HRS: A MASSIVE ALONG THE TRACK STEREOSCOPIC CAPABILITY FOR SPOT 5

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SUMMARY:  
To face the increasing needs of Earth observation and to supply the Digital Terrain Models market (DTM), the SPOT 5 satellite, scheduled for launching in November 2001, will carry a High Resolution Stereoscopic instrument (HRS) on board.

In the first part, we will present the market which motivated the development of the HRS system and the main characteristics of its mission.

We will continue with a description of the system and of the HRS instrument, and its integration into the SPOT system.

Finally, we will conclude with a presentation of the characteristics of the HRS products.

1. THE HRS MISSION

1.1. General objectives:

Recent market analyses have shown the interest of stereoscopic imaging and of its by-products, the digital terrain products with decametric accuracy, for the years 2000's and beyond. To meet this market demand, Spot Image proposes on the basis of a common initiative with Matra Marconi Space the development of an HRS system, based on the presence of an optical instrument on board the SPOT 5 satellite, the production of the associated ground segment and the marketing of these products.

The existence of a space available for a passenger on SPOT 5 makes this operation particularly interesting. The project which aims at building a unique offer of Digital Terrain Models (DTM) on very extensive ranges, is supported by existing partnerships with major players in this field such as the French National Geographic Institute (IGN) and DTM and associated product maker and distributor ISTAR company.

1.2 The stereoscopic imaging and DTM market

1.2.1 Market segments

The analysis of the current commercial activity reveals the existence of four main segments for Digital Terrain Models with decametric accuracy:

- the institutional cartography market,
- the Geographical Information System (GIS) market,
- the telecommunication market,
- the Defence market.

1.2.2 Analysis per segment

1.2.2.1 The institutional cartography market

The cartography needs world-wide are substantial: 75% of the land surface remain to be covered by data bases or mapped to a 1:25000 scale, 40% to a 1:50000 scale.

In developed countries, the needs mainly concern 1:25000 scale data (1:50000 scale data are derived
from it). The main problematics is updating existing maps or data bases in the light of the extensive existing sources.

In developing countries on the other hand, the needs mainly concern 1:50000 scale maps considering the scarcity of available financing and of existing maps.

Producing 1:25000 scale maps requires metric resolution images (2 to 3 meters at least) both from the image information content standpoint and from the geometry standpoint, especially for relief plotting. However, 1:50000 scale maps may be produced from lesser resolution images: 2 to 3 meters for planimetric data, 5 to 10 meters for relief plotting.

Thus, the market accessible through a stereoscopic satellite system mainly consists of 1:50000 scale mapping of developing countries. The scarcity of available financing, whether local or from international organisations, makes satellite system-derived offers very attractive, as the prices of satellite systems can be appreciably lower than those of aerial photography techniques.

1.2.2.2 The Geographical Information System (GIS) market

Currently, geographical information systems are developing fast and should continue to grow at a fast pace during the next decade. Apart from urban GISs the needs of which have been assessed both for imagery and altimetry and are more within a very fine resolution range (0.20 - 0.40 m), SIGs involve very diverse applications:

- agriculture (crop forecasting, damage assessment, land use cartography, assessment of agrarian capability, crop monitoring, irrigation follow-up, etc.),
- environment (regional inventories, impact studies, management of natural or industrial hazards - prevention, follow-up of disaster areas, damage assessment, pollution, etc.),
- forests (inventory and assessment of woodlands, identification of species, assessment of wood resources, access protection / management, assessment of domains, etc.),
- geology / hydrology (exploration and follow-up of resources, identification of pollution hazard areas, etc.),
- urban and land use planning (land use maps, land use plans, urban use maps, evolution maps, planning of specific areas, etc.),
- engineering / construction,
- transport, airport platforms, etc.

All of these GISs use to a variable degree images (aerial photographs or satellite pictures) as information sources: updating, evolution studies, multitemporal processing, base map, etc. These uses require a prior ortho-rectification treatment to ensure image-to-image registration or matching between images and vector information with sufficient accuracy, all the more since image resolution is high. The advent of very high resolution satellites and of digital photography is going to make this type of need increasingly common.

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1.2.2.3 The telecommunication market

The telecommunication market associated with the installation of cellular telephone networks is an emerging market currently representing one of the main outlets for DTMs. Players on this market are manufacturers, engineering companies and network operators.

The positioning of a DTM offer derived from satellite images must be defined in relation to competitor sources which are existing maps (low cost, available but often lacking accuracy), aerial
photography and, eventually, metric satellite systems designed for high accuracy and resolution requirements and limited to small surface areas.

1.2.2.4 The Defence market

In the years to come, numerous countries are going to acquire sophisticated defence tools fitted with on-board navigation systems requiring accurate digital geographical data.

The demand essentially involves altimetric information in the form of Digital Terrain Models (DTM) with decametric accuracy.

Extreme attention must be paid to the effective quality of the products and, in particular, to altimetric accuracy, sampling interval (or grid) and quality of model rendering, safety and control of maximum error (for example, for a flight at low altitude or with no visibility).

1.2. Characteristics of the mission and of the products

1.2.1. Main characteristics of the mission

The purpose of the HRS system is to provide stereo image pairs, the Digital Terrain Models (DTM) used for producing ortho-images and any other application requiring knowledge of relief being one of the main by-products. HRS is designed to offer stereo pairs obtained almost simultaneously from the same orbit, which makes it possible to improve the acquisition capability as compared to the SPOT1-4 system.

The maximum length of stereo segments is close to 600 km, and two consecutive stereo segments are spaced 600 km apart at least. These characteristics are illustrated on the figure below.

1.2.2 Acquisition capability

In order to satisfy the market identified, the system is sized to enable total useful acquisitions of 30 million km² over 5 years, i.e. 6 million km² per year. To compensate for losses due to edge effects and the cloud covers, the gross acquisitions required are assessed at 46 million km² per year.

This scenario leads to the following average daily scenario:
- acquisition: 126,000 km²,
- cumulated duration of exposure: 6 minutes,

The HRS acquisition capability could be increased if necessary, by reducing as much other SPOT 5 missions.

1.2.3. Quality of the products

The radiometric resolution and rendering of image contrasts must be able to ensure the location and identification of the details represented on 1:50000 scale maps.

The geometric quality of images must be such that it makes it possible to determine the absolute location of image pixels with an accuracy greater than 1,500 meters (RMS) before calibration.
The quality of DTMs must be such that the expected altimetric accuracy is 10 meters (RMS).

2. THE HRS SYSTEM, OVERVIEW

2.1. The SPOT system

The current SPOT system consists of several satellites (SPOT1 launched in February 1986, SPOT2 launched in January 1990, and SPOT4 launched in 1998; SPOT3 launched in 1993 was affected by a fault in November 1996) and a ground segment the main functions of which are to control and monitor satellites, to acquire image data and to manufacture products. The system will be completed by the launching of SPOT 5 with the HRS system on board.

2.1.1. The SPOT 5 satellite

2.1.1.1 The SPOT 5 service module

SPOT 5 is a new-generation satellite with a housekeeping module derived from the multimission service module used by SPOT 1/2/3/4, ERS 1/2, and the future European satellites ENVISAT and METOP. It will be put in polar sun-synchronous orbit at an altitude of 830 km in November 2001 and will complete the SPOT system: each point on the globe will be passed over at the local solar time of 10:30 am every 26 days. A new flight control mode, the "yaw steering mode" (already used on ERS1 and 2) will allow permanent compensation of the Earth rotation effect on images: in particular, it will make it possible to obtain a better ground coverage of both fore and aft images of the HRS stereo pairs, and will facilitate the management of HRS data in DTM production phases.

2.1.1.2 The SPOT 5 payload

The main SPOT 5 payload comprising two High Resolution Geometric instruments (HRG) will make it possible to obtain 3 m and 5 m resolution images in the panchromatic band, 10 m resolution images in 3 visible bands and 20 m resolution images in the Mid Infra-Red band. This payload is completed by the High Resolution Stereoscopic instrument (HRS) presented below. This will enable SPOT 5 to:

- continue the basic mission while ensuring service continuity to users,
- improve data and service quality by anticipating the improvement of needs of the various users (cartographers, farmers, foresters, geologists, etc.),
- greatly increase the production capacity of Digital Terrain Models.

2.1.1.3 The SPOT 5 ground segment

SPOT satellites are controlled and monitored by the Centre National d’Etudes Spatiales (CNES).

The Operation Control Centre (OCC) is responsible for the technological follow-up of satellites, for their station keeping on the nominal orbit, for receiving housekeeping telemetry and for sending commands via a network of several stations.

The Programming Centre (CPR), managed by Spot Image, is responsible for preparing daily the satellite payload work programme by optimising the use of resources to better meet customer requirements. This work programme is then sent to the OCC and downloaded on board the satellites which run it as required.

Image data is received by two main stations, in Toulouse and in Kiruna. Both stations receive in real time the data acquired by satellites inside their visibility circle but they also receive in deferred time the data recorded elsewhere.

Other stations, called direct receiving stations, can receive in real time the data acquired inside their visibility circle.

As soon as received on ground, the image data is sent to the Archiving and Pre-processing Centre, managed by Spot Image. An identical centre located in Kiruna processes image data received at this station. These centres are responsible for
processing image data, assessing quality (clouds, snow, technical problems, etc.), and archiving them.

The Image Catalogue, managed by Spot Image, is supplied by the Archiving and Pre-processing Centres. It allows users to check whether the SPOT data they are interested in already exists. Otherwise, customers apply to Spot Image which programs the satellites for the acquisition of data corresponding to their requirements.

Image quality is followed up throughout the life of satellites by the System Image Quality Centre which carries out instrument calibration runs to produce the parameters required for image telemetry processing. This centre also conducts investigations on image telemetry in case of an anomaly.

2.2 The HRS system within the SPOT system: interfaces

2.2.1 Interfaces at satellite level

HRS is perfectly integrated with the SPOT 5 payload in which it is considered as a third instrument. It simply uses the resources of the main payload: image compression, coding, memorisation and telemetry.

2.2.2 Interface with the SPOT 5 system development

Although decided upon only recently, the development of the HRS system is in perfect harmony with the development of the SPOT 5 system, in particular concerning development planning thanks to the following conditions:

- interface provisions clearly taken into account in the current SPOT 5 satellite definition,
- limited number of interface adaptations both on the satellite and the ground segment because of the similarity between the HRS instrument and the HRG instruments,
- start-up as early as possible in the development of the HRS instrument to minimise the impacts on satellite development,
- very high “commonality” between the HRS and HRG image ground segments. The development plan for the HRS ground segment is fully integrated with the one for the SPOT 5 ground segment.

2.2.3 Operational interface with SPOT 5 programming

As HRS is an instrument without a side deflection, the programming function is limited to the definition of acquisition segments on satellite track while taking weather forecasts into account. The requirements concerning the "validation loop" are much more flexible than for the HRG, considering the systematic time interval of 26 days between two exposure occurrences on the equator and of 5 days at high latitudes.

In addition to HRS, the acquisition planning of large stereo coverages will comprise HRG instruments, and the instruments of other satellites SPOT 1, 2 and 4 (side stereo), as well as other sources (SAR interferometry, radargrammetry, map digitising, etc.), in order to complete the coverage following a number of unsuccessful HRS attempts (residual clouds, etc.). It is estimated that, on average, 80% of HRS images contribute to the production of DTM data bases and 20% are DTMs derived from other capture sources.
2-3 The HRS instrument

2.3.1 Architecture and functional subassemblies

The architecture of HRS instrument is briefly described through the diagram given hereafter:

The HRS instrument functions are provided by the following functional subassemblies:

- *The optical subassembly*: it collects the light flux from the panchromatic band and focuses it on detector lines. It filters any flux outside the panchromatic band to minimise interference fluxes.

- *The detection chain*: it converts the light signal into electrical signals, dynamic adaptation, digitising of signals and their transmission to payload telemetry in a defined format.

- *The structure*: it provides an interface with the SPOT 5 satellite, mechanical control of equipment and stability performance between items of equipment.

- *Thermal control*: it maintains the various instrument components within the temperature ranges compatible with their implementation and performance and provides thermal decoupling with the satellite.

- *The management and housekeeping electronics*: it provides an interface with the SPOT 5 satellite data artery, implementation of modes, monitoring and active heat control of the instrument.

These functional subassemblies are briefly described by the diagram below:

2.3.3 Characteristics of the exposure:

They are summarised in the table below.

<table>
<thead>
<tr>
<th>Parameters of the images</th>
<th>Characteristics of the images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pixels per row</td>
<td>12000</td>
</tr>
<tr>
<td>Ground size of pixels</td>
<td>row, 10 m column, 5 m</td>
</tr>
<tr>
<td>Viewing angle</td>
<td>+20° (fore camera) -20° (aft camera)</td>
</tr>
<tr>
<td>Spectral range</td>
<td>0.48 µm - 0.70 µm</td>
</tr>
<tr>
<td>Minimum observable luminance</td>
<td>L1 = 20</td>
</tr>
<tr>
<td>Maximum useful observable luminance</td>
<td>L4 = 379</td>
</tr>
</tbody>
</table>

The diagram below shows the effect of sampling every 5 m on the ground along the track.
The deliberate choice of not having an out-of-track sighting capability available, for simplification reasons, imposes a minimum ground coverage greater than 109 km at the SPOT separation between track (choice 120 km) to ensure access to any point on the earth surface.

As fore and aft cameras of the HRS instrument located at an altitude of 830 km are tilted by + and - 20° respectively in relation to the nadir in the track direction, the maximum length of stereo segments is around 600 km, and two consecutive stereo segments are spaced 600 km apart at least. These characteristics are illustrated in the figure below.

Thus, an HRS segment has the following maximum characteristics:
- coverage: 600 x 120 km², i.e. 72000 km²,
- duration of exposure: 3 minutes,
- memory volume taken on board following compression: 18 Gbits.
3.2.1 Radiometric pre-processing of received images making up stereo pairs

3.2.1.1 Requirements for radiometric pre-processing, calibrations:

For each camera, the following values are defined:

- \( G_m \), the analog gain \( m \) of the electronic amplification chain (8 possible values, among which the reference gain \( G_3 = 1 \)) (measured before firing)

- \( A \), the absolute calibration coefficient of the spectral band considered (\( \text{Wm}^{-2}\text{sr}^{-1}\mu^{-1} \)) (measured before launch: arithmetic mean of all pixels at the reference gain, after subtracting the darkness signal, and dividing by the equivalent luminance with:
  
  \[ + C_{nbm}, \text{darkness residues:}\] average value sent by pixel \( n \) of register \( b \) immersed in darkness at a given analog gain \( G_m \): they are measured before launch and once a week by darkness image taken at all gains in operational phase (average according to the columns of each detector on the image)

- \( + L \), equivalent luminance: luminance of the entire landscape with an atmosphere on a given frequency interval

- \( \Upsilon_{mb} \), the cross-register levelling coefficient of register \( b \) (4 registers per CCD strip) for each value of the analog gain \( G_m \) to compensate for differences between registers (measured before firing, and on uniform sites in operational phase at gains \( G_m \) not leading to image saturation)

- The list of atypical pixels (pixels with radiometry which is not representative of luminance): list provided before launch, if any, and in operational phase

- Cross-calibration of fore camera / aft camera: obtained from a high number of comparisons of the radiometry of images acquired simultaneously by both cameras from varied landscapes to fully take into account possible spectral differences (one run every 3 months).

All these elements make it possible to model radiometry \( X_{nbm} \) of each pixel \( n \) in register \( b \) at gain \( G_m \) by:

\[ X_{nbm} = A.G_m.Y_{mb} \gamma_{nbm} \cdot L + C_{nbm} \]

3.2.1.2 Radiometric pre-processing of images:

Its purpose is to obtain, from raw images received, a corrected \( Y \) radiometry image of detector levelling, directly representative of equivalent luminance \( L \) of the landscape observed in the band considered, by a relation of the type:

\[ Y = A.G_m.L \]

This radiometric pre-processing therefore consists, for each raw image pixel, in:

- subtracting darkness residues, and dividing the result by the product of cross-register and cross-pixel levelling coefficients (within the same register):

\[ Y_{nbm} = \frac{(X_{nbm} - C_{nbm})}{\Upsilon_{mb} \times \gamma_{nbm}} \]

- interpolating each atypical pixel, if any, from neaby pixels.

3.2.2 Radiometric processing of radiometric pairs for the preparation of DTMs

The general principle for calculating the altitude, finally provided by the DTM for each of the points taken into account, is the following iterative process:

- choice of a grid unit: raw and column interval, its size depending on previous knowledge and on the type of terrain (very coarse for slightly uneven terrain),

- search for the best complementary image point: search for the best radiometric correlation between the quick look image surrounding a point on the first image of the pair and the picture surrounding the point supposed to be identical to the second image of the pair (filtering makes it possible to eliminate dubious points which do not correspond to a well "plotted" correlation),
- smoothing: taking into account of adjacent points to enhance the location accuracy of complementary image points when the correlation of these adjacent points is good, and interpolating this location where correlation is bad.

- DTM calculation (determination of local altitudes): obtained by identifying shifts generated by the parallax effect. If the density of complementary image points is insufficient, the process is reiterated with a finer grid unit (provided that image "sharpness" resulting from the Modulation Transfer Function and the signal/noise ratio allows it).

HRS DTMs will be delivered in the form of data bases exactly covering the area of interest to the customer. A DTM mosaicking and trimming process will be carried out.

The altimetric accuracy of HRS DTMs will be between 5 and 10 meters RMS (AC).

3.3 HRS DTM: quality assurance

As the altitude restitution accuracy greatly depends on the quality of images correlated, the Modulation Transfer Function (characterising image sharpness) and the signal/noise ratio have already been closely followed up during the instrument definition phases.

In addition, HRS provides a quality assurance plan which extends far beyond the HRS system limits to encompass DTMs.

In other words, this means that the technical characteristics of the most important HRS images in terms of DTM accuracy and reliability (MTF, S/N, internal consistency, location, etc.) will be the subject of a follow-up and an ongoing assessment by the CNES/ QIS (Image Quality Control Center). This cell will forward back to DTM producers the calibration data necessary for taking images into account in an optimum manner.

That way, HRS DTM users will be guaranteed a perfect consistency of data and process throughout the manufacturing circuit.

CONCLUSION

The HRS instrument, the result of a triple co-operation between MMS, Spot Image and the CNES, is designed so as to minimise the cost of DTMs obtained:

- by reducing the development time and related risks using simple concepts, tested technologies and recurrent elements from HRG instruments,
- by simplifying the interfaces and adaptation on the satellite. HRS is like a third instrument providing an additional data flow at the input of the image chain on board due to its similarity with HRG instruments. The HRS mission shares the use of the SPOT 5 payload telemetry resources with the main HRG mission,
- by limiting the impacts on satellite development and, in particular, on the development of case structure and TMCU modules.

The HRS initiative is likely to make SPOT 5 the most complete and efficient Earth Observation satellite of its time. Its purpose is to provide the user community, whether cartographers or not, with altimetric data

- at controlled quality,
- available on very extensive areas,
- at a minimum cost.

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