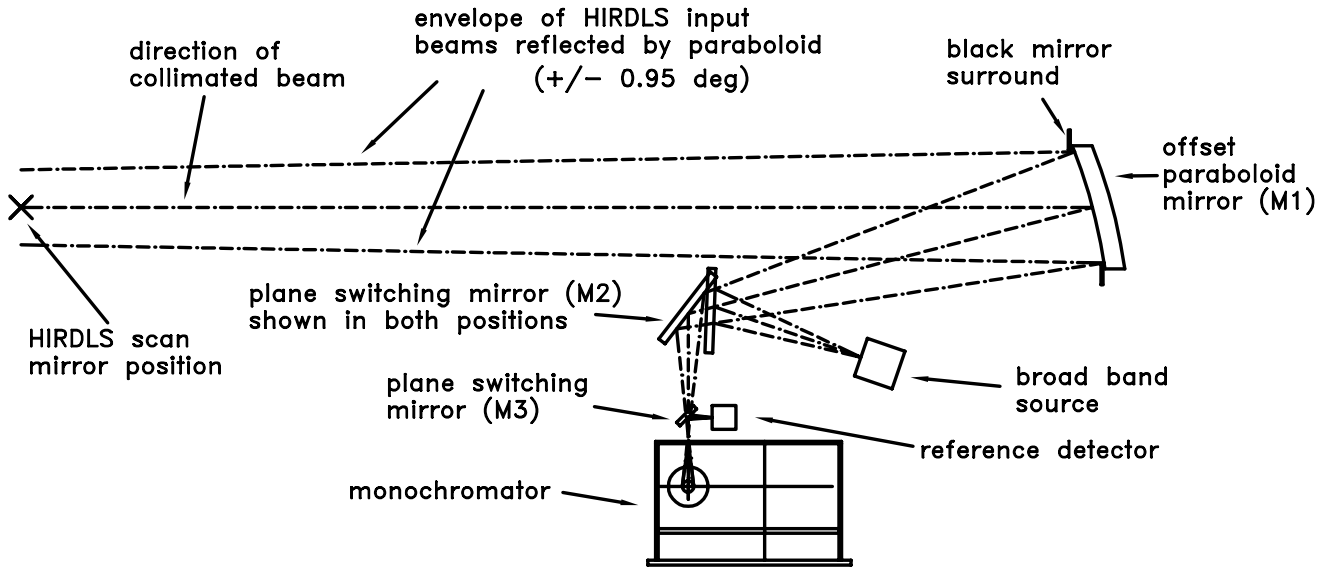

Figure 2. Side view of monochromator, collimator and broad band point source.

Mirror M1 has a focal length (of the parent) of 1352 mm and an offset of 350 mm. Both M1 and M2 will be gold coated. They will be mounted on a stable structure, and an autocollimator will be used reflecting off a mirror mounted on the instrument optical bench adjacent to the scan mirror to monitor any angular displacement between the instrument and the test equipment.

3.2.1 COLLIMATOR

The collimator source will consist of an aperture in a temperature-controlled plate, behind which is placed a black electrically heated element operating at approximately 1400K. Cooling will be provided to remove excess heat. For ISAMS testing an alumina Opperman-type glow bar as used on Perkin Elmer laboratory interferometers was employed, and this approach may be used again. The glow bar together with a thermocouple was wrapped in platinum foil which has low infrared emissivity, except for an opening in the view direction. The form of the aperture will be changeable, although not remotely. Currently it is proposed to use a small rectangle (corresponding to about 10% of the linear size of one element of the instrument field of view) for detailed mapping of the near field of a detector element. A large rectangle (100% of an element size) will be available for mapping the far field, and a pin hole will also be available to locate any unexpected features. A multiple aperture will also be used in an end-to-end verification of the modulation transfer function. A slow chopper (e.g. 1 Hz) will be placed between the infrared source and the aperture. Ideally the faceplate will operate at a similar temperature to the mirror (M1) annulus and (less important) M1 itself. Those temperatures have not yet been selected but will probably be a few degrees below ambient.

3.2.2 MONOCHROMATOR

Monochromatic radiation is required to fill the entrance pupil of the instrument, illuminating the entire detector element of any single channel at one time. Several options have been explored, but the

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one selected is a single grating monochromator in a Czerny-Turner mounting, with 600 mm focal length mirrors. The Czerny-Turner configuration uses separate spherical mirrors to image the input and exit beams on to the grating, giving superior scattering performance. The optical layout is optimised for this application, with re-diffracted stray light paths between the grating and both collimating mirrors eliminated, and a small asymmetry between input and exit focal lengths. A possible alternative was a double 300 mm monochromator, which would have given improved stray light performance but less throughput causing it not to meet the requirements for the longer wavelength channels.

Four gratings of 102×102 mm active area with groove spacing of 5.56, 6.67, 8.33 and 16.67 μm will be available on demand, mounted on a turret. This is derived from a design being developed for the Bentham Instruments QM600 600 mm focal length instrument but modified for vacuum operation, and will provide 10 μrad positional accuracy and 100 μrad step size. The entrance slit will be variable on demand over the range 0.025–3 mm in steps of 0.02 mm. This will provide a resolution of $1 \, \text{cm}^{-1}$. The exit slit has the same adjustment range, but will normally operate at a fixed width of 0.46 mm, which is imaged to fill the field of one detector. Special tests with reduced and increased field illumination are also planned. The turret and slits will be manufactured by Bentham Instruments (Reading, UK).

The monochromator will be equipped with a slow chopper, a calibration detector to monitor the intensity of the output beam, a remotely commandable polariser, and possibly gas cells which can be placed (by remote command) into the path to the calibration detector to provide wavelength calibration.

3.3 BLACK BODY TARGETS

Two black body targets will be required for the radiometric calibration. One will be maintained at about 100 K and will provide effectively zero radiance, and the other will be at a temperature variable between about 100 and 320 K. They will be of similar design, having a 250 mm entrance aperture, a depth of 972 mm and an internal base diameter of 308 mm. This is large enough to more than fill the entire instrument field of view defined by the chopper field mask and the primary diffraction baffle. Numerical modelling has been used to design the internal form; this has led to the base having 4 concentric V-grooves of 34° included angle with a central cone. The internal surfaces will be coated with Nextel Velvet Black 811-21 (containing polyurethane microspheres). The overall target emissivity is predicted to exceed 0.9995 at all HIRDLS wavelengths.

Both targets will be cooled with cryogen cooling loops employing mixed liquid/vapour nitrogen, but the variable temperature target will also include electrical heaters and controllable heat leaks. The wall temperatures will be measured using seven 27 Ω rhodium-iron resistance sensors (4 on the base, 3 on the walls) each separately measured by an a.c. bridge, and calibrated against an in-house secondary standard which itself is accurate to 1 mK absolute (by calibration against UK national primary standards). The absolute measurement accuracy of the target sensors is expected to be 20 mK. A stability of 20 mK over 60 sec is planned.

The targets will be located at different fixed azimuth angles on either side of the collimator/monochromator, which will allow both types of measurements to be made without opening the chamber to reconfigure the equipment. Ideally both targets would be at the same azimuth angle at different elevations, but they would need to be at an excessive distance (tens of metres) for this to be possible. To enable measurements at variable elevation angles, one of the targets will be mounted on a commandable variable height platform which will pivot the target about a virtual centre at the instrument scan mirror.

A 'linearity baffle' will be optionally placed in front of the aperture of the variable temperature target. This will have a front surface cooled to 100 K and contain two apertures, either of which can be masked on command by a shutter. With the target at a higher temperature, tests can be made that the signals with neither, either or both apertures open are additive. Linearity can also be checked from the

variation of signal with target temperature (without the linearity mask in place), but this relies upon knowledge of the spectral pass band.

A target at cryogenic temperature will also be provided, set into one of the "environment" walls, to fill the instrument space reference view on the +Y face of the instrument.

4. TEST SEQUENCES

The major scheduling constraint for calibration is the thermal vacuum environment. This could take as long as 48 hours to establish depending on the level of out-gassing of water vapour during the pump-down phase. This, together with the requirement that the instrument has to be monitored at all times by test engineers when powered or under vacuum, means that the most effective use of time is to test continuously. This is very demanding on the test team, and cannot be maintained indefinitely with the same group of personnel working in shifts. Hence testing will be arranged in Cycles, with rest periods between each Cycle when the thermal vacuum chamber is vented to allow for any necessary reconfiguration of instrument or test equipment. In addition it is important to allow adequate time for data analysis during and between Cycles to ensure that problems are discovered in time to take corrective action. A further constraint is that certain data are needed early to enable the planning of later tests and the interpretation of later data.

The test equipment will consist of the following items, with the configuration options shown:
 i) Both black body radiometric targets: always available, but the linearity mask can only be installed or removed with the chamber open.
 ii) Collimator: always available, but the source aperture can only be changed with the chamber open.
iii) Monochromator: always available; grating, slit-widths and polarizer orientation all selectable on demand.

The monochromator, collimator and radiometric targets cannot be viewed simultaneously, but switching between them will only take a few seconds. Hence the configuration options are essentially whether the radiometric linearity mask is installed, and which aperture is employed on the collimator broad-band source.

This has led to the following planned sequence of initial calibration Cycles:

Cycle 1: Equipment available: linearity mask fitted; collimator fitted with small rectangular aperture. Instrument temperatures: nominal beginning of life (BOL) temperatures, focal plane at nominal temperature (65 K) or warmer for the second linearity test.
- Linearity calibration.
- FOV map.
- Polarization study for selected channels.
- Repeat linearity measurements with warmer detectors.

Cycle 2: Equipment available: linearity mask not fitted; large rectangular aperture fitted to collimator. Instrument temperatures: nominal BOL temperatures, focal plane at nominal temperature.
- In-band spectral measurements for all channels.
- End-to-end radiometric calibration (cold to warm ramp).
- FOV map at low spatial resolution (for out-of-field).
- Spectral field-dependence test for selected channels.

Cycle 3: Equipment available: linearity mask not fitted; small rectangular aperture fitted to collimator. Instrument temperatures: nominal BOL, various optical bench temperatures, focal plane at nominal temperature.
- Scan stray.
- Radiometric noise measurement.

- FOV map with perturbed instrument optical bench temperatures.
- Begin out-of-band spectral measurements.
- Vary mirror temperatures to measure emissivities.
- In-band spectral measurements with perturbed optical bench temperatures.

Cycle 4: Equipment available: linearity mask not fitted; collimator employing small rectangular aperture. Instrument temperatures: cold and warm instrument conditions, focal plane at nominal temperature.
- In-band spectral measurements all channels, cold instrument conditions.
- End-to-end radiometric calibration under cold instrument conditions.
- In-band spectral measurements for all channels, warm instrument conditions.
- End-to-end radiometric calibration, warm instrument conditions.
- FOV map, warm instrument conditions.

Cycle 5: Equipment available: linearity mask not fitted; multiple aperture fitted to collimator. Instrument temperatures: nominal BOL temperatures, focal plane at nominal temperature.
- Complete out-of-band spectral measurements.
- Spectral study of any cross-talk features.
- End-to-end FOV test.
- End-to-end radiometric calibration (cold to warm ramp).
- Orbital cycling of environment walls.

The above is intended as a minimum set of measurements that will occupy about half of the time available for calibration (9 months); once they are complete it will be decided which to repeat and which additional measurements are necessary. This sequence only provides for measurements at the nominal instrument focal plane temperature of 65 K, except for the radiometric linearity test. A complete set of measurements is required at detector temperatures immediately below and above 65 K to characterise the temperature dependence, and also at a significantly higher temperature (e.g. 75 K) in case operation at that temperature is ever necessary.

6. ACKNOWLEDGEMENTS

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