Comparing geometric and radiometric information from GeoEye-1 and WorldView-2 multispectral imagery

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Abstract
A comparison between GeoEye-1 (Geo format) and WorldView-2 (Basic and Ortho Ready Standard format) multispectral (MS) imagery regarding both geometric and radiometric characteristics was carried out over the same study area. Firstly, the attainable geopositioning accuracies on seven single MS images from both very high resolution sensors were compared in the same conditions, both along the sensor orientation and orthorectification phase. The orthoimages planimetric accuracy was ranging from 1.86 m to 2.22 m. The best results were achieved in the case of GeoEye-1 MS orthoimages, nearly followed by those coming from WorldView-2 ones. Secondly, and regarding the radiometric characteristics of both MS sensors tested, a higher digital numbers' histogram compression in the case of WorldView-2 was found in the four common bands shared by both MS sensors, especially in the blue band. A no-reference assessment of image quality by using blur ratio was also computed in order to attain image sharpness metric. The blur ratio presented slightly lower values for the GeoEye-1 images.

Keywords: GeoEye-1, WorldView-2, orthorectification, multispectral, radiometric, blur.

Introduction
The age of very high resolution (VHR) satellites began with the launching of IKONOS in 1999. Since then, many other commercial VHR satellites have been successfully launched, usually presenting a notable improvement in resolution, availability and cost. Nowadays the couple of commercial VHR satellites more innovative are GeoEye-1 and WorldView-2, launched in September 2008 and October 2009 respectively. Since January 2013 both satellites belong to DigitalGlobe company. GeoEye-1 (henceforth GE1) is currently the commercial satellite with the highest geometric resolution, i.e. 0.41 m GSD (Ground Sample Distance) at nadir for PAN imagery and 1.65 m GSD for MS images, including the four classic bands: blue (B, 450 to 510 nm), green (G, 510-580 nm), red (R, 655-690 nm) and near infrared (NIR, 780-920 nm) [GeoEye, 2009]. On the other hand, WorldView-2 (WV2), with 0.46 m and 1.84 m nominal GSD at nadir in PAN and MS images respectively [DigitalGlobe, 2010], presents improved multispectral characteristics, since it includes two
sets of MS bands (MS1 and MS2). The MS1 set contains the conventional MS bands, i.e., blue (B, 450-510 nm), green (G, 510-580 nm), red (R, 630-690 nm) and near infrared (NIR1, 760-895 nm), whereas the MS2 set consists of four newly added bands such as coastal (C, 400-450 nm), yellow (Y, 585-625 nm), red edge (RE, 705-745 nm) and near infrared-2 (NIR2, 860-1040 nm). In fact, WV2 is the first commercial VHR satellite providing 8 MS bands. However, image products from both GE1 and WV2 satellites had to be down-sampled to 0.5 m and 2 m in PAN and MS respectively, for commercial sales, as a requirement levied by the U.S. Government. In this regard, on June 11, 2014, DigitalGlobe received notice from the U.S. Department of Commerce on its application to allow the company to sell its highest-quality and industry-leading commercial satellite imagery. From that date onwards, DigitalGlobe offers customers the highest resolution imagery available from their current constellation. Orthorectification of satellite data is one of the most important pre-processing steps for mapping applications. In fact, much research work has been carried out in the last decade to study and improve the orthorectification process from PAN or pan-sharpened VHR satellite images [Kay et al., 2003; Toutin, 2004; Aguilar et al., 2007; Li et al., 2007; Aguilar et al., 2008; Fraser and Ravanbakhsh, 2009; Åstrand et al., 2012; Gianinetto et al., 2014; Maglione et al., 2014]. The first stage, in order to carry out the orthorectification process, would be the triangulation process or sensor orientation, whereas the second stage would be headed up to remove the distorting effects of terrain relief by using a proper digital elevation model (DEM) as ancillary data. In this way, many researchers around the world have investigated several mathematical models for VHR satellite sensor orientation and 3D geopositioning. All these models, supported by an adequate framework of ancillary 3D ground control points (GCPs), can be categorized into three main groups: 1) 3D deterministic (or physical) models based on collinearity and coplanarity conditions [Crespi et al., 2009; Capaldo et al., 2012]; 2) empirical models mainly based on 3D rational function models [Toutin, 2004; Tao and Hu, 2001; Grodecki and Dial, 2003; Fraser and Hanley, 2005]; and 3) hybrid deterministic models based on physical models but using ‘virtual’ control points computed through rational function model [Toutin et al., 2012]. However, scientific researches involving the use of MS VHR satellite imagery have been, until now, mainly addressed to identify a broader range of land features (i.e. image classification), leaving aside orthoimages accuracy [Koc-San, 2013]. In this way, it is important to note that geometric correction or orthorectification can be performed after image classification for using original digital numbers (DNs) values during the classification. Anyway and bearing in mind that features extracted by image classification should be based on proper georeferencing, a higher number of studies about geopositioning accuracy of VHR MS satellite imagery would be required. In this way, it is highly relevant to study the potential geopositioning accuracy offered by VHR satellites MS imagery under operational conditions. DigitalGlobe offers the Advanced Ortho Series for customers who require fully processed imagery with clearly defined aesthetic and accuracy specifications. In this sense, customers can buy two MS orthorectified image products from GE1 and WV2 providing map accuracies, measured as circular error at 90% confidence (CE90), of 10.2 m and 4.2 m for Mapping and Precision ortho product respectively [DigitalGlobe, 2014]. In fact, many classification works for thematic maps production directly use this type of VHR satellite MS orthoimages [Dalponte et al., 2012]. In other case, WV2 MS single image was only geo-registered using 2D GCPs to an up-to-date orthophoto, achieving a planimetric root.
mean square error (RMSE) of 4 m [Ozdemir and Karnieli, 2011]. However, GE1 and
WV2 also provide MS products with a lower level of processing, what gives rise to the
possibility of generating highly accurate orthoimages by using commercial off-the-shelf
software and ancillary data such as DEMs and 3D GCPs. The format called Geo is the most
advisable GE1’s product for attaining accurate orthoimages [GeoEye, 2009], whereas in
the case of WV2 [Aguilar et al., 2013a], two products could be used: 1) Basic images and
2) Ortho Ready Standard Level-2A (ORS2A). Both GE1 Geo and WV2 ORS2A products
are radiometrically corrected and projected to a plane with constant height (map-projected
level), having nearly the same processing level [GeoEye, 2009; DigitalGlobe, 2014]. In
fact, in its last product guide DigitalGlobe changed the name of the format Geo by ORS2A
[DigitalGlobe, 2014]. On the other hand, WV2’s Basic products are radiometrically
corrected but not projected to a plane by means of a map projection or datum, so presenting
the least level of corrections from WV2 sensor and being very close to the raw images. The
sensor correction blends all pixels from all detectors into the synthetic array to form a single
image. The resulting GSD varies over the entire product because the look angle slowly
changes during the imaging process [DigitalGlobe, 2014].

Furthermore, the importance of the radiometric characteristics of the images on the final
cartographic accuracy of the products derived from VHR satellite images has been already
contrasted. For example, when an automated area based matching procedure is applied,
radiometrically blurred images lead to bring more successful matching pairs but also
resulted in more inaccurate matching points in the extracted digital surface models (DSMs)
[Liu et al., 2005; Shih and Liu, 2005]. Moreover, the differences observed between the
DN distribution and visual appearance of PAN and MS images from GE1 and WV2 VHR
satellites could result in different classification accuracy [Aguilar et al., 2013a]. Along
the chain from image sensing to the final value-added product, the quality of the images
plays a crucial role. Image quality is defined by several parameters, as the radiometric
resolution and its accuracy, represented by the noise level, and the geometrical resolution
and sharpness. These parameters are usually described in VHR satellite imagery by both
the noise level and the Modulation Transfer Function (MTF) [Choi, 2002; Crespi and De
Vendictis, 2009], although a new no-reference assessment of image quality based on blur
and noise ratios has been recently proposed by Choi et al. [2009].

The principal objectives of this research paper are the followings:
1) To compare, in approximately the same conditions, the geopositioning accuracy capabilities
of GE1 (Geo product) and WV2 (ORS2A and Basic products) MS single images for producing
orthoimages planimetric accuracy under a typical operational environment. In this point, a statistical
analysis is carried out in order to determine the influence on MS orthoimages planimetric
accuracy of several factors such as type of input VHR MS satellite image, sensor orientation
model, number of GCPs, off-nadir viewing angle and, finally, accuracy of the ancillary DEM.
To the best knowledge of the authors, there are no published papers comparing, in the same
operational conditions, the potential geometric accuracies attained from MS single images of
the two more sophisticated VHR sensors currently orbiting on the Earth surface.
2) In addition, the radiometric characteristics of common bands shared by both MS sensors
(i.e. MS for GE1 and MS1 for WV2) are compared according to both DNs’ distribution and
no-reference assessment of image quality. This point adds another important novelty for the
readers of this work.
Study Site and Data Sets
This work is part of a large programme of research investigating the monitoring and modelling of the evolution and vulnerability of coastal areas carried out in a pilot study area between the harbors of Villaricos and Garrucha. The study area is centered on WGS84 geographic coordinates of 37.2109° North and 1.8027° West, comprising a heavily developed coastal area of Almería (Southern Spain), approximately 11 km long and 775 m wide (Fig. 1). It presents a smooth relief with heights above mean sea level ranging from 0 m to 55 m and an average value close to 7 m.

Figure 1 - Location of the study site. The working area has been delimited by the yellow polygon. Coordinate system: WGS84 UTM zone 30N.

WV2 Data
A map-projected WV2 ORS2A 8-bands MS image (MS1 and MS2), covering the whole working area, was acquired on July 19, 2011. Likewise, on August 18, 2011, a WV2 Basic stereo pair was taken. It contained two 8-bands MS Basic scenes both covering the entire working area. One of the aforementioned Basic images was also ordered in WV2 ORS2A format. All the MS WV2 images presented a spatial resolution of 2 m GSD and included the rational polynomial coefficients (RPCs) corresponding to the sensor camera model. The WV2 images were shipped with a dynamic range of 11-bit and without any color correction or contrast enhancement. The WV2 images had a cubic convolution resampling. The complete characteristics of the images are shown in Table 1.
Table 1 - Characteristics of MS images from GE1 (Geo and GeoStereo) and WV2 (ORS2A and Basic Products) acquired at the study site. R: Reverse, F: Forward.

| Image ID    | GE11 | GE12 | GE13 | WV21 | WV22 | WV23 | WV24 |
|-------------|------|------|------|------|------|------|------|
| Sensor      | GE1  | GE1  | GE1  | WV2  | WV2  | WV2  | WV2  |
| Product     | Geo  | Geo  | Geo  | ORS2A| Basic| Basic| ORS2A|
| Acquisition Date | 29/9/2010 | 27/8/2011 | 27/8/2011 | 19/7/2011 | 18/8/2011 | 18/8/2011 | 18/8/2011 |
| Acquisition Time, GTM | 11:01 | 10:55 | 10:56 | 11:23 | 11:22 | 11:23 | 11:23 |
| Cloud Cover | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   | 0%   |
| Scan Direction | R    | R    | R    | F    | F    | R    | R    |
| Sun Azimuth | 159.3° | 144.1° | 144.4° | 142.5° | 152.3° | 152.8° | 152.8° |
| Sun Elevation | 48.4° | 58.3° | 58.4° | 70.5° | 63.7° | 63.8° | 63.8° |
| Collection Elevation | 69.4° | 81.5° | 66.9° | 85.0° | 67.7° | 80.0° | 80.0° |
| Collection Azimuth | 221.9° | 40.4° | 183.6° | 278.9° | 4.8° | 216.3° | 216.3° |
| Collected Col GSD | 1.84 m | 1.66 m | 1.92 m | 1.87 m | 2.00 m | 1.89 m | 1.89 m |
| Collected Row GSD | 1.80 m | 1.65 m | 1.76 m | 1.86 m | 2.16 m | 1.90 m | 1.90 m |
| Product Pixel Size | 2 m | 2 m | 2 m | 2 m | 2 m | 2 m | 2 m |
| Bits per Pixel | 11 | 11 | 11 | 11 | 11 | 11 | 11 |

**GE1 Data**

A GE1 Geo MS image was acquired on September 29, 2010, whereas a GE1 GeoStereo product containing two MS images was taken on August 27, 2011 (Tab. 1). All the MS images, covering the whole working area, included the corresponding RPC sensor camera model. The images were ordered with a dynamic range of 11 bits per pixel and without any adjustment (i.e. maintaining absolute radiometric accuracy and full dynamic range for scientific applications). All the images had a cubic convolution resampling. It is worth noting that the two single images making up the GeoStereo pair product are identical to Geo product single images.

Figure 2 shows the image extent of all the projected MS VHR satellite images used in this work (i.e., GE11, GE12, GE13, WV21 and WV24). It is important to note that the Basic images from WV2 (i.e., WV22 and WV23) are complete scenes centered in the pilot area and approximately covering 256 km² (i.e., a swath width of 16 km).
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Figure 2 - Study site in green and VHR MS image extents. Dashed red line represents the GE11 image extent, red line the GE12 and GE13 extent, blue line the WV21 image and dashed blue line the WV24 extent. Coordinate system: WGS84 UTM zone 30N.

Ground Control Points Collection
The coordinates of 42 GCPs and 50 independent check points (ICPs) were measured by differential global positioning system (DGPS) receivers in real time kinematic mode (RTK). Concretely, a Topcon Hiper Pro RTK base and rover GPS system was used to carry out this task. They were surveyed with reference to the European Terrestrial Reference System 1989 (ETRS89), UTM projection and orthometric heights. The geoid based on the global Earth Gravitational Model of 1996 (EGM96) was used for attaining the final orthometric heights. The selection of GCPs and ICPs was based on well-defined and homogeneously distributed features over the entire study area (Fig. 3). Notice that this task was not easy to face bearing in mind that the GSD of all MS images was 2 m. In fact, the image pointing error of the GCPs and ICPs marked on MS images (using RGB color space as a visual reference; see Fig. 4) was actually higher than those marked over PAN images [Aguilar et al., 2013b].
Figure 3 - Distribution of 50 ICPs (red crosses) and 42 GCPs (yellow circles) overlaid on a GeoEye-1 multispectral orthorectified image. Coordinate system: WGS84 UTM zone 30N.

Figure 4 - Visual comparison of potential pointing error for a certain GCP between (a) PAN GE12 image and (b) MS RGB GE12 image over a limited area located at Villaricos harbor (28 m x 32 m).
**Digital Elevation Models**

Two DEMs previously used by the authors [Aguilar et al., 2012; Aguilar et al., 2013b] were tested as ancillary data for computing the MS orthoimages from GE1 and WV2 imagery:

1) A medium resolution 10 m grid spacing DEM generated from a photogrammetric flight at an approximate scale of 1:20000. The corresponding DEM vertical accuracy, measured as vertical root mean square error (RMSE\(_z\)) and estimated upon 62 DGPS highly accurate ICPs located at open terrain, took a value of 1.34 m.

2) A highly accurate LiDAR derived DEM presenting 1 m grid spacing. It was taken on August 28, 2009, by using a Leica ALS60 airborne laser scanner. The estimated vertical accuracy (RMSE\(_z\)) of this DEM took a value close to 0.09 m.

**Geometric Accuracy**

**Sensor Models Tested**

Although several mathematical models can be used for VHR satellite images orientation, the well-known sensor model based on 3D rational functions, counting on vendor supplied RPCs and after being refined by using a few GCPs, has been pointed out as the best model working on single GE1 MS images [Aguilar et al., 2012]. This sensor model also achieved the best orientation accuracy working on PAN WV2 imagery [Åstrand et al., 2012]. The aforementioned rational functions are expressed in the form of two ratios of third order polynomial functions referred to object space coordinates. This model can be applied without GCPs support due to the fact that third order RPCs for the forward form are distributed by image vendor in the case of GE1 and WV2 VHR MS sensors. In this sense, specifications about positional accuracy without GCPs for both GE1 and WV2 sensors are only given for PAN images, again not contributing to provide knowledge about the particular geometric accuracy of VHR MS imagery.

However, the accuracy of the supplied rational function model can be improved by refining the RPCs through a few highly accurate 3D GCPs. In this work, OrthoEngine®, the commercial photogrammetric module included in Geomatica version 2012 (PCI Geomatics, Richmond Hill, Ontario, Canada), was used to compute each orientation project. The OrthoEngine® RPC indirect method to refine the vendor supplied RPCs is based on the block adjustment method developed by Grodecki and Dial [Grodecki and Dial, 2003], which can be carried out by means of a simple two-dimensional shift (i.e., zero order transformation, RPC0), applying an affine transformation in the image space (RPC1), or using a second order polynomial adjustment (RPC2). Thus, only one GCP would be necessary to calculate RPC0 model, three GCPs for RPC1 and at least six GCPs in the case of RPC2 [Aguilar et al., 2012]. In other work several software packages were tested on PAN WV2 images orientation (Geomatica, ERDAS Imagine and SISAR software) using both rigorous and empirical models [Åstrand et al., 2012]. In all the cases the orientation accuracy proved to be practically software independent.

**Geometric Quality Assessment**

The geopositioning capabilities of MS GE1 and WV2 single images have been studied, both at the sensor orientation phase and final orthorectification stage, depending on different variables such as: 1) type of input VHR satellite MS image, i.e., GE1 Geo (GE11, GE12 and GE13), WV2 Basic (WV22 and WV23) or WV2 ORS2A (WV21 and WV24); 2) sensor model (RPC0, RPC1 and RPC2); 3) number of well-distributed GCPs ranging from 2 to 10; and 4) off-nadir viewing angle ranging from 5 to 23.1 degrees. The geometric accuracy assessment...
tests are very similar to those recently carried out over PAN and pan-sharpened single images by the authors [Aguilar et al., 2013b], although this time, focused on the geometric accuracy of VHR MS satellite imagery.

First, direct geopositioning of GE1 and WV2 MS products without the support of GCPs was tested. For that, seven orientation projects (one for each of the single images tested) were performed by means of OrthoEngine by only using the vendor supplied RPCs. Geometric accuracies, measured as mean error, standard deviation and planimetric RMSE ($\text{RMSE}_{\text{2D}}$), were always computed from the residuals attained at the 50 permanent ICPs. When the vendor supplied RPCs were refined to improve the orientation accuracy, different combinations of $n$ GCPs (2, 4, 7 and 10) were extracted from the original set of 42 GCPs (Fig. 3). Five replicates were sampled over the study area for each number of GCPs (i.e. 20 different sets of ancillary GCPs) always looking for an even distribution both planimetric and vertical (stratified random sampling). The same sets of GCPs were used for each of the seven single MS images tested. Taking into account that some sensor models needed a minimum number of GCPs to be computed, 20, 15 and 10 projects were carried out in the case of RPC0, RPC1 and RPC2 respectively. It is important to underline that all the residual populations corresponding to the sensor orientation phase (both for $X$ and $Y$ axis) were tested for normality of their distribution by means of Kolmogorov-Smirnov goodness-of-fit test. Furthermore, no blunder errors were identified in the residual populations after applying the 3-sigma rule [Daniel and Tennant, 2001].

In order to study the influence of the four aforementioned factors and their corresponding cross-interactions regarding sensor orientation accuracy, an analysis of variance (ANOVA) test was carried out by means of a factorial design with five replicates [Snedecor and Cochran, 1980]. In essence, ANOVA is a common statistical tool used to analyze datasets for which we are interested in evaluating the importance of several factors at once. Additionally, it allows us to quantify the influence of each factor on the global geometric accuracy ($F$-test). In this case the observed variable was $\text{RMSE}_{\text{2D}}$, always computed at the same 50 ICPs. When ANOVA test results turned out to be significant ($p<0.05$), the separation of means was carried out by using the Duncan’s multiple range test at a 95 percent confidence level.

Finally, the geometric accuracy of the MS orthorectified images containing only RGB bands was also tested. For each one of the seven original MS images tested in this work, ten orthoimages with 2 m GSD were produced by means of RPC0 supported by the five sets of seven well-distributed GCPs and using both the LiDAR and photogrammetrically derived DEMs. Only 32 ICPs out of the original 50 ICPs could be used for the geometric accuracy assessment at this phase because of their difficult pointing onto the orthoimages when they were located at corners of buildings and as such not being placed on the ground (non-open terrain points). A sinusoidal resampling kernel ($\sin(x)/x$ with $16 \times 16$ windows) was applied to original image cells during the orthorectification process [Toutin, 2004]. As in the case of sensor orientation stage, Kolmogorov-Smirnov test and 3-sigma rule were applied to the residual populations extracted from the MS orthorectified images. An ANOVA test was also carried out at this phase.

Radiometric Analysis
The smaller the details the satellite is able to read, the higher the resolution. In other words, the image resolution is not only related to the GSD, but also to the sensor’s optic and its radiometric resolution. In this sense, the size of the discernible lines which can be distinguished in an image indicates its radiometric quality and resolution. MTF is the most
widely system quality metric used in remote sensing [Choi, 2002; Kohm and Mulawa, 2008; Crespi and De Vendictis, 2009; Crespi et al., 2010]. Practically, MTF is a measure of system sharpness measured on-orbit by analyzing high-contrast edges which often uses fixed high-contrast targets [Kohm and Mulawa, 2008]. However, this method requires that a high number of good quality edges, ranging from 20 to 40 [Choi, 2002; Crespi and De Vendictis, 2009], have been previously selected in the scene.

Recently, a new no-reference assessment of image quality method was proposed [Choi et al., 2009] using both blur ratio (Br) and noise ratio (Nr), which turned out to present high correlation with respect to the subjective Difference Mean Opinion Score (DMOS). Although image quality is affected by many features like hue, edge, noise, and contrast, it was assumed that noise and blur were the most important factors for explaining image quality degradation. Both Br and Nr are measured by simple numeric operations on pixel’s DN, and their estimations are based on edge detection as the first step.

Regarding the radiometric analysis, the original radiometric characteristics of common bands for both GE1 (MS) and WV2 (MS1) images were also compared. The radiometry of an image is satisfactory when the relationship between the ground reflectance of the target and the grey level of the pixel on the image are correct [Crespi and De Vendictis, 2009]. Notice that MS VHR satellite images are mainly used for land features image classification. Therefore an analysis about the radiometric information captured by both MS sensors, in approximately the same conditions, would be very useful or even necessary. In this way, the DNs’ histograms corresponding to the whole working area for each original (non orthorectified) map-projected VHR MS images tested in this work (i.e. GE11, GE12, GE13, WV21 and WV24 images) were compared for R, G, B and NIR bands (R, G, B and NIR1 in the case of WV2).

Furthermore, the Br and Nr ratios were applied in this work to describe the radiometric quality and sharpness of the MS VHR satellite images. The Br and Nr values were computed, for each band and image, in five different square areas within our study site, comprising each one about 300x300 pixels (i.e., 360000 m²), and representing the land covers of our working area. The areas named U1 and U2 were labeled as urban areas. Another two areas (M1 and M2) were classified as mixed areas (containing features belonging to both urban and agricultural or bare soil). The remaining area (B) presented only agricultural and bare soil land cover. It is noteworthy that the source code for computing these ratios according to Choi et al. [2009] was implemented in MATLAB® R2008b by the authors and it is available in the following web site link: https://www.ual.es/Proyectos/GEOEYE1WV2/index_archivos/links.htm.

**Results and Discussion**

**Direct Geopositioning of GE1 and WV2 MS Images without GCPs**

First of all, it should be clearly stated that the study area is not optimal to carry out a quality geometric accuracy assessment because it is small, flat, with a very long and narrow shape, and with a large extent of the water body. However, in this pilot area several VHR satellite images from GE1 and WV2, taken almost in the same conditions and similar dates, were available.

Overall, direct geopositioning accuracies achieved from WV2 Basic (WV22 and WV23) or ORS2A (WV21 and WV24), measured as standard deviations, were slightly better than those attained from GE1 (Tab. 2).
Table 2 - Direct geopositioning accuracy at 50 ICPs presented as Mean error, Standard Deviation ($\sigma$) and RMSE$_{2D}$ for GE1 and WV2 MS single images without GCPs support.

| Image Product | Image ID | Off-Nadir | X     | Y     | 2D     | X     | Y     | 2D     | RMSE (m) |
|---------------|---------|-----------|-------|-------|--------|-------|-------|--------|----------|
| GE1 Geo       | GE12    | 8.5º      | 1.33  | 2.70  | 3.01   | 0.85  | 0.86  | 1.21   | 3.16     |
|               | GE11    | 20.6º     | 1.73  | 0.78  | 1.89   | 0.94  | 0.92  | 1.32   | 2.30     |
|               | GE13    | 23.1º     | 1.28  | 3.06  | 3.32   | 0.74  | 0.96  | 1.21   | 3.44     |
| WV2 ORS2A     | WV21    | 5º        | 0.89  | -0.09 | 0.90   | 0.82  | 0.84  | 1.17   | 1.47     |
|               | WV24    | 10º       | -1.65 | 1.73  | 2.39   | 0.73  | 0.83  | 1.10   | 2.63     |
| WV2 Basic     | WV23    | 10º       | -0.95 | 1.07  | 1.43   | 0.75  | 0.78  | 1.08   | 1.79     |
|               | WV22    | 22.4º     | -1.45 | 0.18  | 1.46   | 0.86  | 0.87  | 1.23   | 1.84     |

Likewise, lower biases or mean errors were yielded by using WV2 MS images. In fact, planimetric systematic errors lower than 3.5 m were achieved from GE1 images (i.e., GE11, GE12 and GE13), whereas values lower than 2.5 m were computed in the case of WV2. Regarding standard deviations or random errors, the 2D values attained from MS images were ranging from 0.55 pixels to 0.66 pixels (considering the nominal product ground pixel size of 2 m), mainly depending on the off-nadir angle and the satellite used. Table 2 also shows geopositioning accuracies without GCPs measured as RMSE$_{2D}$ values. This global accuracy estimator includes both standard deviation (i.e., random errors) and mean error (i.e., bias or systematic errors). The RMSE$_{2D}$ values were ranging from 1.47 m to 3.44 m. It is noteworthy that standard deviations in Table 2 could be supposed as the best possible geopositioning accuracy results after applying bias corrections by using the local support of a few GCPs. Direct geopositioning accuracies attained from GE1 Geo and WV2 (Basic and ORS2A) MS images were very similar in terms of standard deviation measures. However bias errors (mean errors 2D) are slightly higher for GE1 images than in the case of WV2 ones. This fact was also reported by Aguilar et al. [2013a] working with PAN images from GE1 and WV2. It is important to note that the image pointing error of the ICPs marked on MS images is higher and much more changeable than those marked over PAN images.

**Accuracy Assessment at Sensor Orientation Phase**

Several ANOVA tests were developed in this work in order to strengthen the results about geometric accuracy assessment. The first general ANOVA statistical test was performed on 315 sensor orientation projects using RMSE$_{2D}$ as observed variable. Orientation accuracy was significantly affected ($p<0.05$) by the four main factors analyzed. In fact, and regarding ANOVA test results, the kind of sensor model (RPC0, RPC1 and RPC2) was the most important factor affecting orientation accuracy (F-test value of 64.23), whereas number of GCPs was the next more significant source of variation (F-test of 15.82). The others two variables, i.e. type of input VHR satellite MS image and off-nadir viewing angle, were less significant, reporting F-test values of 7.30 and 4.85 respectively. According to main factors cross-interactions ANOVA results, only the crossed effects of sensor model and number of
GCPs (F-test of 2.69) turned out to be significantly related (p<0.05), demonstrating that the sensor models tested behave in a different way depending on the number of GCPs used.

The mean values of RMSE$_{2D}$ computed at 50 ICPs from GE1 Geo, WV2 ORS2A and WV2 Basic MS images according to the number of GCPs and sensor model are shown in Table 3. Among them, the worst accuracies were clearly provided by RPC2 model for any type of MS image. On the other hand, and although RPC1 yielded very good results for a high number of GCPs, RPC0 can be considered the ideal sensor model for both GE1 and WV2 MS single images. In this regard, adding terms to the image-to-space transformation by using RPC1 or RPC2 instead of RPC0 could improve the accuracy of sensor orientation, but only when there are higher order distortions in the images [Fraser and Hanley, 2005], and, from the DigitalGlobe’s satellite constellation, this fact only occurs for QuickBird basic images [Fraser et al., 2006]. In this way, several researchers working on GE1 and WV2 PAN images have reported the RPC0 model as the most accurate and simple sensor model [Fraser and Ravanbakhsh, 2009; Chen and Chaapel, 2010].

Returning to Table 3 and under a statistical point of view, the best planimetric accuracy for the GE1 Geo MS images tested in this work was achieved from applying RPC0 sensor model supported by seven GCPs. Notice that the value of 1.26 m is followed by letters “bc” in Table 3, and thus this figure is not statistically different from 1.34 m (mean value of RMSE$_{2D}$ for 4 GCPs and followed by letters “ab”) or 1.23 m (mean value of RMSE$_{2D}$ for 10 GCPs and followed by letter “c”). In the same way, the number of GCPs recommended to compute RPC0 model from WV2 Basic and ORS2A images turned out to be four.

When only the mean values of RMSE$_{2D}$ computed with seven GCPs and RPC0 were considered in a one-way ANOVA test, any significant difference was detected regarding the type of MS images. In this ideal case, the best planimetric accuracy for the orientation phase did not depend on the type of input VHR satellite MS image, presenting an average value of 1.23 m (0.62 pixels) and standard deviation of 0.11 m.

### Table 3 - Comparison of RMSE$_{2D}$ mean values computed from GE1 Geo, WV2 ORS2A and WV2 Basic MS images at sensor orientation stage depending on the number of GCPs (No. GCPs).

For each sensor model tested, values in the same column followed by different superscript letters indicate significant differences at a significance level p<0.05.

| Sensor model | No. GCPs | GE1 Geo RMSE$_{2D}$ (m) | WV2 ORS2A RMSE$_{2D}$ (m) | WV2 Basic RMSE$_{2D}$ (m) |
|--------------|----------|------------------------|--------------------------|--------------------------|
| RPC0         | 2        | 1.38 $^a$              | 1.43 $^a$                | 1.30 $^a$                |
|              | 4        | 1.34 $^{ab}$           | 1.29 $^{ab}$             | 1.24 $^{ab}$             |
|              | 7        | 1.26 $^{bc}$           | 1.23 $^b$                | 1.19 $^{ab}$             |
|              | 10       | 1.23 $^c$              | 1.19 $^b$                | 1.13 $^b$                |
| RPC1         | 4        | 1.46 $^a$              | 1.51 $^a$                | 1.45 $^a$                |
|              | 7        | 1.39 $^a$              | 1.39 $^{ab}$             | 1.32 $^{ab}$             |
|              | 10       | 1.26 $^b$              | 1.30 $^a$                | 1.20 $^b$                |
| RPC2         | 7        | 1.63 $^a$              | 1.55 $^a$                | 1.54 $^a$                |
|              | 10       | 1.38 $^b$              | 1.51 $^a$                | 1.56 $^a$                |
Table 4 - Comparison of $\text{RMSE}_{2D}$ mean values in the case of RPC0 model supported by seven GCPs and computed from GE1 Geo, WV2 ORS2A and WV¬2 Basic MS images at sensor orientation stage depending on off-nadir angle. For each image product tested, values in the same column followed by different superscript letters indicate significant differences at a significance level $p<0.05$.

| MS Image Product | Image ID | Off-nadir (degrees) | RMSE$_{2D}$ (m) |
|------------------|---------|---------------------|-----------------|
| GE1 Geo          | GE12    | 8.5                 | 1.19$^a$        |
|                  | GE11    | 20.6                | 1.33$^c$        |
|                  | GE13    | 23.1                | 1.27$^b$        |
| WV2 ORS2A        | WV21    | 5                   | 1.29            |
|                  | WV24    | 10                  | 1.17            |
| WV2 Basic        | WV23    | 10                  | 1.14            |
|                  | WV22    | 22.4                | 1.23            |

The plots of ground coordinate residuals shown in Figure 5 provide another point of view. In that figure, the repetition number 1 using seven well-distributed GCPs was analyzed for RPC0 and RPC1 sensor models. Thus, 50 residuals from ICPs (black lines) and 7 from GCPs (red lines) were plotted. The residuals coming from GE12 image by using both RPC0 (Fig. 5a) and RPC1 (Fig. 5b) showed a quite random distribution suggesting the absence of any further systematic error. In fact, the residuals in both cases were very similar for each ICP or GCP. The ground coordinate residuals from WV24 image for both RPC0 and RPC1 sensor models (Fig. 5c and Fig. 5d respectively) presented a different pattern in each point with regard to GE12 image, although no systematic error were detected. The pointing errors in each of the 57 ground points for each MS image were addressed as the most important factor regarding the final residuals’ pattern. In this way, three major ICPs’ residuals rose above the rest in the case of GE12 image (Fig. 5a and Fig. 5b). Probably, these higher residuals were produced by an error in marking the points into the image space (see Fig. 4b).

Focusing on off-nadir viewing angles, and in the case of RPC0 with seven GCPs (Tab. 4), RMSE$_{2D}$ mean values for both GE1 Geo and WV2 Basic MS images were usually higher as a result of larger off-nadir angles, yielding significant differences ($p<0.05$) only in the case of the three GE1 Geo images. This trend was not observed in the case of WV2 ORS2A MS images, likely because the tested off-nadir angles were very similar. Worse planimetric accuracy when increasing off-nadir angles was observed working on WV2 PAN single images [Åstrand et al., 2012]. Furthermore, Aguilar et al. [2013b] reported that the influence of off-nadir angle on orientation accuracy, at least for PAN GE1 and WV2 images, would be related to an increase of both collected GSD and image pointing error with larger image look angles.
Figure 5 - Ground coordinate residuals distribution from MS images after orientation phase in 50 ICPs (black lines) for seven well-distributed GCPs (red lines). (a) First repetition for RPC0 sensor model and GE12 image, (b) First repetition for RPC1 sensor model and GE12 image, (c) First repetition for RPC0 sensor model and WV24 image, and (d) First repetition for RPC1 sensor model and WV24 image.
Accuracy Assessment of Orthoimages

Table 5 shows the mean values of the planimetric accuracy (RMSE$_{2D}$) computed at ICPs corresponding to orthorectified GE1 Geo, WV2 ORS2A and WV2 Basic images depending on the use of two different ancillary DEMs. Although there seems to be a trend to improve orthoimages geometric accuracy when applying the more accurate LiDAR derived DEM, the registered differences did not become significant (p<0.05). It is worth noting that, in the particular case of VHR satellite MS images (2 m GSD), the vertical accuracy of the ancillary DEM used for the orthorectification process plays a less important role in the final orthoimage geometric accuracy than in the case of VHR satellite PAN images (0.5 m GSD). These results ratify those obtained working on a single GE1 Geo MS image [Aguilar et al., 2012]. It is widely known that image viewing angle has a great influence on the geometric accuracy of orthorectified VHR PAN image [Toutin, 2004; Åstrand et al., 2012; Aguilar et al., 2013b]. However, the relationship between off-nadir viewing angle and MS orthoimages planimetric accuracy turned out to be unclear. In this sense, it is necessary to take into account that image pointing error reaches high values in the case of VHR MS images and, therefore, the effect of off-nadir angle as well as DEM accuracy might be somehow masked by it.

Finally, when a one-way ANOVA test was carried out considering the type of input products as the only factor, significant results (p<0.05) were attained. In this way, the best and statistically significant planimetric accuracies were achieved from the GE1 Geo MS orthoimages (RMSE$_{2D}$ mean value of 1.96 m). On the other hand, there were no statistically significant differences between WV2 ORS2A and Basic MS orthoimages, presenting RMSE$_{2D}$ values of 2.09 m and 2.11 m respectively.

Table 5 - Comparison of RMSE$_{2D}$ mean values computed at 32 ICPs from GE1 Geo, WV2 ORS2A and WV2 Basic MS orthoimages generated by applying RPC0 model and seven GCPs. For each ancillary DEM and image product tested, mean values in the same column followed by different superscript letters indicate significant differences at a significance level p<0.05.

| MS Image Product | Image ID | Off-nadir (degrees) | Orthoimage LiDAR DEM RMSE$_{2D}$ (m) | Orthoimage Andalusia DEM RMSE$_{2D}$ (m) |
|------------------|----------|---------------------|-------------------------------------|----------------------------------------|
| GE1 Geo          | GE12     | 8.5                 | 1.84                                | 1.86$^a$                               |
|                  | GE11     | 20.6                | 1.89                                | 1.98$^a$                               |
|                  | GE13     | 23.1                | 2.01                                | 2.19$^b$                               |
| WV2 ORS2A        | WV21     | 5                   | 1.99                                | 2.00$^a$                               |
|                  | WV24     | 10                  | 2.12                                | 2.22$^b$                               |
| WV2 Basic        | WV23     | 10                  | 2.12                                | 2.20$^a$                               |
|                  | WV22     | 22.4                | 2.03                                | 2.07$^b$                               |

Radiometric Characteristics

There is no effective difference in the possible range of grayscale values or DNs between WV2 and GE1 imagery products, being 11-bits the dynamic range obtained by the current VHR satellites. This means that 2048 possible DN values per each band could be potentially collected by both sensors. However, a compression of the range of DNs is undertaken on
purpose by the imaging companies to account for extremely reflective surfaces which could create flares [McCarty, 2010]. Because of that, DN values rarely exceed 1500 in raw VHR satellite imagery if any especial color correction or contrast enhancement is applied. Table 6 shows the histogram statistics for the whole working area corresponding to the MS bands of the three GE1 Geo images tested in this work. On the other hand, the histogram statistics for the two WV2 ORS2A MS images tested in this work are presented in Table 7. A higher compression of DNs’ histogram for each band (i.e. lower standard deviation values) was observed in the WV2 ORS2A images (Tab. 7), especially in the case of the blue band. In the same way, even a much more intense difference in histogram compression between PAN GE1 and PAN WV2 images has been recently observed [Aguilar et al., 2014].

This compression of the histogram seems to be related to the fact that, at least in PAN mode, WV2 ORS2A images looked blurrier and so showed a lesser contrast than the GE1 Geo ones [Aguilar et al., 2014]. The top row in Figure 6 shows a visual quality comparison between the original GE12 Geo (Fig. 6a) and WV24 ORS2A (Fig. 6b) PAN images where it can be clearly appreciated the aforementioned difference in sharpness. This effect can also be appreciated for WV2 and GE1 PAN images in the figure number two of a recent published work [Agugiaro et al., 2012] over Trento testfield (Italy), although the authors did not make any mention about it. However, and paying attention to Figure 6c and Figure 6d, where the MS blue bands for GE12 and WV24 images are depicted, any important difference regarding image visual quality could be clearly noticed. The same could be point out for Figure 6e and Figure 6f showing the RGB MS images from GE12 and WV24 respectively.

Table 6 - Histogram statistics for the whole working area corresponding to red, green, blue and NIR bands corresponding to the original GE1 Geo MS images.

| Image ID | GE11 Mean | GE11 σ | GE12 Mean | GE12 σ | GE13 Mean | GE13 σ |
|----------|-----------|--------|-----------|--------|-----------|--------|
| Red      | 464.27    | 206.79 | 492.65    | 180.72 | 573.48    | 195.70 |
| Green    | 480.67    | 161.67 | 502.97    | 138.51 | 587.48    | 149.749|
| Blue     | 595.08    | 157.78 | 612.09    | 133.83 | 716.47    | 146.052|
| NIR      | 694.75    | 236.96 | 671.32    | 197.90 | 775.52    | 211.021|

Table 7 - Histogram statistics for the whole working area corresponding to red, green, blue and NIR1 bands corresponding to the original WV2 ORS2A MS images.

| Image ID | WV21 Mean | WV21 σ | WV24 Mean | WV24 σ |
|----------|-----------|--------|-----------|--------|
| Red      | 307.70    | 114.55 | 489.61    | 161.20 |
| Green    | 494.48    | 139.95 | 472.49    | 115.98 |
| Blue     | 341.87    | 78.98  | 331.31    | 63.63  |
| NIR1     | 424.45    | 122.18 | 635.69    | 173.31 |
In order to probe more deeply into the radiometric differences between both MS sensors and to compare with PAN images, Figure 7 presents the $Br$ value corresponding to each subarea (U1, U2, M1, M2 and B) within the study site computed from the five VHR images for each MS common bands as well as PAN band. Clear differences can be noted between $Br$ values computed from GE1 Geo PAN and WV2 ORS2A images. In the case of PAN images, average values for the five considered areas of 0.392, 0.389 and 0.496 for GE11, GE12 and GE13 respectively were reported [Aguilar et al., 2014], whereas higher $Br$ values of 0.787 and 0.902 were attained for WV21 and WV24. Moreover, the differences in $Br$ between GE1 and WV2 PAN images were much lower on the zone B (bare and agricultural soil without urban areas) than in the urban or mixed zones (U1, U2, M1 and M2). The last was due to the lower number of edges in agricultural areas where compute $Br$ value than in urban or mixed zones. In the MS classical bands, the three GE1 MS images showed a similar $Br$ value for every
MS bands. However, there was a big difference between both WV2 MS images. Probably, it might be due to operational aspects of the image acquisition or different atmospheric conditions [Poli et al., 2010]. It is also noted that the standard deviation computed from the DNs’ histogram was not always related to Br values. For example, WV24 MS presented the highest Br values (Fig. 7). However, its standard deviations resulted lesser than the ones attained for MS image identified as WV21 for Red and NIR1 bands (Tab. 7). Anyway, unlike PAN images, there were no clear differences in the Br values computed from the MS bands of GE1 and WV2 images. In addition, and just the same as for the PAN images, higher Br values were computed in bare soil and agricultural as compared to those obtained in urban or mixed ones. Finally, it is worth noting that we have focused on Br here because any significant difference was detected between GE1 and WV2 images about Nr index.

![Figure 7 - Blur ratio (Br) computed for each MS common bands (R, G, B, NIR) and PAN band from GE1 and WV2 images. U1 and U2: urban areas. M1 and M2: mixed areas containing features belonging to both urban and agricultural or base soil. B: agricultural and bare soil.](image_url)

Aguilar et al. Comparing GeoEye-1 and WorldView-2 MS imagery
Conclusions

Regarding the geometric analysis carried out on VHR satellite MS images from GE1 and WV2, and always working under operational conditions, the best and statistically significant (p<0.05) geopositioning accuracy at orientation phase when using both sensors single MS images was attained by using RPC0 model. Although only one highly accurate GCP would be needed to compute this model, a higher number of GCPs ranging from four to seven would be fully recommended. In this way, accuracies close to 0.60 pixels were achieved by using RPC0 with the support of seven GCPs for each MS image.

With regard to the orthorectified images generated under ideal conditions (RPC0 and seven GCPs), similar accuracies were achieved from MS images by applying a highly accurate LiDAR derived DEM or a less accurate photogrammetrically derived one. In the same way, the influence of off-nadir viewing angle on the MS orthoimages accuracy could not be clearly demonstrated. The final orthoimages computed from GE1 Geo MS images presented the highest and statistically significant (p<0.05) planimetric accuracy, whereas WV2 ORS2A and WV2 Basic MS orthoimages yielded similar accuracies. Summing up, geometric accuracy values (RMSE$_{2D}$) very close to one pixel (2 m GSD) can be attained in MS orthoimages from VHR GE1 and WV2 MS images when counting on off-nadir angles lesser than 24º and relatively coarse and not very accurate DEMs (estimated vertical accuracy of around 1.3-1.4 m).

Concerning the radiometric information contained within VHR MS images from GE1 and WV2, slightly differences between the common bands of the map-projected MS images of both sensors were found. They were mainly quantified in terms of a higher DNs’ histogram compression for WV2 ORS2A than for GE1 Geo. Regarding the Br index, it turned out to be a good estimator for carrying out a no-reference image quality assessment. Although the observed lower range of DNs for WV2 ORS2A images and the differences regarding Br values were not as clear for MS images as in the case of PAN image, it would be extremely important to take this research line on to investigate whether the aforementioned radiometric differences between the tested satellite MS sensors could actually affect the final classification accuracy results. Anyway, the aforementioned radiometric behavior of GE1 and WV2 VHR images, both MS and PAN, should be contrasted in further works. Moreover, a thorough comparison between MTF and Br ratio should be carried out in order to have a metric quantifying of the sharpness of the VHR satellite images. However, the last would be worthy of an independent work mainly addressed on PAN images.

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