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A Multi-spectral Stereo Method to Retrieve Cloud top Height applied to Geostationary Satellite images

Anna Anzalone, Francesco Isgrò

Abstract: *In this paper we present a method to retrieve the Cloud Top Height (CTH), that is a refined version of a stereoscopic method present in literature. It is applied to stereo image pairs obtained by observations of the Meteosat Second Generation (MSG) geostationary satellites in a stereo setup. The performance of the method is tested both as mono band and multi spectral stereo. The estimated CTH are compared with the cloud altitude maps provided by the MODerate resolution Imaging Spectroradiometer (MODIS) on Terra-Aqua polar satellites. The results show that the new version of the method, performs better in comparison with the original algorithm despite the not proper stereo features of the system.*

Key words: *Clouds, Infra Red Images, Multi-spectral Stereo*

INTRODUCTION

Clouds have a relevant impact on weather and climate systems for their influence on the radiative balance and global climate changes and in general on the radiative processes. CTH estimation in particular provides information on cloud vertical structure that improves the knowledge of the cloud radiative effects. CTH evaluation is important not only for meteorologists but it is also matter of interest in very different frameworks such as the JEM-EUSO (Japanese Experiment Module-Extreme–Universe Space Observatory) mission [1] whose main objective is to detect from space, Extreme Energy Cosmic Rays with energy above $5*10^{19}$eV. The presence of clouds can affect the detection if the phenomena appear beneath the clouds. For this reason an infra red camera has been designed taking into account the possibility of using several different ways to retrieve the required atmospheric information even by stereoscopic approach.

Being aware that methodologies for CTH retrieval can have applications in contexts that do not have all the information provided by the meteorological instruments [10], we have focused our attention on a method that is mainly geometric. A stereo method in fact uses two different images of the same scene acquired from space and exploits the parallax between the two images to reconstruct the cloud altitude. The algorithm we present in this work, is based on [4], and some improvements are here presented and discussed.

STEREO METHOD

During the last twenty years the stereoscopic method from space has been studied and improved thanks to new polar multi-view instruments, faster scans and higher pixel resolution of the geostationary satellite devices [3,7,5,6,8,2]. While the common radiative methods depend on accurate radiometric calibration and need of additional information, the CTH stereo retrieval has the characteristic of being independent of information regarding cloud/atmosphere parameters apart from the ones retrieved from the image processing and from the geometry of the stereo system. However it is dependent on an accurate image analysis and on the geometric relationships of the cloud features.

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Standard stereo vision in general attempts to infer information on the 3-D structure [11,9], from two images taken by spatially separated cameras. Image processing algorithms are applied to extract the 3-D information. The consequent parallax effect is used to reconstruct the *depth* information, i.e. the distance of the object from the visual sensor.

Remote sensing measurements of CTH can be done by different stereo configurations both with geostationary and polar satellites. Geostationary orbiters can be coupled in such a way that the intersection of both field of views, provides quasi synchronous stereo pairs of the same scene. Binocular stereoscopy is also obtained by some polar satellites having onboard instruments designed for this purpose (MISR/Terra-Aqua, ATSR2/ERS-2). Whereas in case of monocular vision, stereo views can be obtained exploiting the movement of the camera (satellite motion) with respect to a static object as in [1]. The proposed method to retrieve CTH can be applied to both cases.

The main task of stereo CTH retrieval is the 'matching' step that identifies the same features in the two views and for each, estimates the parallax effect. This is revealed on the images as an apparent displacement called *disparity* and it depends on the cloud height. In the ”monocular stereo” the accuracy of the determination depends also on the temporal distance of the acquisitions, in fact the closer in time they are, the more similar are both views. Conversely the time delay should imply a baseline long enough to retrieve the most part of the range of cloud heights in the scene. After having found the disparity and hence the projection points of the observed cloudy pixel, the reconstructed optical rays are triangulated for the final depth reconstruction (Fig.1). In the next section the details of the algorithm are described.

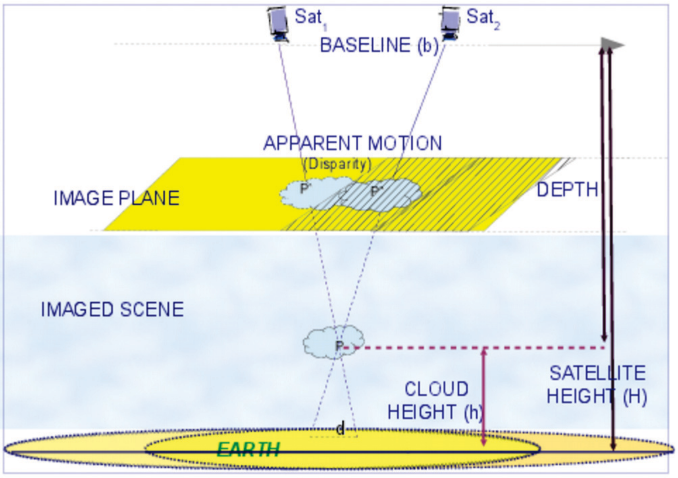

Figure1. Stereo Reconstruction. The scheme shows the height reconstruction for the cloudy pixel P. Its projections P' and P'' are detected by means of the retrieved disparity and the depth its recovered by triangulating the optical vectors. Finally the height is calculated by subtracting these values from the satellite altitude. The multi band stereo acquisition is highlighted by the grid/no-grid on the cloud.

STEREO ALGORITHM

A refined version of the algorithm in [4] has been tested for this work. The method presented by the authors is a multi-spectral stereo algorithm and here it is a brief description. It is based on the idea that the height can be estimated using a coarser resolution than the single pixel, because the CTH is better determined for a cloud layer assuming that in small areas pixels having same temperature are very likely to have the same altitude.

Each member of a stereo pair is segmented in regions by splitting in sub- intervals, the range of the pixel Brightness Temperatures (BT). The height dependent disparity, will be assigned to each region by the next matching step. In the original version of the algorithm (OA in the following) the range of BTs is split by using the absolute minimum temperature as inferior bound. While an increasing value, as superior bound, is calculated adding a fixed step to the minimum, until the maximum BT is reached. In this way the image is segmented by a region growing process that creates an amount of binary masks with increasing areas till to obtain the whole image. If N is the number of sub-intervals, M the resulting masks, I the BT image, p a pixel of the image and finally t_{min} the minimum temperature, the masks are obtained as follows:

$$M_{ji}(p) = \begin{cases} 1 & \text{if } t_{min} <= I(p) <= t_i \quad t_i = t_{min} + i * step \quad j = 1,2 \quad i = 1,..,N \\ 0 & \text{otherwise} \end{cases}$$

Each mask of a member of the stereo pair is then matched with the corresponding one obtained for the other image.

Instead of using a growing strategy of the regions, in this article a different technique is implemented. Both the lower and the upper limit change for each interval, so that the whole range of values is evenly split into separated sub-ranges of temperatures.

$$M_{ji}(p) = \begin{cases} 1 & \text{if } t_i <= I(p) <= t_{i+step} \quad t_i = t_{min} + i * step \quad j = 1,2 \quad i = 1,..,N-1 \\ 0 & \text{otherwise} \end{cases}$$

In this way the selected masks do not include pixels of the other masks and detect different areas in the image (Fig.2). This mechanism avoids that pixels of different cloud levels contribute to the mask matching, affecting above all the matching of the last masks when the hottest pixels are added. The results are discussed in the next section.

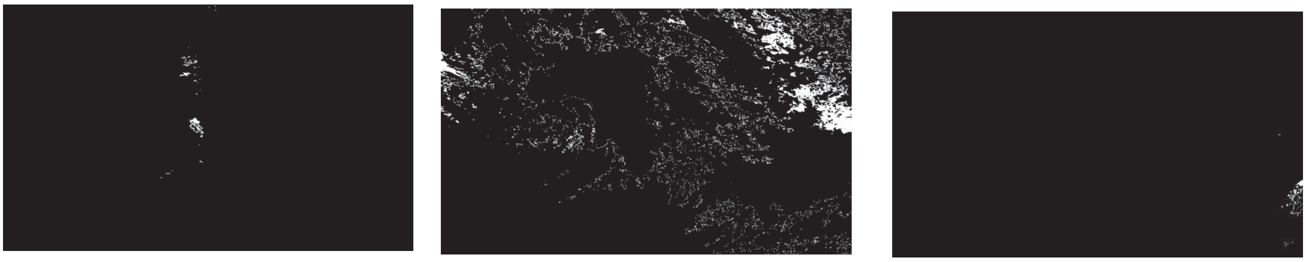

Figure2. Segmentation and binary masks referring to the left image in Fig.3. Left. Mask corresponding to the BT interval 214-216K, (coldest clouds). Centre. Mask corresponding to the BT interval 246-248K (mid level clouds). Right. BT interval 299-302K corresponding to the land area.

A further change was also introduced in the disparity retrieval. A bi-directional matching is applied, matches are looked for by treating the masks of the first image as reference and those of the second as search masks and viceversa. For each pair of corresponding masks the disparity is reconstructed as the geometrical translation applied to the mask of the reference image and maximising the overlap between the two masks. In the end two disparity maps are retrieved. The possible dissimilarities are then detected by the *consistency check method* widely used in stereo matching. In our case the method considers the two estimated disparity maps d_{12} and d_{21} and for each pixel *p* it produces a disparity value *d,* as follows:

$$d(p) = \begin{cases} d_{12} & \text{if } \mathrm{abs}(d_{12} - d_{21}) < k \\ \text{not assigned} & \text{otherwise} \end{cases}$$

where k is a threshold value, meaning that the error we can tolerate in the disparity must be not larger than t pixels. The pixels that do not satisfy the consistency test, are not assigned a height for this study. To reconstruct the pixel final depth, the optical rays have to be triangulated. They are detected by pairs of conjugate points found by means of the disparity and the satellite positions at the time of the acquisitions of each pixels. Due to the uncertainties in the correct orbiter location, to the geolocation precision and the coupling made by the matches, the optical vectors might cross each other not exactly at the right 3-D point.

DATA

For our test we have used the MSG/SEVIRI (Spinning Enhanced Visible and InfraRed Imager) observations and the MODIS height maps as ground truth to evaluate the retrieved stereo heights. The stereo configuration includes the satellites MSG-2 and MSG-3, located on the Equatorial plane respectively at 9.5°E and 0°E at about 36,000 km of altitude. MSG-3 provides an entire scan of Europe and Africa every 15 minutes, whereas the Rapid Scan System of MSG-2 provides data for the Northern hemisphere every 5 minutes. The Equatorial region till to the North Pole, intersection of both field of views, is then observed by two different positions with a pixel resolution at the Sub Satellite Point of 3km. The distance between both positions i.e. the baseline, is approximatively 7000 km that is not enough to provide an accurate reconstruction for all clouds, as it is explained in the next section. Therefore it is expected that the whole range of heights of clouds present in the analysed scenes, will not be well reconstructed.

These data allowed us to check the general performance of the algorithm in worse conditions than in [4] because of the coarser size of the pixel, the bigger height/baseline ratio and the smaller range of disparity. Furthermore the original and the new versions of the algorithm, were tested and compared both on mono-band stereo and multi-spectral stereo pairs. The 10.8μm MSG band was chosen for the first test and 10.8μm, 12μm bands were used for multi-band stereoscopic analysis. These bands were selected to apply cloud analysis in thermal-infra red bands and also because are of interest in other contests as in [1].

The MSG data base provides also ancillary data that include the actual satellite positions for each row of the images that are utilised for the estimation of the optical rays.

As referential height, *MODerate resolution Imaging Spectroradiometer (*MODIS) data were used. MODIS is an instrument on board Terra satellite that provides a huge amount of products and we have considered the height maps provided in the same bands chosen for our study. The resolution used by MODIS data differs of 2 km more from the one of SEVIRI and a resampling of the height map was necessary before comparing the results.

RESULTS

The algorithm has been applied to several images, here we show the results for the MSG-2 and MSG-3 06/02/2015 h:15:22 UTC scene, both as mono-band stereo in 10.8 μm and as multi-spectral stereo in 10.8 μm and 12 μm. The scene (Fig. 3) is located over the Atlantic Ocean except in the south-east corner where a small part of the African coast is present. The observed scene is mainly cloudy with the coldest part i.e. the highest clouds, in the middle. The MSG brightness temperatures range between 211-306 Kelvin and the hottest values correspond to the land part and the ocean. The range of altitudes according to the MODIS height map, is between 0 and 16.5km with low, mid and high clouds present in the scene.

As observed in the previous section, the short baseline causes the difficulty to reconstruct the altitude for the lowest clouds, because they do not have a detectable disparity.

Following [6], the accuracy of the CTH determination, σ_{CTH}, can be expressed as:

$$\sigma_{CTH} = \frac{\sigma_d}{b/H_s} \qquad (1)$$

where σ_d is the disparity estimation error on ground, b is the baseline of the stereo system, and H_s is the satellite altitude. Hence in our case, considering an average disparity error of no more than half a pixel and therefore $\sigma_d = \pm 1.5$km, the resulting accuracy is within 7.6 km. Then if the disparity is estimated with an accuracy of half a pixel, in this MSG satellite configuration clouds with heights h in [7.5,15] km might not be distinguished, while lower clouds could be merged to the background. It is worth pointing out that this measure of the accuracy considers only the geometry of the system, and does not take into account other sources of errors.

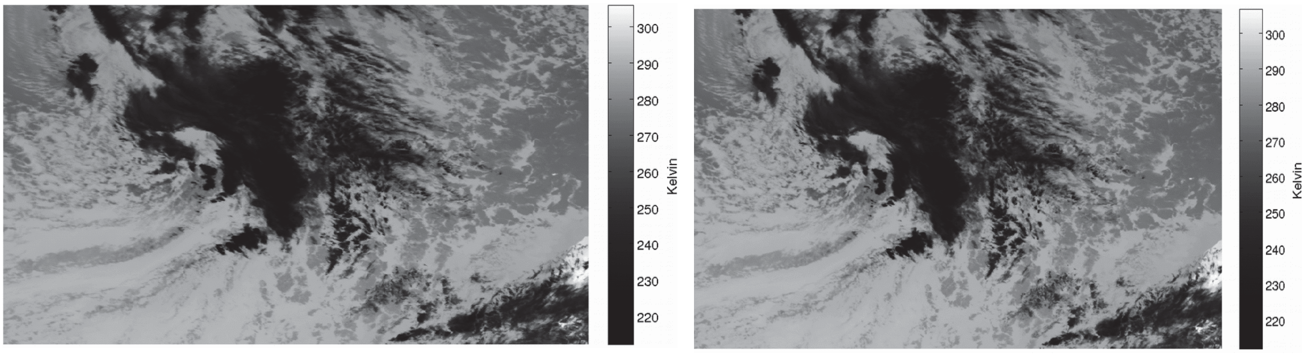

Figure 3. Stereo image pair. MSG-2 and MSG-3 scene 06/02/2015 h:15:12 UTC, Brightness Temperatures in 10.8μm band. The coldest then the highest clouds, are represented by the darkest colour. Brightest areas represent ocean and land.

The stereo mono band algorithm applied to the scene resulted in a map where the central clouds are assigned the highest value that is represented by the brightness colours in Fig. 4 (left). It was compared with the quasi synchronous map given by MODIS/Terra that observed the same scene at h:15:10 UTC. In Fig. 4 (right), a quantitative analysis is shown. Almost 70% of the error for the reconstructed heights is less than 3km, that is, according to Equation (1), below half a pixel error in the disparity. Stereo heights are a bit higher than MODIS and in some cases low-mid clouds (3-7 km) are merged as expected. The multi-spectral stereo has performed differently detecting more low clouds, but getting worse the cumulative error histogram due to the overestimation of them. In Fig. 5 it can be noted that about 60% of the error is less than 3km.

Note that some elements can affect the final CTH reconstruction. For instance the two MSG imaging instruments are quasi-synchronous on the selected scene and there is a time lag of about5 minutes between the two acquisitions that can imply estimation errors because of the possible cloud motion. Moreover in the comparison it should be taken into account the different MODIS resolution and time acquisition with 12 min of delay.

After having validated the results obtained by the new version of the algorithm (NA here after), they have been compared with the ones given by the OA applied to the same scene. In Fig. 6 and 7, it can be observed that mono and multi-spectral stereo height maps are quite similar and both include more parts of ocean merged to low clouds than the NA (south left part of the image). The cumulative error histograms highlight a worse performance, in fact only about 40% of the error for the estimated altitudes is less than 3km.

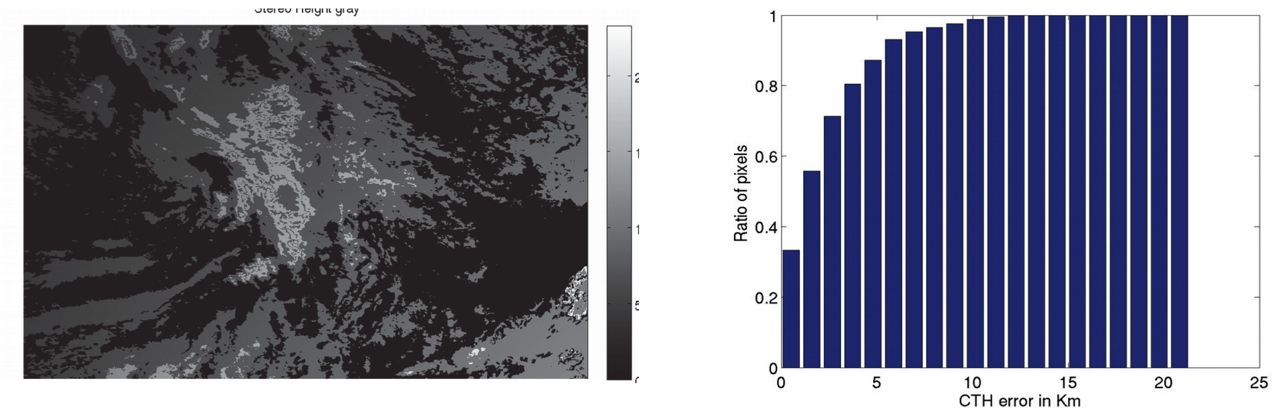

Figure 4. Mono band stereo NA. Left. Reconstructed CTH map. Brightest colour are assigned to the highest clouds in the middle. Right. Cumulative Error histogram in comparison with the heights estimated by MODIS.

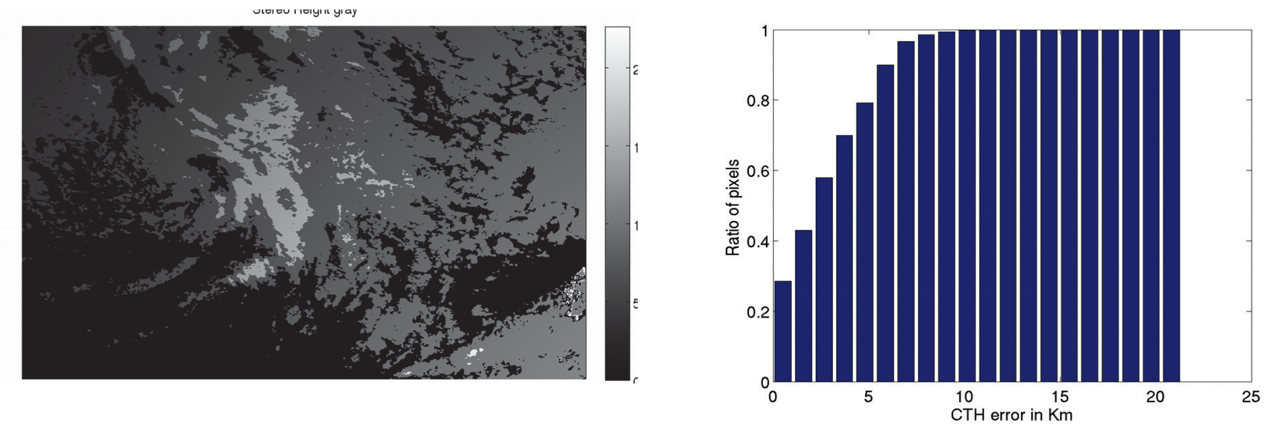

Figure 5. Multi-spectral stereo NA. Left. Reconstructed CTH map. Brightest colour are assigned to the highest clouds in the middle. Right. Cumulative Error histogram in comparison with the heights estimated by MODIS.

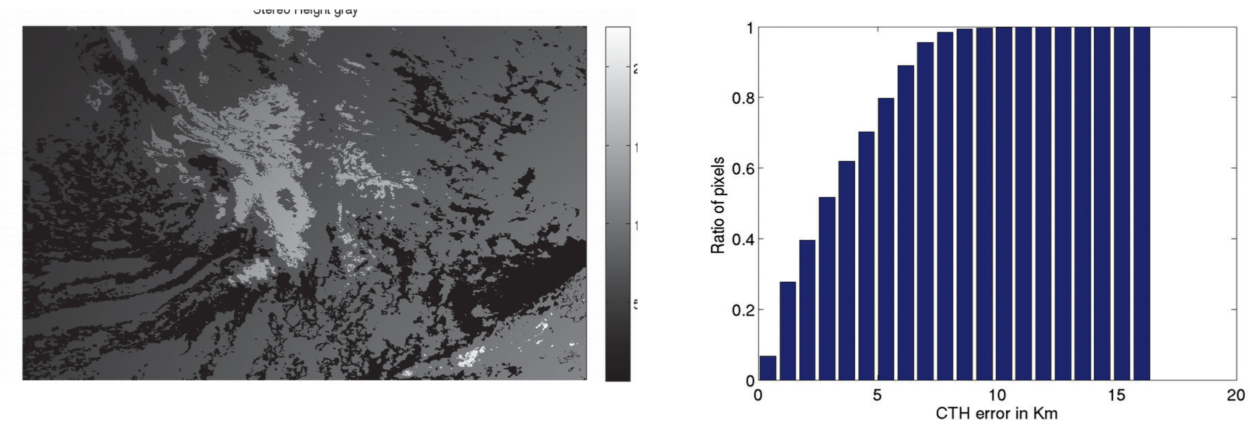

Figure 6. OA Mono band stereo. Left. Reconstructed CTH map. Brightest colour are assigned to the highest clouds in the middle. Right. Cumulative Error histogram in comparison with the heights determined by MODIS.

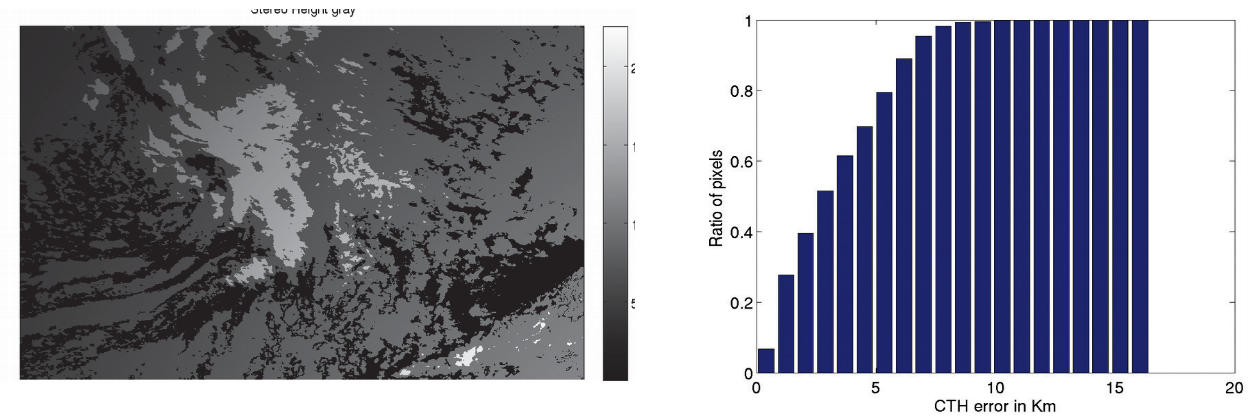

Figure 7. OA Multi-spectral stereo. Left. Reconstructed CTH map. Brightest colour are assigned to the highest clouds in the middle. Right. Cumulative Error histogram in comparison with the heights determined by MODIS.

CONCLUSIONS AND FUTURE WORK

In this paper we have proposed an algorithm for the estimation of the cloud top height from satellite infra-red images. In particular we present a refined version of a method presented in [4].

The application in thermal infra-red bands, of the new version of the algorithm described in the paper, has led to a height map more accurate than the one obtained by the original version. A quantitative evaluation of the error against a reference map, has highlighted an improvement of the accuracy in the final CTH retrieval. It is also visible on the final maps where the NA shows a better accuracy in the ocean parts in comparison with the OA height maps. This is mainly due to the segmentation step, where the region growing of the OA algorithm generates masks including pixels of very different temperatures: this is particularly for the pixel on the background, i.e. low clouds and sea/land, since the hottest parts are added in the end. In this way the computation of the disparity for the background is somewhat affected by the *motion* of the coldest parts of the scene.

The same result has been reached both applying the method to a mono-band stereo pair and to a multi-spectral stereo pair of geostationary satellites. Furthermore a slight better performance of the reconstruction in general, is given by the mono-band case as expected, despite the not proper stereo features of the chosen configuration.

In the future we plan to test the performance of the method on imagery of different satellites designed for stereo retrieval, where the disparity range available for the stereo pairs, allow to detect heights of a wider interval of cloud altitudes.

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