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CALIBRATION OF THE SSOT MISSION USING A VICARIOUS APPROACH BASED ON OBSERVATIONS OVER THE ATACAMA DESERT AND THE GOBABEB RADCALNET STATION

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ABSTRACT:

This work presents the results of the absolute radiometric calibration of the sensor on-board the "*Sistema Satelital de Observación de la Tierra*" (SSOT) using the vicarious approach based on in-situ measurements of surface reflectance and atmospheric retrievals. The SSOT mission, also known as FASat-Charlie, has been successfully operating for almost nine years –at the time of writing–, exceeding its five-year nominal design life and providing multispectral and panchromatic imagery for different applications. The data acquired by SSOT has been used for emergency and disaster management and monitoring, cadastral mapping, urban planning, defense purposes, among other uses. In this paper, some results of the efforts conducting to the exploitation of the SSOT imagery for remote sensing quantitative applications are detailed. The results of the assessment of the radiometric calibration of the satellite sensor, performed in the Atacama Desert, Chile, using the data acquired and made available by the Gobabeb Station of Radiometric Calibration Network (RadCalNet), Namibia, are presented. Additionally, we describe the process for obtaining the absolute gains for the multispectral and panchromatic bands of the SSOT sensor by adapting the reflectance−based approach (Thome et al., 2001). The outputs achieved from the Atacama data collection have generated consistent results and average differences in the order of 3% with respect to the RadCalNet TOA reflectances. The presented results are an example of the benefits of having access to the RadCalNet data and how it increases the opportunity of conducting Cal/Val activities using endorsed calibration sites.

1. INTRODUCTION

As it has been widely studied and recognized, the Calibration and Validation (Cal/Val) activities, performed for monitoring and updating the radiometric response of a satellite sensor, are crucial for the achievement of the objectives of a mission and the development of remote sensing quantitative applications (Chander, 2013). According to Dinguirard and Slater (1999), it is of paramount importance to discriminate if the variations observed in the received signal come from the earth's surface –or from the phenomena under study–, or if these differences have been generated by fluctuations in the radiometric response of the instrument that senses the data. Hence, as the calibration coefficients vary across the whole operational life of a sensor, it is necessary to apply and integrate different approaches for updating and compensating the deviations detected in its radiometric response (Slater, 1986; Lachérade et al., 2013).

While in-flight, the absolute radiometric calibration of a satellite sensor can be conducted either by direct or vicarious methods (i.e. indirect) (Koepke, 1982; Slater and Biggar, 1996). The direct method relies on the on-board calibrator (OBC) data, whereas the vicarious methods do not (Chander, 2013). Vicarious approaches are multiple and are based on observations performed over different zones or natural surfaces, such as instrumented sites, deserts, or oligotrophic oceanic areas (Meygret et al., 2000; Thome, 2001). Besides, depending on the technique, the vicarious approaches can also utilize in-situ measurements, namely surface reflectance, radiance or irradiance, and data collected for the estimation of atmospheric retrievals (Slater et al., 1987).

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In this regard, some Cal/Val tasks have been conducted for the exploration and implementation of calibration methods and protocols for monitoring the New AstroSat Optical Modular Instrument-1 (NAOMI-1), the sensor on board the SSOT. This mission, developed by EADS Astrium, was launched on a Soyuz-STA/Fregat rocket from the Kourou Cosmodrome, French Guiana, on December 16th, 2011. The design lifetime was 5 years and the nominal ground sampling distance (GSD) of the bands are 5.8 m and 1.45 m (multispectral and panchromatic, respectively). The swath of the scenes is ~10 x 10 km. The relative spectral responses (RSR) of the sensor bands are shown in figure 1.

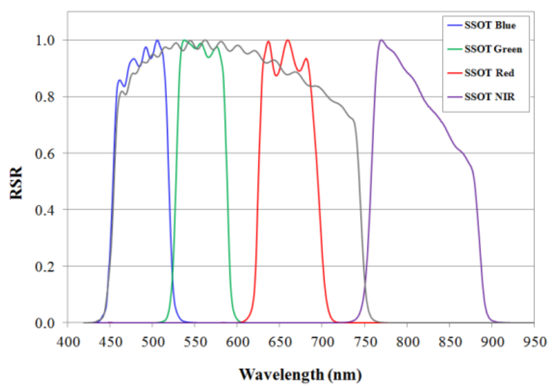

Figure 1. Relative Spectral Response (RSR) of the NAOMI-1 sensor bands.

Since the SSOT lacks on-board calibration infrastructure, this research has relied on vicarious methods, particularly using the reflectance-based approach (Thome at al., 2001). Some works in the field of Cal/Val of this sensor have been reported by Mattar et al. (2015) and Barrientos et al. (2016), using surface reflectance measurements and the cross-calibration technique based on simultaneous nadir observations (SNO's), respectively.

The satellite monitors the Committee on Earth Observation Satellites (CEOS) - Working Group on Calibration & Validation (WGCV) endorsed sites, either instrumented sites or pseudo-invariant calibration sites (PICS) (Cosnefroy et al., 1996). More recently, the stations established by the Radiometric Calibration Network (RadCalNet) Working Group (WG) (RadCalNet WG, 2019) are being monitored, as well. RadCalNet is an initiative implemented by the CEOS-WGCV, and it is a group that includes researchers from different space and governmental agencies, academia, among others. The network has implemented 4 automated stations in La Crau, France (LCFR); Railroad Valley, US (RVUS); Gobabeb, Namibia (GONA); and Baoutou, Inner Mongolia, China (BTCN) (Bouvet et al., 2019).

RadCalNet provides SI-traceable surface and top-of-atmosphere reflectance in the range 380–2500 nm, sampled at 10 nm, and at 30-minute time intervals. Besides, atmospheric retrievals (aerosol optical depth at 550 nm, water vapor content, columnar ozone, Ångström exponent), meteorological data (surface pressure and surface temperature) at the same periodicity, and the uncertainties for all the parameters are provided. Thanks to the efforts of the CEOS-WGCV, the RadCalNet data has been made publicly available in June 2018 through the portal https://www.radcalnet.org (RadCalNet WG, 2019). Figure 2 presents SSOT scenes collected over the four RadCalNet reference sites.

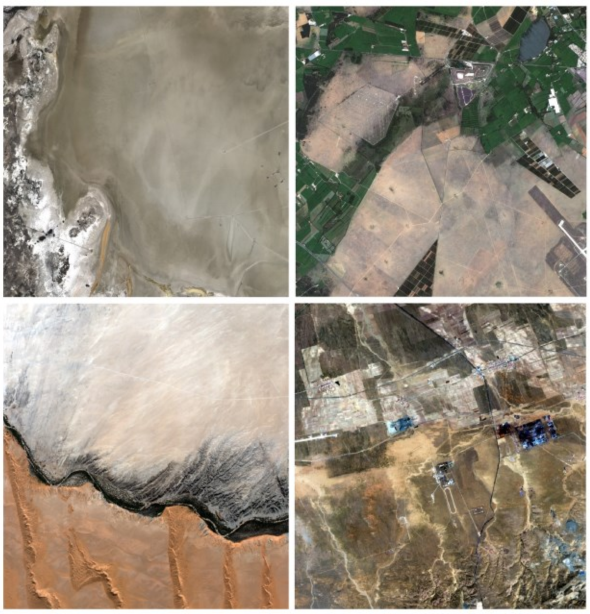

Figure 2. RadCalNet sites monitored by SSOT: Railroad Valley (UL), La Crau (UR), Gobabeb (LL) and Baotou (LR).

In the next sections, we describe how the reflectance-based approach has been adapted and implemented for updating, monitoring, and assessing the absolute radiometric calibration of SSOT. We present the outputs obtained from the last campaign in the Atacama Desert and the results achieved using the data provided by RadCalNet GONA station.

2. ABSOLUTE RADIOMETRIC CALIBRATION OF THE SSOT IN THE ATACAMA DESERT, CHILE

2.1 Description of "El Tambillo" calibration site

In August 2014, a field campaign for the spectral and atmospheric characterization was conducted in the area of "El Tambillo" (TA-1), located beside the Atacama Salt Flat, Chile (Pinto et al., 2015; Mattar et al., 2017). This area is characterized by hyper-arid conditions, high spatial homogeneity in the order of 2%, very low aerosol loading, and is situated nearly at 2.400 m.a.s.l., providing appropriate conditions for earth-observing sensor calibration and validation, as suggested by Scott et al. (1996). Also, a high amount of solar incident radiation and low probability of cloud cover have been reported (Rondanelli et al., 2015; Molina et al., 2017). The coordinates of the calibration site are 23.134° S, 68.071° W.

The study area in the Atacama Desert is shown in figure 3, it includes an SSOT true color combination of "*El Tambillo*" calibration site and the spatial homogeneity map. This map was obtained by averaging the spatial coefficient of variation (CV %) of the multispectral bands. At the satellite level, the average observed CV of the site is lower than 1.2%.

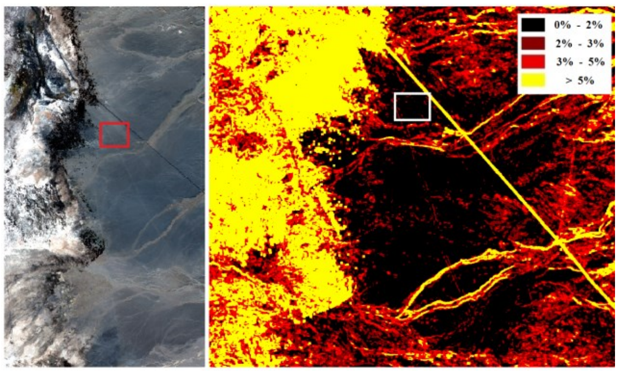

Figure 3. Spatial homogeneity of the calibration site in the Atacama Desert expressed in terms of spatial coefficient of variation.

Multiple campaigns have been performed in the Atacama Desert by a group that includes members of the Aerial Photogrammetric Service (SAF), Space Operations Group (GOE), *Instituto Nacional de Pesquisas Espaciais* (INPE) and Laboratory for the Analysis of the Biosphere (LAB) of the University of Chile. Because of this work, along with the participation in trainings and field campaigns in established calibration sites (Lau et al., 2018), the application of vicarious protocols has been possible. In the absence of a sunphotometer, the reflectance-based method has been adapted. The retrievals derived from sun irradiance measurements have been replaced by atmospheric products provided by the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC) of NASA.

Due to the advantageous characteristics of the site, this particular area in the Atacama Desert was one of the candidates considered for the installation of the fourth RadCalNet station (Bouvet, 2014). In figure 4 we provide some graphs that reveal the main atmospheric characteristics of the area, specifically the histograms obtained from the outputs of the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) algorithm (GMAO, 2019). The selected variables are monthly average values of aerosol optical depth at 550 nm (AOD_{550}), atmospheric content of water vapor (g/cm^2) and total columnar ozone concentration (DU). The data were accessed through the Geospatial Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI) (Acker, Leptoukh, 2007). The analyzed time period is 1980-2019.

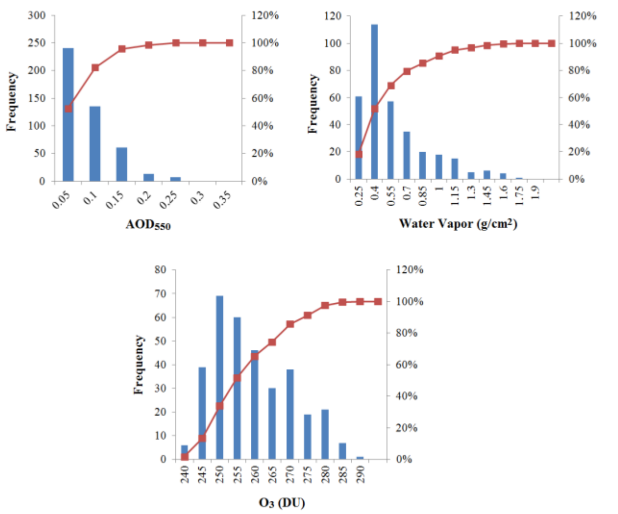

Figure 4. AOD_{550}, water vapor and columnar ozone over the calibration site in Atacama.

2.2 Data collection in the Atacama Desert

The last acquisition over “El Tambillo” (TA-1) site was performed on June 18th of 2019 at 14:58 UTC. The surface reflectance measurements for the calibration of the SSOT have been obtained using a GER-2600 spectroradiometer and a Spectralon reference panel. The radiance measurements of the reference panel are followed by the measurements of the radiance of the site surface. The relative reflectance values are converted to absolute surface reflectance values by applying the calibration factors of the reference panel, estimated at laboratory against NIST traceable sources. In figure 5 we show the average surface reflectance factor and the variability across the calibration site. The coefficient of variation of the absolute reflectance of the site is in the order of 3% across the whole spectral range.

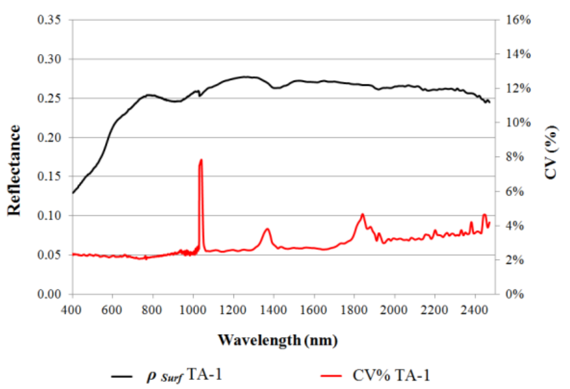

Figure 5. Surface reflectance of the Atacama calibration site. The peak of the CV observed around 1030 nm is located in the transition area of the Si and PbS detectors of the GER-2600 spectroradiometer.

The calibration area is a polygon of 50 m x 50 m, systematically sampled by means of equally spaced transects, using a method known as stop and measure (Lau et al., 2018). The use of this measurement protocol is determined by the characteristics of the available instrumentation (i.e. GER-2600).

In figure 6 a general sight of the study area is presented along with pictures obtained during two field campaigns, using different spectroradiometers for data collection. The stop and measure method using the GER-2600 and a Spectralon panel normally used during the field trips of the research group is shown in the lower-left picture.

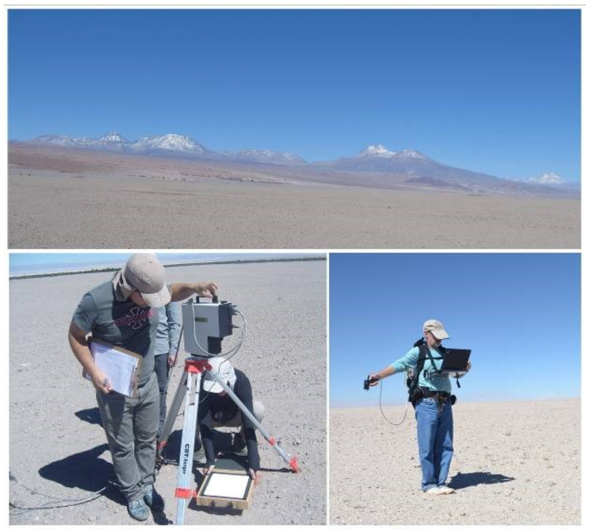

Figure 6. Field campaigns at "El Tambillo" calibration site, Atacama Desert, Chile.

2.3 Atmospheric characterization and modelling

For the atmospheric characterization, information from TERRA-Moderate Resolution Imaging Spectrometer (MODIS) L2 products (MOD04, MOD05, and MOD07) and from MERRA-2 have been explored and used (LPDAAC, 2019; GMAO, 2019). In the case of MERRA-2 data, hourly temporal resolution data, made available after the respective time-lag (1-2 month), were used as reference. The AOD_{550}, the water vapor content and total column ozone during the overpass were 0.018, 0.39 g/cm^2 and 256 DU, respectively. The time difference between the SSOT and TERRA-MODIS acquisitions was 27 minutes.

The propagation of the in-situ measurements to TOA level was performed using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) V1.1 radiative transfer code (RTC) (Vermote et al., 1998). The radiometric calibration parameters were obtained through a linear fit between the digital numbers (DN’s) of the calibration area and at-sensor radiances.

3. RADCALNET BASED CALIBRATION

3.1 Imagery acquisition over the GONA station

The SSOT performed 2 quasi-nadir acquisitions over Gobabeb RadCalNet station, Namibia. The observation conditions and atmospheric information are detailed in table 1.

Date	05-10-2019	07-07-2019
UTC Time	9:29:41	9:27:35
Sat. Incidence Angle	2.313	3.532
Satellite Azimuth	278.516	98.821
View Angle Along Track	−0.128	0.192
View Angle Across Track	2.099	−3.205
Sun Azimuth	29.270	28.434
Sun Zenith	45.877	52.025
AOD 550 RadCalNet	0.047	0.016
WV (g/cm^2) RadCalNet	1.46	1.03
O_3 (DU) RadCalNet	307	301

Table 1. Atmospheric retrievals, observation and illumination geometry for the acquisitions over Gobabeb.

GONA is equipped with a 12-filter CIMEL sunphotometer that operates under the AERONET concept, using a data collection protocol that measures direct and diffuse irradiance, and directional surface reflectance (Bouvet et al., 2019; RadCalNet WG, 2019). This system, installed on July 2017, is known as RObotic Station for Atmosphere and Surface (ROSAS) and works mounted at the top of a 10 m-height mast (Meygret, 2011). The coordinates of the GONA calibration site are 23.6002º S, 15.11956ºE.

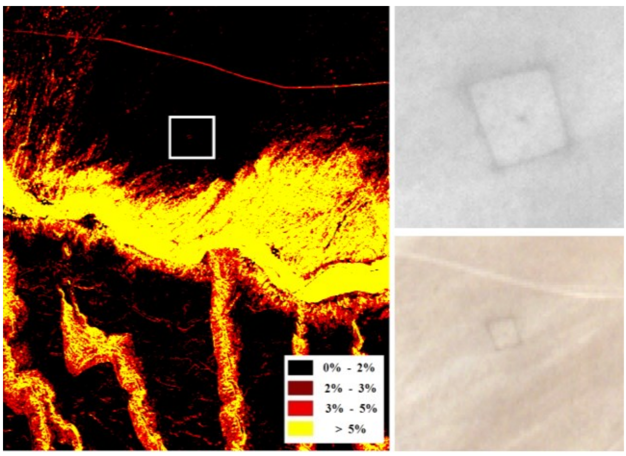

Figure 7. Spatial homogeneity map (CV%) of the Gobabeb calibration site as observed by SSOT multispectral bands (left) and subsets of the higher and lower resolution imagery (right).

The TOA simulations for all the data collected by the RadCalNet stations are processed using the MODerate resolution atmospheric TRANsmission (MODTRAN) v5.3 radiative transfer code (Berk et al., 2014). As stated, the provided TOA reflectance spectra are representative of a disk of 30 m radius, with its center on the mast (RadCalNet WG, 2019).

3.2 Data processing and assessment of the Atacama Desert results

The data processed by RadCalNet was downloaded from the portal. The data selected for processing were collected at 09:30 UTC, quasi simultaneously with the satellite acquisitions. Two approaches were followed for the calibration: the assessment of the results obtained with the data collected during the last acquisition over the Atacama site, and the estimation of the absolute gains using the data collected over GONA.

3.2.1 Assessment of the radiometric calibration obtained using the Atacama Desert data: The assessment of the results obtained using the calibration coefficients estimated from the Atacama data collection was accomplished at TOA level. The at-sensor radiance calculation was performed using (1):

$$L_\lambda = Gain * DN \tag{1}$$

where L_λ = cell value as at-sensor radiance *(W/m²·sr·µm)*
$Gain$ = gain value for a specific band *(W/m²·sr·µm)*
DN = cell value digital number

Then, the TOA reflectance values were obtained according to the standard formula (2) and the reported exoatmospheric sun irrandiance values:

$$\rho_{TOA} = (L_\lambda * \pi * d^2)/ (E_0 * \cos\theta) \tag{2}$$

where ρ_{TOA} = cell value as TOA reflectance
L_λ = cell value as at-sensor radiance
d^2 = sun-earth distance in astronomical units
E_0 = exoatmospheric sun irrandiance
θ = zenith angle

Using the equation 3, the TOA reflectance spectrum, provided for the time and date of the overpass of the satellite over the site, was convolved to the RSR of the sensor:

$$\rho_i = \int \rho_\lambda \, RSR_\lambda \, d\lambda \;/\; \int RSR_\lambda \, d\lambda \tag{3}$$

where ρ_i = TOA reflectance for the band i
ρ_λ = TOA spectral reflectance
RSR_λ = relative spectral response of the sensor

After the convolution of the TOA reflectances (i.e. MODTRAN simulated values), the ratio between SSOT values to RadCalNet were calculated for all the bands.

3.2.2 Estimation of calibration coefficients using GONA in-situ data and radiative transfer simulation: Using the surface reflectance data, the atmospheric parameters provided by RadCalNet, and the information of illumination and acquisition geometry, the TOA simulations were run using 6SV1.1. As in the Atacama case, this process was performed under the assumption of Lambertian behavior and no adjacency effects. Once the results at TOA level were obtained, the convolution using the RSR of SSOT was performed using (3). Then, through a least-squares linear fit, the coefficients for both dates were estimated and compared with the results obtained using the data collected in Atacama.

4. RADIOMETRIC CALIBRATION RESULTS

4.1 Radiometric calibration based on the Atacama Desert data collection

The calibration coefficients for at-sensor radiance calculations obtained from the data acquisition in the Atacama Desert site are provided in table 2. The exoatmospheric sun irradiance values for the NAOMI-1 bands are included as well. As recommended by the CEOS-WGCV, the Thuillier solar spectrum has been used (Thuillier et al., 2003).

https://doi.org/10.5194/isprs-annals-V-1-2020-133-2020 |

Band	Blue	Green	Red	NIR	Pan
Gain	1.1151	0.9588	0.7733	0.5747	0.4541
E_0	1975.85	1825.06	1536.95	1027.58	1698.04

Table 2. Absolute gains for SSOT NAOMI-1 ($W/m^2 \cdot sr \cdot \mu m$) and exoatmospheric sun irradiance values ($W/m^2 \cdot \mu m$).

4.2 Radiometric calibration based on GONA RadCalNet station

4.2.1 Assessment of the Atacama results using GONA data: The results, including the percentage difference values (i.e. TOA reflectance provided by GONA v/s the value obtained using the gains of Atacama), are detailed in table 3.

Band	Ratio May	Δ% May	Ratio July	Δ% July	Average Ratio
Blue	0.969	3.1%	0.992	0.8%	0.981
Green	0.990	1.0%	1.019	−1.9%	1.005
Red	0.951	4.9%	0.985	1.5%	0.968
NIR	1.022	−2.2%	1.061	−6.1%	1.042
Pan	0.977	2.3%	1.009	−0.9%	0.993

Table 3. Proposed calibration results for May and July 2019 for SSOT.

The obtained ratios show low to moderate depart from unity, presenting values in a range previously reported by other researchers. These groups have used RadCalNet data as reference for monitoring and assessing the radiometric behavior of satellites such as Sentinel 2A/B, Landsat 7/8 and TERRA/AQUA MODIS, Worldview-3 (Wenny et al., 2016; Angal et al., 2018, Bouvet at al., 2019; Jing et al., 2019).

However, it must be considered that the results presented in this particular contribution depend on the response and aging of the sensor being studied, the approach followed for the implementation of the reflectance-based method, the periodicity of Cal/Val activities, the characteristics of the sites, and the conditions during the overpass, among others. All those aspects support the need for monitoring the other sites of the network, as shown in the cited research.

4.2.2 Radiometric calibration results based on GONA in-situ data and radiative transfer simulation: in table 4 we provide the absolute gains estimated using the surface reflectance, atmospheric data, the 6SV1.1 RTC and both SSOT acquisitions over the Gobabeb RadCalNet station:

Site	Date	Blue	Green	Red	NIR	Pan
GONA	05/10/19	1.152	1.008	0.838	0.618	0.470
GONA	07/07/19	1.121	0.962	0.806	0.584	0.449

Table 4. Absolute gains estimated using acquisitions and field data collected at Gobabeb RadCalNet station ($W/m^2 \cdot sr \cdot \mu m$).

In general, the absolute gains obtained from the 3 datasets show good consistency, as shown in figure 8. The closer agreement is observed between the gains estimated with the acquisitions of June and July, in Atacama and GONA, respectively (the exception is the red band). It must be mentioned that those dates –May and July– were selected due to the temporal proximity to the June SSOT acquisition over the Atacama site. Other acquisitions were requested and planned; however, the conditions were not appropriated for data collection and there were not available in-situ measurements at GONA.

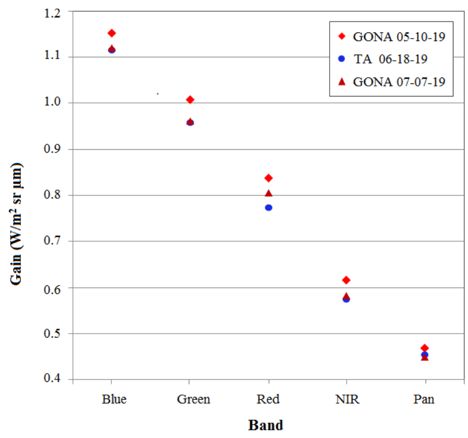

Figure 8. Comparison of the results obtained from the data collected in the Atacama v/s the outputs using GONA RadCalNet station data.

Besides, for the visualization of the discrepancies introduced mainly by the RTC option, in table 5 we detail the percentage differences of the TOA reflectances provided by RadCalNet and the 6S simulated results, after the RSR convolution (MODTRAN values as reference):

Band	Blue	Green	Red	NIR	Pan
05-10-2019	−0.5%	−1.6%	−1.2%	−1.8%	−1.6%
07-07-2019	−0.3%	−1.0%	−1.5%	−1.1%	−0.9%
Average	−0.4%	−1.3%	−1.3%	−1.5%	−1.2%

Table 5. Comparison of the convolved simulated TOA reflectance values.

The observed differences are below 2% and, as the aerosol loading is very low, they are mostly influenced by the fluctuations on the water vapor content and the ozone concentration in the air column. Another factor that cannot be neglected, is that some absorption peaks of atmospheric gases are sensed by the RSR of the NAOMI-1 sensor, namely the O_2 feature at ~690 and ~760 nm, and the H_2O absorption area at ~740 and ~830 nm.

Since the RadCalNet WG has been working on the improvement of their information and generating the RadCalNet 2020 data collection, the presented results will be re-evaluated. As stated by the WG, the improvements consider advances in the quality control, processing of surface reflectance and atmospheric data, uncertainties estimation, and changes in the full width at half maximum (FWHM) of the function used for spectral integration, among others (RadCalNet WG, 2020).

5. CONCLUSIONS AND FUTURE WORK

In this work the calibration of the SSOT using the Atacama site and RadCalNet data has been addressed. The results presented in this document are very promising, particularly for smaller research groups who initiate the implementation of vicarious protocols, in the frame of new and modest space programs. For this reason, the RadCalNet sites should be monitored during the rest of the operational life of the SSOT satellite. The monitoring, along with additional research activities, will allow the integration of the historical imagery archive to the data that will be collected either by a continuity mission or by other platforms.

Since RadCalNet data was made publicly available, enormous possibilities for the calibration and the assessment of the results obtained using other calibration sites are open. This has particular importance for the groups which have been working with modified approaches, mainly when available tools and resources are limited. In this sense, as stated by Bouvet et al. (2019), there are more than 300 users from over 35 countries, revealing that RadCalNet data will foster the research and operational activities in the Cal/Val of other new groups and will positively impact on the frequency in which these tasks are conducted.

Also, the proliferation of low cost missions (i.e. micro/nano satellites lacking the OBC) operating under the constellation concept, along with the increasing imagery data flow from them, bring challenges and needs (Czapla-Myers et al., 2017). Not only the study of these individual sensors, but also the intercalibration among the different sensors of any constellation, demand integrated vicarious strategies for calibration and validation (Chander et al., 2013). In addition, the exploitation and harmonization of historical data sets, and the consistent integration with the imagery of other missions, reinforces the importance of the application of vicarious methods based on SI-traceable in-situ measurements (Datla et al., 2016). Then, it will be of great importance increasing the amount of validation activities and the assessment of the derived products and, in such case, RadCalNet is a key contribution.

Particularly, in the case of the SSOT mission, it is strongly recommended increasing the number of acquisitions over the network sites (i.e. whenever possible). This will be of benefit for the monitoring of the radiometric response of the sensor before its operational life ends and for the assessment of L2 products. Besides, a topic that needs to be addressed in the processing chain is the understanding of the uncertainty propagation. Other topics, such as the impact of other parameters on the absolute radiometric calibration, will be considered for future research (e.g. relative radiometric calibration, quantization error, BRDF characterization of the calibration sites). This point has been identified as a future work that will help to improve the obtained results in the Cal/Val area.

Eventually, all the conducted experiments and experiences will be important for the design and implementation of a calibration program of future Chilean satellite missions. The lessons obtained from the feedback with other research groups will lead to improvements in the field protocols, best practices in processing and analysis stages. The Cal/Val activities in Atacama Desert will continue along with the remote monitoring of other CEOS endorsed sites.

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