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Five Years Orbit Experience of a Small Satellite Hyperspectral Imaging Mission

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Abstract

This paper will summarise the results of a hyperspectral imaging mission that has now completed more than five years in orbit and is providing a wealth of data to Users across the world. The mission has demonstrated, fairly conclusively, that such sophisticated payloads can be implemented successfully on a small satellite platform.

The instrument being flown is the Compact High Resolution Imaging Spectrometer (CHRIS) developed within the Optical Payload Group (OPG) of Surrey Satellite Technology Ltd. The instrument is flying on PROBA, a small agile satellite, which was launched in October 2001.

The platform provides pointing in both across-track and along-track directions, for target acquisition and multi-angle observations, particularly for measurement of the Bi-directional Reflectance Distribution Function (BRDF) properties of selected targets.

The instrument covers a spectral range from 400nm to 1050nm, at ≤11nm resolution with a spatial sampling interval at perigee of 17m and programmable band sets. The swath width imaged is 13km at perigee.

Observations requests for the science mission are selected, prioritised and scheduled into feasible observations on a daily basis. The Mission continues to operate successfully even in its sixth year and demonstrates the success of the mission and the utility of the platform and instrument.

1. INTRODUCTION

The Compact High Resolution Imaging Spectrometer (CHRIS) instrument was developed by the Optical Payload Group of Surrey Satellite Technology Ltd (formerly the Space Group of Sira Technology Ltd).

The main purpose of the CHRIS Mission was to provide remote sensing data for land applications. To date much of the usage has been in forest and vegetation classification and coastal monitoring, although a wider range of applications has been explored.

The CHRIS instrument is the principal payload on the European Space Agency (ESA) small satellite platform Proba-1 (Project for On-Board Autonomy). This platform was launched from the Indian PSLV on the 22nd October 2001. It is a highly manoeuvrable small satellite without propulsion, with fine control over yaw, pitch and roll using momentum wheels. The platform is currently orbiting the Earth with an apogee of 684.4km and a perigee of 552.3km.

The CHRIS instrument provides nadir ground sampling of 17m, at perigee; over image areas 13km square and can, depending on the imaging configuration, offer a spectral range from 400nm to 1050nm at a spectral resolution <11nm.

The Proba-1 platform and CHRIS instrument are commanded to provide a set of images of each selected target area for a minimum of five different pointing angles in a single overpass. The five nominal pitch angles are 0°, ±36° and ±55°. The precise observation azimuth and elevation angles are computed after image acquisition and provided with the data files supplied to users. To access the targets the platform can provide roll angles up to ±25° limited by solar blinding of the star trackers. The acquisition of the multi-angular data is of particular interest in analysing the directional effects in the radiance of targets, which can provide useful data on vegetation identification and crop conditions.

The satellite downlink infrastructure includes the ESA ground stations in Redu, Belgium and a ground station in Kiruna, Sweden.

The programme is managed under the umbrella of the ESA Third Party Missions by ESRIN (European Space Research Institute) in Frascati, Italy.

2. SCIENCE OBJECTIVES

The scientific objective of the CHRIS Mission is to provide data on Earth surface reflectance in the visible/near-infrared (VNIR) spectral band, at high spatial resolution but also with multiple view angles. The instrument uses the Proba-1 platform pointing capabilities to acquire Bi-directional Reflectance Distribution Function (BRDF) data (variation in reflectance with view angle) for selected scenes on the Earth surface. This is particularly important, first, to validate existing vegetation models but also as a means of classifying ground cover, crops and forest. Thus the instrument has found numerous applications for land cover assessments. One of the original aims of the mission was to validate techniques for future imaging spectrometer missions, particularly with respect to precision farming, regional yield forecasting and forest inventory. This is now being realised within the observational programme by a number of different researchers. The high resolution of the instrument has also found application in coastal region monitoring and is a useful addition to the data sets provided by MERIS where the sampling distances are 300m.

3. PLATFORM

The Proba-1 platform weighs approximately 100kg, including payloads and measures approximately 60cmx60cmx80cm. The details of the platform are described elsewhere[1]. The spacecraft was designed with a nominal lifetime of two years with the intention to operate Proba-1 in space for one year only. The demand for scientific data from the CHRIS instrument has been so great that an extra five years of post-launch support has been funded by ESA and it is likely to continue for further years as long as the platform remains in good health.

Figure 1 PSLV Launch 22nd October 2001 from Sriharikota Island, India

Proba-1 was launched from Shriharikota in India, aboard an Indian Space Research Organisation (ISRO) Polar Satellite Launch Vehicle (PSLV), see figure 1. The platform orbit is sun-synchronous, with an equatorial crossing time at launch of 10:30.

The orbit is elliptical and at launch the altitude varied between 550km and 670km. Both the semi-major axis and the equator crossing time have shown minimal variation since launch offering relatively stable conditions for Earth observations. However, atmospheric drag makes it impossible to predict more than about one to two months in advance whether a given site will be visible on a particular day. Consequently, TLEs are used to make forward predictions every two weeks. This prediction is undertaken by ESSC, in Reading University, England

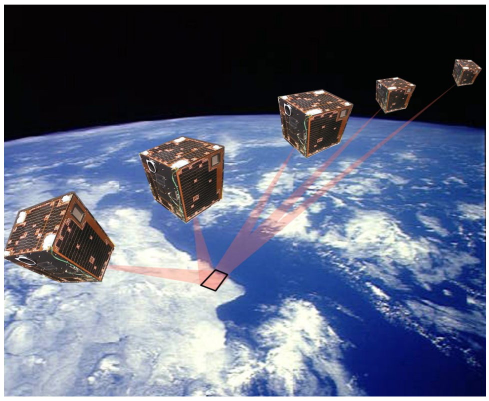

Figure 2 Representation of the multi-angle observation sequence of Proba-1

The platform agility in roll and pitch enables images to be acquired at role angles up to 25º and pitch angles of ±55º for multi-angle viewing, see figure 2. In addition yaw rotation enables a special calibration device to be illuminated by the sun. A further feature of the platform maneuvers is the ability to implement Forward Motion Compensation (FMC) during imaging to enable the CHRIS instrument to enhance signal to noise and increase the number of spectral bands that can be read out. The FMC factor is 5.

4. CHRIS INSTRUMENT

The CHRIS 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 detector is an e2v thinned, back-illuminated, frame-transfer Charge Coupled Device (CCD). CCD rows are assigned to separate wavelengths, and CCD columns to separate resolved points in the Earth image.

As indicated above the platform 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 performance, at the baseline spatial and spectral sampling interval, and to limit internal electronic bandwidths and data rates.

The spectral waveband covered by the instrument is limited, nominally, to the band 415nm to 1050nm, which can be achieved using a single CCD area-array detector.

3.1 Optical Design

The instrument optical design is shown in Fig. 3. It includes a catadioptric telescope and a spectrometer.

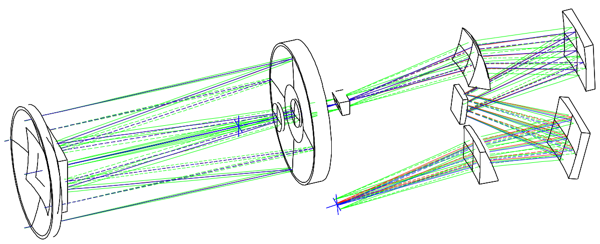

Figure 3 Optical Design

3.2 Telescope

The CHRIS instrument uses a catadioptric telescope design. The focal length of the telescope is approximately 746mm, and the aperture diameter at 120mm (f/6). The axially-symmetrical design allowed conventional construction methods to be applied, it is very compact, and it provides a very broad spectral range without aspheric elements.

3.3 Spectrometer

The spectrometer is a design patented and assigned to SSTL. It uses two Féry prisms (with curved surfaces) integrated into a modified Offner relay – a system of two concave mirrors and one convex mirror. The spectrometer does not have a common optical axis, but all surfaces are spherical, and all centres of curvature are in a common plane. These features are important for minimising cost of optics, and for ease of alignment. Like the telescope, the system is very compact. The spectral resolution of the spectrometer varies from approximately 1.25 to 11.3nm across the spectrum with the highest dispersion at 415nm and the lowest in the near infrared at 1050nm. (In practice the spectrometer can be used at 400nm but has significantly reduced performance.)

The spectrometer design provides registration to better than 5% of the pixel, in both spectral and spatial directions, with spatial and spectral resolution limited essentially by the detector pixel size.

3.4 Detection Electronics

The detection electronics includes:

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

The electronics provides 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 variable widths. Signals can also be integrated 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 and the resulting reduction in readout time is used to increase the number of spectral bands that can be read out.

For each line image (CCD frame) it is possible to read out 18 spectral bands at the highest spatial sampling and the full swath width, plus one band assigned to smear/stray light calibration. However, it is possible to read out much larger numbers of spectral bands with relaxations of spatial resolution and/or swath width. Current user configurations are listed in table 1.

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

Table 1 CHRIS Nominal Operating Modes

Relaxed Ground Sampling Distance (GSD) (associated with increased integration periods) provides enhanced signal-to-noise ratios. Some small variations on the selected band sets defined for each mode have been implemented, for instance to measure Photochemical Reflectance Index (PRI)[2].

3.5 Calibration

Calibration is provided by a mixture of on-ground and in-orbit measurements. (The small platform provides limited scope for on-board calibration facilities.)

On-ground measurements included:

- full aperture radiometric calibration,
- stray light analysis,
- spatial resolution,
- spectral and spatial registration assessment,
- spectral bandwidth characterisation
- wavelength vs. CCD row
- wavelength calibration vs. temperature
- linearity and saturation
- noise measurements

In-flight measurements included:

- DC offset measurements
- relative gain measurements,
- linearity and saturation measurements,
- spatial resolution
- wavelength calibration
- solar calibration
- power consumption

Wavelength calibration was undertaken in flight using atmosphere absorption features, particularly the oxygen absorption band at 762nm. The wavelength of selected spectral bands is temperature sensitive and thus the spectral location of the bands needs to be redefined after image acquisition using details of the instrument temperature, the temperature of the instrument during in-orbit calibration and the wavelength vs. temperature formula. The instrument temperature variation that has to be accommodated is approximately 6ºC.

Dark charge images are acquired on a monthly basis and to date the change in the peak of the distribution is only of the order of ½ electron compared to signal levels of a few thousand electrons. However, the histogram distribution is developing higher counts at larger bin sizes but this typically corresponds to much less than 1% errors.

Vicarious calibration is an essential aspect in establishing confidence in image data sets. This has been undertaken using data recorded in dark and bright scenes of known effective radiance. The work has been supported by two groups of PIs[3,4].

3.6 Physical Characteristics

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.

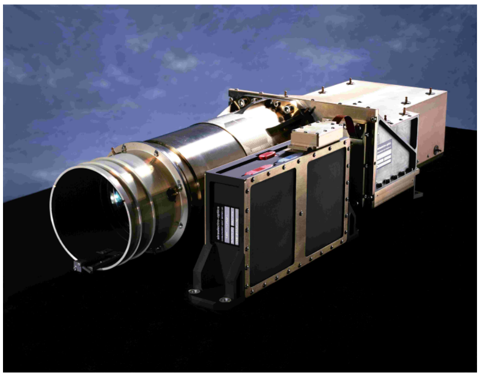

Figure 4 CHRIS Instrument

An illustration of the instrument, comprising the telescope, spectrometer and the electronics box, is shown in Fig. 4.

4. MISSION ASPECTS

4.1 Background

The CHRIS Mission is currently coordinated by ESRIN (European Space Research Institute) in Frascati, Italy under the umbrella of the ESA Third Party Missions. The Proba-1/CHRIS Mission is now in its 6th year of operation and continues to serve the science community with daily images.

4.2 Observation Programme

Image site visibility is calculated by ESSC, Reading University, UK using TLE information. Observations requests for the science mission are selected by ESRIN, prioritised and scheduled into feasible observations on a daily basis by RSAC Ltd, UK. These observations are then compared with a UK Met Office 48 hour cloud prediction product before selecting the preferred image acquisition for each day. Instrument configurations files and target coordinates are then transmitted to the platform from SSTL in Guildford, UK via the ESOC ground station in Redu, Belgium. The platform implements the request and downloads the data to either Redu or Kiruna in Sweden. Redu implements 4 downloads per day and Kiruna 5-6, the latter dependent on the User demand. Data is then transmitted to SSTL for Level 1a processing before being placed on an FTP server for access by the investigators. Quick-look images are also placed on a user accessible website. Other mission details are available on the ESA Third Party Mission Website, which is managed by ESRIN: http://earth.esa.int/missions/thirdpartymission

The daily imaging capacity of Proba-1/CHRIS Mission, with the Redu and Kiruna ground stations, is three image sets (i.e. three sites) of five images every 24 hours, plus a small number of public relation and Disaster Charter images. In total more than 10,000 images have been acquired.

Observations have to be selected with sufficient orbit separation (i.e. longitudinal separation) between consecutive image acquisitions to enable the data from the previous acquisition to be downloaded before new acquisitions are made. For example within a 24 hour period one image set can be acquired over each of the Americas, Europe/Africa and the Far East/Australasia.

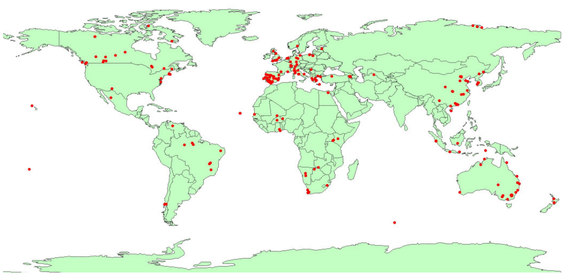

Figure 5 Site location in the 2007 Acquisition Plan

CHRIS observation sites for the science programme are largely located in Europe and North America, see Fig. 5, although, as indicated in the above figure, a smaller number of sites are distributed elsewhere around the globe.

For 2007, the user community has expanded to 87 PIs requiring images over 206 sites in 39 countries. The Proba-1/CHRIS Mission also supports requests from the International Charter with the first image being acquired of the December 2004 Tsunami. To date 510 images have been acquired for the International Charter in support of disaster monitoring campaigns.

5. SCIENCE PROGRAMMES

The science programme has been exceedingly active since 14th May 2002 when the first image was acquired over Venice and to date CHRIS has acquired over 8500 science images. In addition five workshops have been held[5,6], the last in April 2007 at the ENVISAT Symposium in Montreux, Switzerland.
The current CHRIS applications are largely split between land processes and inland and coastal water applications.

Applications include:

- Assessment of forest species and fire hazards
- Assessment and classification of canopy covers
- Land use strategies in Central Namibia
- Chlorophyll & nitrogen status in Uzbekistan cotton fields
- Assessment of shrub abundance in desert grasslands
- Monitoring of biological soil crusts
- In-land water quality assessments
- Bathymetric research & coral reef mapping using novel techniques
- Assessments of semi-arid wetlands.

6. FUTURE PLANS

Proba-1/CHRIS Mission continues into 2007 and hopefully further as long as the platform and instrument continue to exhibit the excellent performance that has been seen over the last 5½ years.

To encourage utilisation of the data sets it has been decided to develop an image processing toolbox, similar to the BEAM Toolbox (www.brockmann-consult.de/beam). Tools that will be provided include:

- Patter noise removal
- Cloud masking
- Geometric correction
- Atmospheric correction
- Aerosol optical depth
- Land surface optical reflectance

A data reader is already available in BEAM ver. 4.

The success of the mission and the continued interest from PIs suggests that constellations of such instrument/platforms could form the basis of future operational programmes with higher repeat capability[7], lower risk and possibly lower overall cost than is feasible with more conventional mission approaches.

7. CONCLUSIONS

The CHRIS Mission is now just completing its sixth year of operation and continues to provide some exceedingly good images for the scientific applications. Whilst the overall cost of the mission is low, compared to conventional missions, the benefit to the users has been high enabling them to acquire valuable data to evaluate algorithms and develop applications that can be explored in more depth in the coming years and on future missions A few examples images are shown below.

8. ACKNOWLEDGEMENTS

The author would like to acknowledge the support of the British National Space Centre, for funding for the CHRIS instrument, the commissioning programme and a software tool development activity, and the European Space Agency, for the opportunity to launch the instrument on Proba-1 and provide funding for five years of operation.

Additional thanks go to Dr Jeff Settle at ESSC Reading University for support in orbital modelling, RSAC Ltd for support in organising the observation campaign, and development of the cloud prediction technique, and to the staff at ESTEC, (Noordwijk, The Netherlands), ESOC, (Redu, Belgium) and Verhaert, (Belgium) for technical support before and during the mission and more recently the support of the staff at ESRIN (Frascati, Italy) who manage the ESA Third Party Missions. Finally, thanks also go to the PIs who have provide some exciting results over the last five years and particularly to Luis Guanter from the University of Valencia, Spain and Heike Bach from VISTA in Munich, Germany for their individual contributions to the calibration validation activities.

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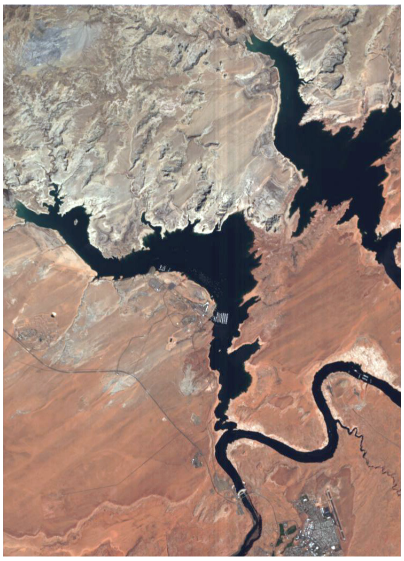

Figure 6 Page, Arizona, USA (13/4/2006)

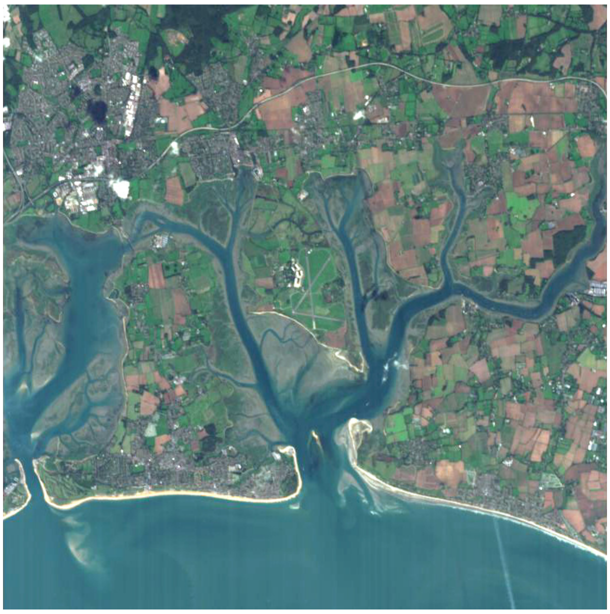

Figure 7 Chichester Harbour, England (7/10/2004)