International Conference on Space Optics—ICSO 2004

Toulouse, France

30 March–2 April 2004

Edited by Josiane Costeraste and Errico Armandillo

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esa icso proceedings cnes

International Conference on Space Optics — ICSO 2004, edited by Errico Armandillo,
Josiane Costeraste, Proc. of SPIE Vol. 10568, 1056805 · © 2004 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308022

DESIGN OF THE COMPACT HIGH-RESOLUTION IMAGING SPECTROMETER (CHRIS), AND FUTURE DEVELOPMENTS

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ABSTRACT

The CHRIS instrument was launched on ESA's PROBA platform in October 2001, and is providing hyperspectral images of selected ground areas at 17m ground sampling distance, in the spectral range 415nm to 1050nm. Platform agility allows image sets to be taken at multiple view angles in each overpass. The design of the instrument is briefly outlined, including design of optics, structures, detection and in-flight calibration system. Lessons learnt from construction and operation of the experimental system, and possible design directions for future hyperspectral systems, are discussed.

1. INTRODUCTION

1.1 CHRIS – platform and orbit

Sira Technology Ltd has developed the Compact High Resolution Imaging Spectrometer (CHRIS). This instrument provides hyperspectral images of Earth, in the visible and near-IR region. It is the main instrument payload on the European Space Agency (ESA) small satellite platform PROBA (Project for On-Board Autonomy), which was launched from the Indian PSLV on the 22nd October 2001. The platform orbits the Earth with an apogee of 673km and a perigee of 560km. PROBA is a highly manoeuvrable small satellite, capable of large, rapid rotations on pitch and roll axes, with fine control over pitch and roll rates.

1.2 CHRIS objectives

CHRIS has two main mission objectives. First, the mission is being used as a technology demonstrator to evaluate the performance of the compact design form. Experience gained from development and operation of CHRIS will feed into the design decisions of hyperspectral systems for future small satellite missions and provide some pointers for design to more demanding requirements, such as those of the hyperspectral instrument for the proposed ESA Earth Explorer Mission SPECTRA.

The second mission objective is scientific. CHRIS is providing data on Earth surface reflectance in the visible/near-infrared (VNIR) spectral band, at high spatial resolution. The instrument uses the PROBA platform pointing capabilities to provide Bidirectional Reflectance Distribution Function (BRDF) data (variation in reflectance with view angle) for selected scenes on Earth surface. The instrument is used mainly to provide images of land areas, and is of interest particularly in recording features of vegetation and aerosols. One aim is to validate techniques for future imaging spectrometer missions, particularly with respect to precision farming, regional yield forecasting and forest inventory. The high resolution of the instrument has also found application in coastal region monitoring.

To evaluate the scientific benefits of the mission three key Principal Investigators (PIs) have been selected covering Land - (Prof. Mike Barnsley, Swansea University, UK), Aerosols - (Dr Jeff Settle, ESSC, Reading University, UK) and Coastal - (Dr Samantha Lavender, Plymouth University, UK). In addition approximately 60 investigators have been selected following Announcement of Opportunity (AO) which was issued by the European Space Agency on behalf of the CHRIS Steering Group. These 60 investigators based in, Europe, the USA, Canada, Australia and elsewhere.

1.3 CHRIS basic performance

At perigee, CHRIS provides a ground sampling distance of 17m on ground, over typical image areas 13km square. It has a spectral range from 415nm to 1050nm, at spectral resolution <11nm. The instrument provides sets of images of selected target areas, at different pointing angles, forming a minimum of 5 images of each target in a single overpass. Currently, the platform data storage and telemetry system allows 1 complete image set to be transmitted to ground per day. The data is being used to analyse directional effects in the radiance of targets, with particular emphasis on vegetation targets and aerosols.

2 INSTRUMENT CONCEPT

The instrument is an imaging spectrometer of basically conventional form, with a telescope forming an image of Earth onto the entrance slit of a spectrometer, and an area-array detector at the spectrometer focal plane. The instrument operates in a push-broom mode during Earth imaging.

The platform provides pointing in both across-track and along-track directions, for target acquisition and for BRDF measurements. The platform also provides slow pitch during imaging in order to increase the integration time of the instrument. This increase in integration time is needed to achieve the target radiometric resolution, at the baseline spatial and spectral sampling interval, and also allows relatively large numbers of bands to be recorded. The pitch rate is varied, as a function of the view direction, to achieve a consistent 17m along-track sampling distance associated with the nominal integration period. The integration time is increased, compared with that which would be achieved without pitch adjustment, by a factor 5.

The spectral waveband covered by the instrument is limited to 1050nm in the near-IR by the upper limit for useful response of silicon detectors, and to 415nm in short visible wavelengths by limitations of coating performance.

3 CHRIS OPTICAL DESIGN

The CHRIS optical design is shown in figure 1.

3.1 Telescope

Telescope parameters are listed in Table 1. The telescope design form is selected mainly for low-cost and easy assembly within a tight schedule for development. It is an axially-symmetrical two-mirror system, with a concave primary mirror and a convex secondary. Lens elements are used to allow all surfaces to be spherical, and to provide acceptable correction for a moderate field. The front element is a meniscus lens that essentially provides correction for spherical aberration; it also provides a convenient location for the secondary mirror, which is cemented to it. Two small lens elements near the focal plane extend correction for off-axis aberrations, and correct chromatic aberration of the meniscus.

Table 1 Telescope parameters

Focal length	746mm
Length – lens 1 to slit	325mm
Baffle length	150mm
Entrance pupil	at front lens
Exit pupil	telecentric
Aperture diameter	120mm
Aperture obscuration	58mm x 66mm
Field angle	1.3°
Lens material	fused quartz

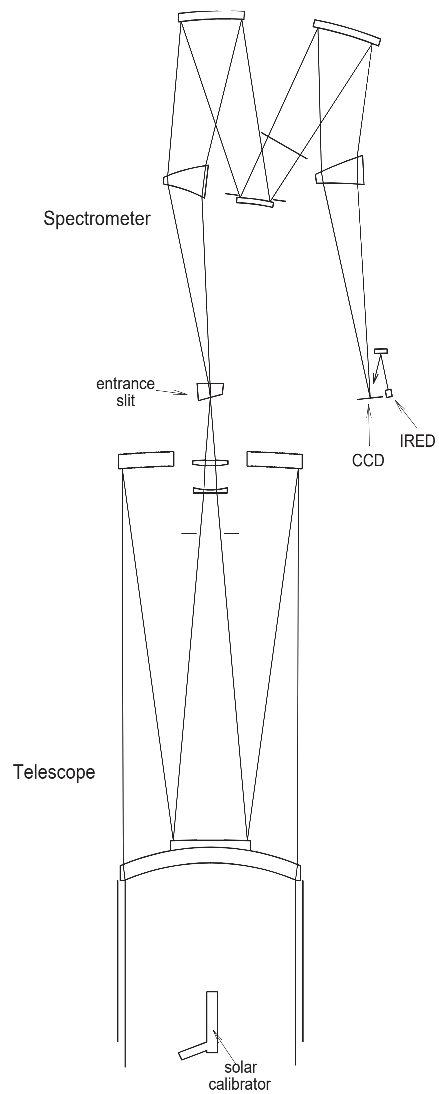

Figure 1 Instrument optical design

All optical components are made of fused quartz, except for the primary mirror; the primary is in a common optical glass to provide an approximate CTE match with titanium structure, in order to control variations in focus with temperature. The lenses are broad-band anti-reflection coated for the range 415nm to 1050nm. The mirror coatings are multiple dielectric layers, providing >98% reflectance over this range.

The axially symmetrical design allows easy manufacture, but has some significant disadvantages. A large axial obstruction of the aperture (by the secondary mirror) reduces the efficiency of the system as a function of optics diameters. There are detailed problems in control of stray light that can reach the entrance slit without reflection at either mirror. Most significantly, efficient anti-reflection coatings are needed to control stray light due to double reflections within the telescope system. Good anti-reflection coatings are not feasible for much wider spectral ranges, so that the design will be considered inappropriate for systems covering the short-wave IR spectral band (SWIR, typically out to 2400nm), in addition to the visible/near-IR (VNIR) band current covered by CHRIS.

3.3 Spectrometer

The CHRIS spectrometer is a design patented by Sira. Parameters of the spectrometerdesign are listed in Table 2.

Table 2 Spectrometer parameters

Magnification	unity
Spectral spread over 22.5 microns at detector	1.25nm at 400nm 11nm at 1050nm
Length, slit to rear mirror	265mm
Width, slit to detector	125mm

Spectral dispersion is provided by refracting prisms that are integrated into a mirror relay system. The relay comprises three mirrors, two large concave mirrors and one smaller convex mirror, similar to a conventional Offner configuration that gives unit magnification. The Offner does not provide a collimated light path, in which flat prism surfaces would introduce no image-blurring aberrations. It is desirable for the prism surfaces to be curved in order to provide good spatial and spectral resolution at the focal plane. The curvatures essentially provide control over spherical aberration; other aberrations are controlled by the balance between angles of incidence on surfaces of the prisms and mirrors. A minimum of two prisms – one in a diverging beam and one in a converging beam – is needed to control a higher-order astigmatism term (at 45° to the principle plane and varying linearly with field angle) that is introduced by axial asymmetry. The design has only spherical surfaces. It uses fused quartz for the prisms; the spectrometer mirrors are made in a common optical glass, as for the telescope primary.

The design using curved prisms is capable of correction for the distortions of the final image that are usually called "smile" and "frown". Smile is curvature and tilt of the image of a straight entrance slit, which introduces a non-uniformity in the wavelengths defined by each row of detector elements. Frown is a variation in tilt of the spectra associated with each point on ground, introducing errors in spatial registration of spectral data read from parallel detector columns. The spectrometer provides registration to better than 5% of the pixel in both spectral and spatial directions, with resolution limited essentially by the detector pixel size.

3.4 Baffling

In the axially symmetrical telescope design, stray light can arrive at the entrance slit without reflection at either of the two telescope mirrors. In the section orthogonal to the slit, this stray path is blocked effectively by a slot baffle in front of the small lens assembly. This does not prevent stray light from reaching the slit from areas of the aperture on either side of the secondary mirror, in the section parallel with the slit. However, this stray light is blocked inside the spectrometer by masks located between the secondary and tertiary mirrors (at a plane indicated in Figure 1), where the optics form an image of the secondary mirror.

The external baffle does not have a very significant role in control of stray light, marginally reducing scatter from telescope optics by reducing their illumination of from the scene. The external baffle is needed mainly to limit temperature variations in spectrometer optics due to variations in radiant inputs from the scene; for this purpose, the baffle is metallic, and conductively coupled to the telescope structure.

3.5 Structure and thermal design

The telescope and spectrometer are constructed mainly in titanium – this choice dictated mainly by considerations of cost and manufacturing schedule. An optical bench approach is used for the spectrometer, while conventional cylindrical structures are used for the axially-symmetrical telescope. Telescope and spectrometer are mounted on a common titanium bulkhead. Aluminium is used for baffles, the spectrometer cover and a radiation shield for the detector. The detector is mounted on a 1kgm block of aluminium to provide thermal inertia.

The system is conductively isolated from the platform by use of three low-conductivity feet that also provide flexure to isolate the instrument from stresses induced by differential expansion with respect to the (aluminium) mounting plate. Radiant isolation is provided by MLI wrapping of the instrument.

Orbital temperature variations are driven mainly by variation in radiant input from Earth in the solar spectral band. This produces a few degrees temperature variation in the telescope front optics – not enough to have a significant effect on telescope resolution. The spectrometer is effectively isolated from this front-end variation by the low conductivity of the titanium structure.

4 DETECTORS AND ELECTRONICS

The CCD detector is an area array from e2v (CCD25-20) with 1152 rows and 780 columns, and a 22.5 x 22.5µm pixel size. The device is thinned and back-illuminated to provide good blue response. It operates in a frame transfer mode, with 576 rows in the image and masked storage zones. The opaque mask is extended along the sides of the image zone to provide 16 transition and dark reference pixels at each end of each CCD row, which are used for dark signal and electronic offset calibration. The spectrometer image fills <200 of the CCD rows, but part of the nominally-unexposed area is used to provide data to compensate for stray light and CCD smear effects. The CCD incorporates a dump gate adjacent to the readout shift register. This provides a facility for fast parallel dumping of charge for regions of the CHRIS spectrum that are not selected for readout.

The instrument electronics includes:

- programmed line integration and dumping on chip for spectral band selection
- pixel integration on chip for spatial resolution control
- correlated double sampling (noise reduction circuit)
- dynamic gain switch for optimum usage of the ADC resolution
- 12 bit ADC.

There is considerable useful flexibility in operation of the CCD. It offers the facility to sum sets of row-signals in the shift register, before read-out – providing users with a facility to compose spectral bands of optimum widths. Signals can also be binned in pairs at the output port, relaxing across-track spatial resolution by a factor 2, and integration time can be increased over a wide range to provide control of spatial resolution along-track (in combination with control over the platform pitch rate). The system also allows images to be restricted to half swath widths to increase the number of spectral bands that can be read out.

It is possible to read out 18 spectral bands during a nominal integration time of 12.7ms, plus one band assigned to smear/stray light calibration in each frame. This spectral coverage will be associated with optimum spatial resolution and maximum swath width. However, it is possible to read out much larger numbers of spectral bands with relaxation of spatial resolution and/or swath width. Current user configurations are listed in Table 3.

Relaxed ground sampling distance (associated with increased integration periods) provides enhanced signal-to-noise ratios.

Table 3 CHRIS operating modes

Mode	No. of bands	GSD (m)	Swath width	Application
1	62	34	Full	Aerosols
2	18	18	Full	Water
3	18	18	Full	Land
4	18	18	Full	Chlorophyll
5	37	18	Half	Land

5 IN-FLIGHT CALIBRATION

5.1 Offset dark signal and smear

The CHRIS detectors provide masked and over-scan pixels in each row, that are used to provide data on electronic offsets and average dark signal levels. Full-frame dark calibration is achieved by a combination of data from full dark-field frames, read while the platform is over dark

Earth areas, with masked pixel data. The masked pixel data is used to correct the full dark fields for effects of temperature drifts between dark-scene and light-scene measurements.

The CCD generates an error due to collection of signal during frame transfer. The error is a weighted average of the signal collected over the whole image area in each column, and is measured using detector rows outside the image area, which receive only the smear signal during frame transfer.

5.2 Response and wavelength calibration

Vicarious methods have been used to provide response calibration for CHRIS. Flat-fielding (relative response between pixels across the field, in each spectrally resolved band) has relied on analysis of data from real scenes, with preference for bland scenes, to detect pixel-to-pixel response variations. In-flight wavelength calibration relies on location of the oxygen absorption band at 762nm, using image data from suitable scenes. This again avoids the need for potentially expensive addition flight hardware. The atmosphere absorption data is used to update full pre-flight data, including smile errors.

The instrument also includes a “solar calibration device”, which is attached to the instrument at the front end of the external baffle, as indicated in Figure 1. This device is shown in greater detail in Figure 2. It is a very simple system, comprising essentially a plano-convex lens in fused quartz, integrated with a prism that reflects sunlight into the lens. The lens has a focal length of 25mm, and forms an image of the sun approximately 0.2mm diameter outside the telescope pupil. The light from the sun image spreads over the small field of the instrument to fill the spectrometer entrance slit and the detector image area.

The focal length of the lens is selected, as a fraction of the aperture diameter, to provide an effective radiance (actual sun-image radiance averaged over the instrument aperture area) equivalent to that of a diffuser in sunlight with 25% reflectance. It therefore provides signals in the instrument dynamic range. The device has been calibrated on ground for effective reflectance, using a sun-simulator and a standard diffuser, so that it can be used like a full-aperture diffuser in flight.

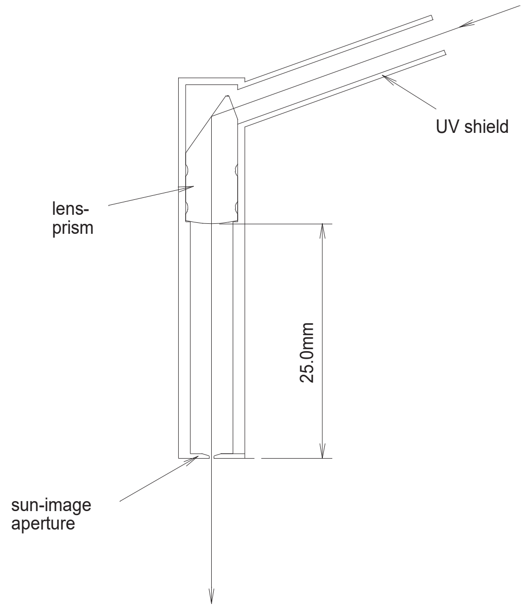

Figure 2 Solar calibration device

The solar calibration device occupies a fixed position in the instrument aperture, and uses a small fraction of the aperture for response calibration. This slightly reduces the aperture area available for useful Earth imaging. During normal Earth imaging, the solar calibration device projects very little light into the main instrument aperture. It is used for calibration when the instrument is over the Antarctic, on the dark side of the terminator – the instrument is in direct sunlight but receiving very little light from ground. The platform must be yawed to receive sunlight on the lens axis.

The field of the device for receiving sunlight is limited to 2° x 4° by a rectangular aperture in the sun-image plane. This field is fully sampled, in pre-flight calibration and in orbit, to check for non-uniformities in transmission of the device and instrument optics over a small area and thus to detect signs of local optics contamination that would obstruct the narrow calibration beam and invalidate the calibration.

The key advantage of the solar calibration device, for the CHRIS development, is that it is very cheap and simple compared with a system using one or more full-aperture diffusers. Because the device uses a small, dedicated aperture area, it requires no moving parts. A clear disadvantage is that it samples only a very small part of the main instrument aperture, so that changes in optics transmission that are not uniform across the aperture will not be accurately measured. Other problems are noted in 7 below.

An internal LED source is included in the instrument, close to the detector, as indicated in Figure 1. Light from the LED is reflected onto the detector by a diffuser mounted above the detector, but out of the main light path. The initial purpose of the LED was only to check function of the detection system during integration, but the LED has also been used to check linearity in flight.

Payload temperature is measured during each image acquisition. Changes in radiometric and wavelength calibration are investigated as a function of the indicated spectrometer temperatures.

5.3 Pre-flight calibration support

Important pre-flight calibration exercises for CHRIS include:

- Absolute radiometric response and calibration of the solar calibration device in operation with a sun-simulator,
- Full wavelength calibration against detector row numbers.

Other normal measurements made on ground included: spectral and spatial resolution, spectral and spatial registration, temperature variations of wavelengths and registration, stray light, linearity, and detection system noise.

6 Physical parameters

Figure 3 CHRIS Instrument

The CHRIS instrument has an envelope of approximately 200 x 260 x 790mm, a mass of less than 14kg and a power consumption of less than 8W. An illustration of the instrument, comprising the telescope, spectrometer and the electronics box, is shown in Figure 3.

7 LESSONS FROM CHRIS

Successes and problems in the development of CHRIS and operation in flight, provide a number of lessons for future instrument developments – particularly for hyperspectral systems. Some of these are discussed below.

7.1 Spectrometer design

The spectrometer design, using curved prisms, is relatively easy to manufacture align and is capable of providing excellent spectral and spatial resolution and registration. It provides good control over stray light due to surface reflections, so that highly efficient coatings are not essential – the concept can be extended to the whole VNIR/SWIR range by addition of suitable detectors. It is not of course the only approach to design of broad-band imaging spectrometers, but is a strong candidate for extension to more demanding requirements, such as those of SPECTRA.

7.2 Structure stability

Unexpected problems have been encountered due to temperature-related movements of the slit image along detector rows (spatial domain), of up to a few microns. This introduces changes in response calibration, due to non-uniform transmission along the slit length, demanding temperature-related corrections. Structure instability is also blamed for distortions of mirrors that have a measurable effect on spatial resolution. (There is also an expected problem of temperature-variation of wavelength calibration, due mainly to the variation of prism refractive index.)

In future spectrometer developments, control of structure stability effects will be needed most critically to control wavelength calibration drifts and spatial registration between bands provided by separate VNIR and SWIR detectors. Use of correction mechanisms (for example local heaters) may be considered.

7.3 Absolute calibration using sunlight

The concept of using direct sunlight in transmission, assisted by platform rotations, has been shown practicable in terms of operation on an agile platform. This has lead to development of more sophisticated concepts using transmitting devices, that will provide alternatives to reflecting diffusers.

The solar calibration device on CHRIS, using a single lens, showed spurious non-uniformities in response across the instrument field. These unexpected defects in flat-fielding performance, which limit the immediate usefulness of the device, have been ascribed to the effects of very fine imperfections, called orange-peal, in polish of optical surfaces in the telescope and spectrometer. Orange peal has no significant effect on resolution but is detected as patterns in the shadow cast by a point source. The CHRIS solar calibration device is in any case over-simple for more demanding missions, but if a similar method is applied again, the single lens will be replaced by a small transmitting diffuser.

8 CONCLUSIONS

The CHRIS instrument is now into its third year in orbit, and it continues to provide images of acknowledged value for scientific applications. Some images are appended below.

Panama

Dallas Airport

Useful lessons in instrument design have been derived for future developments. The basic optics concepts for the spectrometer optical design are successful and likely to be extended in the future to cover the VNIR/SWIR band. The need for structure stability, particularly in spectrometers, is emphasised.

9 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the British National Space Centre, for partial funding of the CHRIS instrument, and the European Space Agency, for the opportunity to launch the instrument on PROBA.

The authors also thank the three Principal Investigators, Dr Jeff Settle of Reading University, Prof. Mike Barnsley of Swansea University and Dr Samantha Lavender of Plymouth University for support in defining the scientific programme, and the staff at ESTEC and ESOC, Redu for operation of the instrument in flight.