TOPOGRAPHY OF GLACIERS AND ICE CAPS WITH SPOT 5 HRS

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ABSTRACT:

Monitoring the evolution of glaciers, ice caps and ice streams in polar areas is of outmost importance because they constitute a good indicator of global climate change and contribute significantly to ongoing sea level rise. Accurate topographic surveys are crucial as they reflect the geometric evolution of ice masses. Unfortunately, the precision and/or spatial coverage of available data from satellite missions (radar altimetry, ICESat) or field surveys is generally insufficient.In 2006, a pilot project led by Spot Image and IGN showed that SPOT 5 stereoscopic pairs could provide 40m Digital Terrain Models of the Antarctic Peninsula and Alaska within an absolute horizontal precision of 30m RMS.In 2007, the French Space Center (CNES) decided, within the framework of the International Polar Year and the GIIPSY project, to fund the SPIRIT (SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies) project, a huge HRS coverage of polar areas. Thanks to this program, jointly managed by Spot Image and the LEGOS, the opportunity is given to the Scientific Community to browse a massive archive of stereoscopic pairs and to freely obtain large amounts of DTMs over the polar areas. This paper will present the stereoscopic coverage achieved so far over Northern and Southern polar areas up to 81°N/S. We will also describe in details the Polar DALI web interface and the specific SPIRIT product.
The conclusion will summarize the impact of the availability of such high accuracy elevation data on glaciology research.

1. INTRODUCTION

During the last two decades, the cryosphere has been the theatre of rapid and major changes. Shrinkage of mountains glaciers and ice caps have accelerated during the past ten years, with a contribution to sea level rise growing from 0.33 mm per year (for the 1961-1990 period) to 0.8 mm per year (for the 2001-2004 period) (Kaser et al., 2006). Break up of Larsen A and B ice shelves in the Antarctic Peninsula have led to the thinning and acceleration of the glaciers located upstream (De Angelis and Skvarca, 2003; Rott et al., 1996; Scambos et al., 2004). Major changes in the ice dynamics have also been recently detected in Greenland, leading to rapid ice loss (Howat et al., 2007; Joughin et al., 2004; Rignot and Kanagaratnam, 2006). Thus, the cryosphere appears as one of the major actor and indicator of ongoing climate change (IPCC International Panel on Climate Change, 2007).

Yet, the topography of glaciers, ice caps, ice shelves of both polar areas remains poorly known. Obtaining a homogenous and precise topography of these remote regions is a top-priority task to understand and characterize their reaction to recent climate change and their contribution to ongoing ocean level rise (Cazenave, 2006). A reference and comprehensive topography of these regions is also necessary to detect future evolutions. Furthermore, as the topography of ice masses is a free surface resulting of external forcings and physical processes within the ice (Remy et al., 1999), it can be used to test ice dynamic models or as an initial condition to predict their evolution (Remy and Parrenin, 2004; Ritz et al., 2001). Its knowledge is also crucial for accurate dating of ice cores (Parrenin et al., 2004).

The topography of polar ice masses is still poorly known because *in situ* observations are difficult and sparse. Space-borne measurements of the ice topography are also difficult and not always a priority. For example, Polar Regions were not surveyed by the Shuttle Radar Topography Mission (SRTM) in February 2000 (Rabus et al., 2003). Satellite radar altimeters on-board ERS1, ERS2 and Envisat have the capability to measure the surface elevation of large ice masses with a resolution of about 1 km and a good relative precision as soon as the slopes are gentle (Legresy et al., 2005; Shepherd and Wingham, 2007). But this technique is not effective for steeper areas and, thus, cannot accurately map the coastal regions of the two ice sheets or most mountains glaciers and ice caps. The GLAS (Geosciences Laser Altimeter System) instrument on ICESat surveys altimetric profiles with a laser footprint of 65 m every 170 m along track. Its revolution period lasts 183 days, which implies a distance between two consecutives tracks varying from 2.5 km at latitude of 80° to 15 km at the equator. GLAS provides very accurate (+/- 10 cm) but sparse measurements of ice surface elevation.

Despite the strong albedo and the lack of texture of snow or ice, stereoscopic optical images have already proved to be a valuable mean to obtain large-scale topographies of ice masses (Berthier et al., 2004; Stearns and Hamilton, 2007). In particular, good results have already been obtained over Alaska icefields and the Antarctic Peninsula during preliminary studies

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using the HRS sensors on-board SPOT 5 (Berthier and Toutin, 2008; Durand, 2006). Following these promising results and to contribute to the International Polar Year (IPY), the French space agency (CNES), Spot Image and the LEGOS (Laboratory Studying Geophysics and Oceanography from Space) decided to launch the SPIRIT (SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies) project. The goal of the present article is to describe the SPIRIT project and demonstrate the high glaciological potential of the SPIRIT data.

2. THE SPIRIT INTERNATIONAL POLAR YEAR PROJECT

The main aims of the SPIRIT project are (1) to build a comprehensive archive of polar ice based on SPOT 5 HRS images and (2), for selected regions, to produce DTMs and ortho-images that will be delivered for free to the scientific community involved in IPY projects. In this section, we will first present the SPOT 5 HRS sensors. We will then describe the target areas and the acquisitions obtained so far (as of 17 April 2008) before presenting the Polar DALI web interface designed to browse the archive. At the end of this section we will provide the characteristics of the SPIRIT product (DTMs and ortho-image) that is going to be delivered to the scientific community.

2.1 The HRS sensors onboard SPOT 5

The HRS sensors, embedded on SPOT 5, were designed for DTM generation by acquiring pairs of images in a single pass of the satellite. It is composed of two telescopes, respectively pointing with an angle of 20° rear and 20° front from the satellite vertical, providing a base-to-height ratio of 0.8. A 600 km by 120 km stereoscopic pair is captured within 180 seconds (Fig. 1), with a ground resolution of 5 m along track by 10 m across track. The acquisition mode is panchromatic (0.48 µm - 0.71 µm).

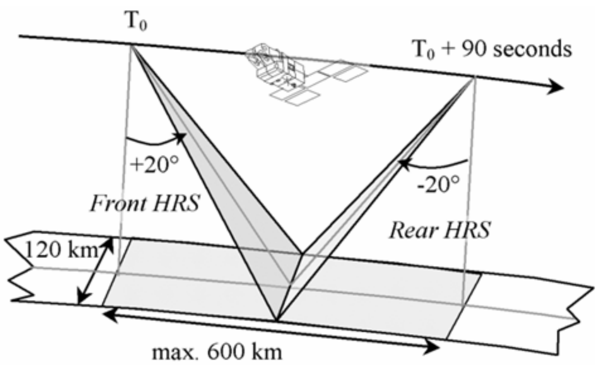

Figure 1. SPOT 5 HRS sensors acquisition process

The relative precision and the radiometric homogeneity are enhanced by the simultaneity of the acquisitions, implying that the textures, illumination, orbital and altitude parameters are the same for both images. Over ice-free landmasses, HRS provides DTMs with a vertical accuracy of 10 m with 90% confidence on slopes less than 20% (Bouillon et al., 2006).

Finally, thanks to the onboard stellar location unit, using star-tracker data (good low frequency accuracy) and gyroscopes data (good high frequency accuracy), the final absolute location precision is 30 m rms.

A more detail description of the SPOT 5 HRS satellite mission can be found elsewhere (Bouillon et al., 2006).

2.2 Building a SPOT 5 HRS archive over polar ice masses.

The first step of the SPIRIT project was the selection of target areas and the definition of their relative priority by the LEGOS (Principal Investigator) in the framework of the GIIPSY (Global Interagency IPY Polar Snapshot Year) project. One major constrain was the 81.15° North – 81.15° South acquisition limits of the SPOT 5 orbit. The flat, snow-covered and homogenous central regions of the Antarctic and Greenland ice sheets were deliberately excluded of the target areas because DTM derived from stereoscopic optical images would not reach the centimetric accuracy already obtained using radar or laser altimetric surveys.

Thus, three majors groups of target areas were considered: the coastal regions of Antarctica, the margins of the Greenland ice sheet and small glaciers and ice caps that surround the Artic ocean and Antarctica. Overall, these three groups encompass more than 2.5 millions square kilometers. These 108 target areas were classified using three different priority degrees (Fig. 2 and 3):

Top Priority: Very sensitive areas in Greenland, Antarctica and fast changing ice caps and icefields (Pine Island Glacier, Jakobshavn Glacier, Patagonian Icefields, Vatnajökull ice cap etc.).

Important Priority: All other major ice streams of the two inlandsis, draining most of the snow of the accumulation areas, whose dynamics is crucial for the mass balance of the polar ice sheets. Identification of all these major outlet ice streams was possible by the mean of SAR velocity mosaics (Rignot, 2006; Rignot and Kanagaratnam, 2006) and also two image mosaics derived from MODIS data (Scambos et al., 2007). This medium priority level encompasses also some small glaciers and ice caps where fast evolutions have been reported (Alaska, Iceland) or poorly known ones such as Vilchek land Ice cap, Franz Josef Land (Dowdeswell, personal communication).

Standard Priority: Remaining areas at the periphery of the Greenland and Antarctic ice sheets and the other ice-covered regions close to the poles of both hemispheres.

The priority levels can be changed in the course of IPY if needed, in case of spectacular events (ice-shelf break-up for example). Few areas can be acquired twice in order to study their quick (one year) evolution. The Antarctic Peninsula has already been surveyed by SPOT 5 HRS in 2006 and will probably be re-surveyed during the second year of IPY in 2009. This is why it was not included in the first southern hemisphere acquisition campaign.

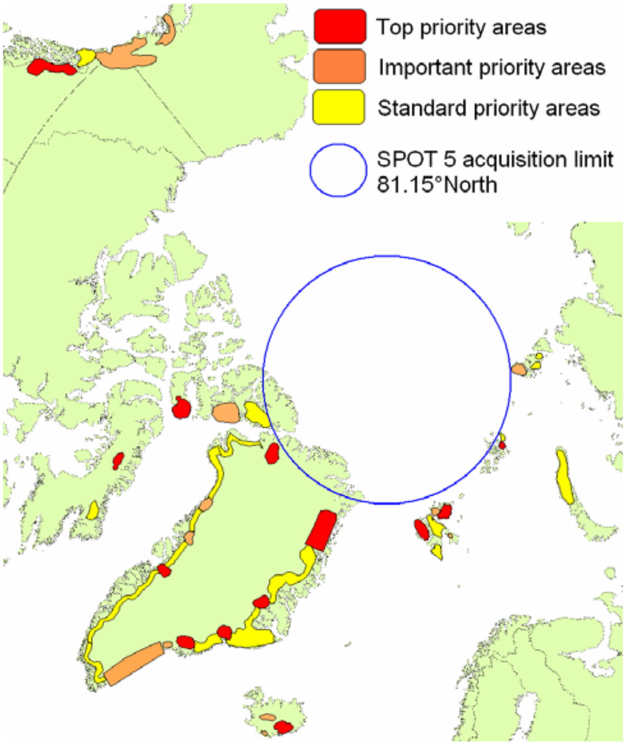

Figure 2. 43 areas of interest delimited in the Northern hemisphere. They cover about 680000km² (see details in Table 6).

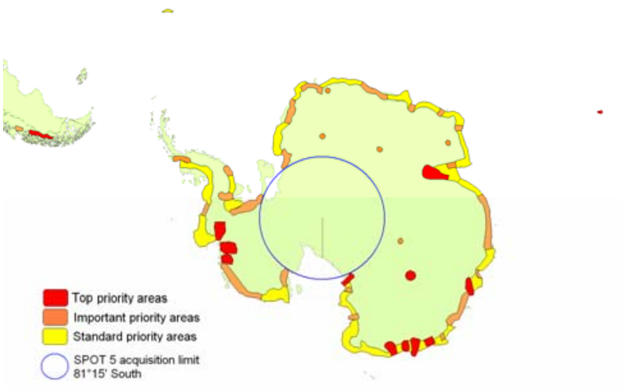

Figure 3. 65 areas of interest retained in the Southern hemisphere. They cover about 1900000km² (see details in Table 7).

The SPIRIT project started the 1 July 2007 and SPOT 5 HRS images will be acquired until 30 April 2009. The acquisition periods for each hemisphere have been chosen to cope with the polar night: June to November for Northern areas, December to April for Southern areas, with local variations according to latitude.

The nominal revisiting period of HRS, considering its along-track acquisition mode, equals 26 days. However, the orbit tightening at high latitudes leads to a briefer delay (sometimes 1 or 2 days) between two acquisitions. Despite some difficult weather conditions, this explains why a significant coverage has already been achieved during the first months over both hemispheres.

Discriminating snow from cloud is really a tough task, almost impossible for the current automatic algorithms, and thus, must be performed by a human operator. To optimize the acquisition campaign, cloud detection needs to be performed on a daily basis. Indeed, once a target region has been covered by cloud free images, it has to be immediately excluded from the satellite schedule so that the satellite resource is devoted to other programming tasks.

Another key issue is the appropriate setting of the HRS sensor gains. The generation of DTM from optical stereo-images is only possible if the radiometric range of the images is sufficient to find homologous points using a correlation window, which implies that the gain must not be too high (images would be saturated) nor too low (too limited radiometric range). Considering a snow-covered Earth surface (albedo of about 0.9), the best sensor gain is evolving depending on the time of year and the latitude (Raup et al., 2000). Consequently, the gain setting is modified on a weekly basis for each areas of interest in order to insure the best correlation score during the DTM production phase.

The cloud-free coverage achieved during the summer 2007 campaign in the northern hemisphere is presented in Fig. 4. About 44% of the total arctic targeted surface (~ 300 000 km²) was covered between 1 July and late October 2007.

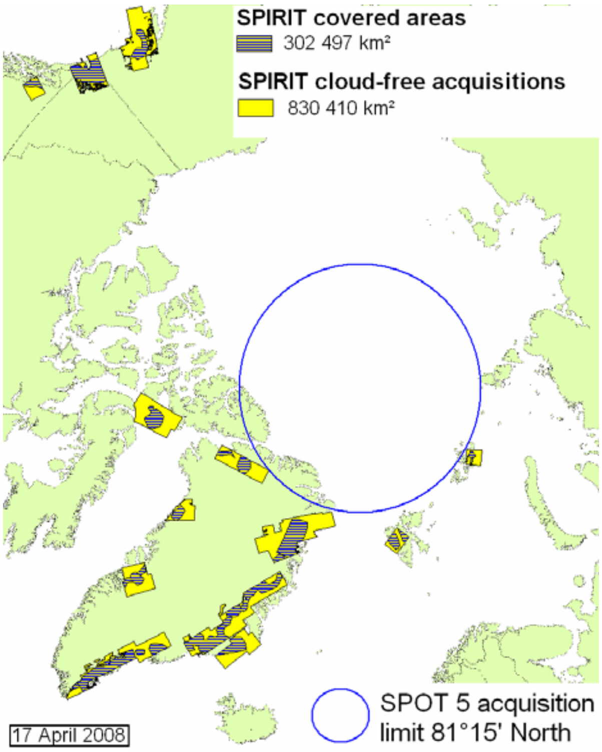

Figure 4. North hemisphere Spot5 HRS coverage during the 2007 acquisition campaign.

The ongoing Southern campaign (December 2007 to April 2008) is even more successful (Fig. 5). As of 17 April 2008, 77.21% of the targeted areas have already been covered (about 1 480 000 km²). This is due to the absence of conflicts in the daily use of SPOT 5.

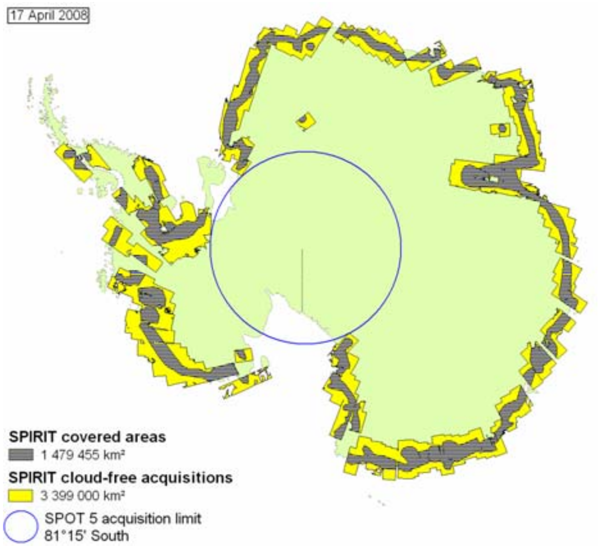

Figure 5. South hemisphere Spot5 HRS coverage achieved so far (as of 17 April 2008) during the 2007-2008 austral summer acquisition campaign.

The details of both campaigns are given in the Table 6 and 7, which gives the area covered for each priority level in each hemisphere and the number of attempts (60*120 km scenes).

Priority	**1**	**2**	**3**	**Total**
Area of interest (km²)	179 925	187 615	312 608	**679 518**
Covered area (km²)	122 965	91 647	87 885	**302 497**
Coverage rate	68.58%	48.85%	28.11%	**44.52%**
Attempts number	140	123	46	**309**

Table 6. Coverage achieved so far during the first SPIRIT collection campaigns in the north (July to October 2007) hemisphere.

Priority	**1**	**2**	**3**	**Total**
Area of interest (km²)	330 040	596 844	989 384	**1 916 268**
Covered area (km²)	272 240	523 650	683 565	**1 479 455**
Coverage rate	82.49%	87.74%	69.09%	**77.21%**
Attempts number	288	811	1 013	**2 112**

Table 7. Coverage achieved so far during the first SPIRIT collection campaigns in the south (December 2007 to April 2008) hemisphere.

Thus, as of 17 April 2008, 1262 stereoscopic pairs have been collected by SPOT 5 HRS. All the quick-looks are available for online consultation on the project dedicated interface: Polar DALI.

2.3 The Polar DALI Interface

The SPIRIT quick-looks (HRS images in lower resolution: 120 meters) can be browsed through the Polar DALI interface. The access is possible through a valid login, delivered to the laboratories upon demand to the CNES International Polar Year team on hrs_ipy@cnes.fr

The Polar DALI webpage, http://polardali.spotimage.fr:8092/IPY/dalisearch.aspx contains the login entry box and is separated in three main parts:

1. General parameters.
2. Region of interest.
3. The output format. Note that the results can be directly displayed under Google Earth.

A short tutorial is also available to facilitate the first image requests.

Once the laboratory has investigated the catalogue and selected its desired images, he can fill an order form to launch the production of a SPIRIT DTM over his area of interest, if his application is accepted by CNES. The SPIRIT product is delivered through ftp.

2.4 The SPIRIT Product

The SPIRIT product has been specifically designed to serve glaciology applications, providing reference topography and ortho-image. It is composed of 2 digital terrain models (DTMs) computed using different sets of correlation parameters adapted to different type of relief, the 2 reliability masks (one for each DTM) and one 5-m ortho-image. The SPIRIT product is derived from a single-date stereoscopic pair only at the French mapping institute (IGN).

The DTMs has the following properties:

1. A 40-m posting interval.
2. The DTM is “no hole” (non-correlated pixels have been interpolated).
3. The DTM is delivered under a DIMAP Geotiff format.
4. The absolute horizontal precision is estimated to be 30 m rms (Bouillon et al., 2006).

The reliability masks assume the following criterions:

1. They indicate the correlation score during DTM generation from 0 to 100.
2. Interpolated pixels are reported with a score of 0 so that they can be easily identified in the DTM.
3. The masks are point-to-point superimposable with the corresponding DTMs.

Finally, the ortho-image presents the following characteristics:

1. Computed from one of the HRS images.
2. 5-m resolution.
3. Same absolute horizontal precision as the DTMs (30 m rms).

The SPIRIT DTMs result of a predefined, automatic processing method developed at IGN (Bouillon et al., 2006), including no manual intervention and no check against any kind of ground truth. Fusion between DTMs from different dates is not included. The original HRS stereoscopic pair (raw data) is not delivered.

3. CONCLUSION

During the international polar year, the SPIRIT project (SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies) supported by CNES, Spot Image and LEGOS allows building a massive high-resolution archive of Spot5 HRS images. With the contribution of the French Mapping Institute (IGN), DTMs and ortho-images will be generated from these pairs of stereoscopic images for selected target areas and will be delivered for free to the scientific community. The SPIRIT project will thus contribute to improve our knowledge of the topography of the polar ice masses. Together with other IPY satellite acquisitions coordinated by the GIIPSY program, SPIRIT will permit to build an IPY snapshot of the poles in order to assess recent and future evolution of the polar cryosphere.

In the coming months, our efforts to validate SPIRIT data will go on. In the Northern hemisphere, we will use the ICESAT 3I laser period that was active just a few weeks after the summer 2007 SPIRIT campaign. We will also analyze DTMs generated from HRS stereo-pairs acquired on the less-textured landscapes of Antarctica to test whether the promising result obtained in the Northern Hemisphere are confirmed. We also invite all users of the SPIRIT products to assess and report on its accuracy through comparison with their own data derived from other space-borne sensors or collected in the field during IPY.

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