

Global Assessment of Directional Effects in the Intercalibration of Optical Satellite Instruments With the TRUTHS Mission

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Abstract—Upcoming SI-traceable satellite (SITSat) missions such as traceable radiometry underpinning terrestrial and helio studies (TRUTHS) aim to achieve unprecedented accuracy for SI-traceable measurements of the Earth-reflected radiation. These measurements will support the generation of low-uncertainty climate records and significantly improve the calibration of other sensors. In such a context, the calibration transfer rather than the reference sensor dominates the uncertainty budget. This study presents an end-to-end global intercalibration simulator capable of assessing the potential uncertainty for multiple scenarios that consider the interrelation of different error sources and match-ups. We first define the sensor-to-sensor match-ups through an orbital analysis that is followed by a top-of-atmosphere (TOA) radiance modeling of each match-up. Finally, we calculate the radiometric uncertainty based on different error sources combined globally. In this first implementation, we have calculated the match-ups of TRUTHS against observations by the Copernicus Sentinel-2A satellite over land areas throughout the year. We calculate the angular mismatch for both viewing differences and solar changes from different overpass times. We define multiple intercalibration scenarios based on temporal, angular, or cloud constraints. These first results show that considering overpasses up to 15-min difference, low cloud probability, and matching field-of-view (FoV), within 5°, we sample most land areas with a mean error <0.1% and bias regression <0.5%. We have also restricted the sun zenith angle (SZA) to 60° to minimize solar angle and view azimuthal dispersion over the poles. This also results in data gaps of several months that might be complemented with dedicated maneuvers or dedicated processing of these polar-region match-ups.

Index Terms—Digital twin, intercalibration, sentinel 2, traceable radiometry underpinning terrestrial and helio studies (TRUTHS), uncertainty.

I. INTRODUCTION

THE last decade has seen the development of missions such as traceable radiometry underpinning terrestrial and

helio studies (TRUTHS) [1] and climate absolute radiance and refractivity observatory (CLARREO) [2], now implemented as a NASA pathfinder mission [3], designed explicitly to provide highly accurate and trusted système international (SI)-traceable climate records. These missions were also designed with the specific intent to provide “in-space” reference calibration to other optical satellite sensors to improve their performance and interoperability. In recognition of this new class of sensor, the Committee on Earth Observation Satellites (CEOS) and World Meteorological Organization Global Space Intercalibration System (WMO-GSICS) have created the name SI-traceable satellite (SITSat) together with an associated formal definition [4].

The TRUTHS satellite achieves and evidences its low SI-traceable uncertainty through regular re-calibration of its hyperspectral imaging spectrometer (HIS), on-board, directly linked to a space-borne primary reference standard, a cryogenic solar absolute radiometer (CSAR). The on-board calibration system (OBCS) provides tunable spectrally resolved radiation that can be distributed between the CSAR, where its power is measured, and the HIS where the now-known power is transformed to radiance illuminating and calibrating the HIS. The process can be considered a space-adapted mimic of a terrestrial calibration in a national metrology institute. The CSAR is a space adaptation of the terrestrial cryogenic radiometer which has served as the primary SI standard of choice for nearly 40 years [5]. TRUTHS is currently in the Phase B2 implementation phase as an ESA Earthwatch mission funded by a consortium of member states led by the U.K. in partnership with Switzerland, Greece, Romania, Czech Republic, and Spain with a target launch date in 2030. The mission has a design goal to globally and continuously measure Earth-reflected spectral radiance from 320 to 2400 nm with a spectral resolution of 4–8 nm, ground sampling distance of 50 m, and uncertainty goal of 0.3% ($k = 2$). In practice, due to data volume constraints, the full spatial resolution is likely to be limited to specific targets, in particular those used for calibration of other sensors, such as the CEOS reference sites [6].

The upcoming SITSat such as TRUTHS, will constitute a system that not only enables harmonization but the establishment of SI-traceability and performance enhancement. In preparation for such a scenario where the reference sensor does not limit the uncertainty of an intercalibration process,

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the study and correction of sources of errors related to the calibration transfer process, e.g., spatial and temporal mismatch, becomes highly relevant.

One of the first broad studies of the error sources associated with satellite intercalibration identified eight dimensions when matching two spacecraft in orbit and studied several of these and their impact on calibration against the proposed CLARREO mission [7]. Similarly, Chander et al. [8] studied the effect of spectral responses, spectral resolution, spectral filter shift, geometric misregistrations, and spatial resolutions. This work also introduced a combined uncertainty of the different effects with final figures that represent overall bounds on the achievable uncertainty estimate. Later Gorroño et al. [9] studied the uncertainty in the spectral, spatial, and temporal dimensions associated with an intercalibration with the TRUTHS satellite as a reference sensor. The study effectively describes the contributions as an error distribution rather than bounds of uncertainty. However, the combination of them does not include all the potential dimensions in the intercalibration. Further work has been carried out in different studies but exploring each of the dimensions independently [10], [11], [12], [13], [14].

The orbit definition for the TRUTHS satellite is another critical step since it defines the number of match-ups with the target sensor, their locations, and angular configuration among others. A conventional sun-synchronous orbit flying in close time tandem with another specific satellite could clearly have near-continuous match-up opportunities within the tandem time delay window. However, satellites outside of this window, other than geostationary satellites, would rarely if ever have time-optimized match-ups. An orbital model that identifies the match-ups between CLARREO and sun-synchronous polar orbital sensors such as clouds and the Earth's radiant energy system (CERES) or visible infrared imaging radiometer suite (VIIRS) is presented in [15]. The work not only identifies the valid match-ups between the sensors but also discusses the number of potential samples required to achieve the climate quality uncertainty in the intercalibration, considering the relatively low instantaneous signal-to-noise ratio (SNR) of CLARREO (nb, observations are intended to be spatially and temporally averaged reducing sensitivity to single pixel SNR). However, the study does not consider all the potential uncertainty sources and the correlation among them in a global context.

The interrelation between different errors (i.e., error correlation) is a factor in deriving an appropriate combined estimate of the potential radiometric uncertainty that could be attributed to the intercalibration process. The general assumption of an uncorrelated scenario (i.e., quadratic summation of different uncertainty contributions) is not necessarily correct and a case-by-case scenario must be carefully assessed. Furthermore, the intercalibration methods generally require the accumulation of different sensor-to-sensor match-ups. This requires the development of a methodology that is capable of defining the achievable accuracy based on an error distribution from which an uncertainty estimate can be derived.

This study defines and implements an end-to-end intercalibration simulator that is capable of assessing the

potential uncertainty on a case-by-case basis for multiple intercalibration scenarios. Here we aim to connect the orbit sampling, the specific scene modeling of each sensor-to-sensor match-up, and the combination of different error sources at a global level. In a way, we are aiming to generate a digital twin prototype for intercalibration studies. For this first study, we present the uncertainty introduced due to an angular mismatch between the TRUTHS satellite and the target reference over land areas. These angular differences can be introduced by differences in satellite viewing angles but also by different solar illumination angles introduced by the delay between satellite overpasses. Furthermore, these angular differences can result in top-of-atmosphere (TOA) radiance errors coming from both surface and atmospheric angular sensitivity.

The general intercalibration methodology aims at measuring ideally identical targets by two sensors with the same view at the same time and possessing similar spatial and spectral responses (e.g., GSICS [16], [17] or CLARREO [2]). For polar-orbiting satellites, this is generally possible through satellite maneuvers that align the angular configuration of the TRUTHS sensor to the target satellite if they differ from a nominal nadir view. CLARREO Pathfinder pointing system is based on a gimbal system that provides flexibility along the orbit to systematically task-aligned observation for a couple of missions. It results in a small difference in angles that are further corrected to minimize its effects [18].

Calibrating third satellite sensors with TRUTHS is one of the primary mission's objectives. Direct intercalibration, with the ray-tracing methods as discussed in the present study, will be essentially achieved with opportunistic quasi-simultaneous near-nadir observations. Coincident overpasses in nadir-views will regularly happen between TRUTHS and other sensors on polar orbits, and between TRUTHS and geostationary missions, at their subsatellite points, yielding a statistically significant match-up database over time. Vicarious calibration, e.g., characterizing pseudo-invariant calibration sites and their surface bidirectional reflectance factor (BRDF) with TRUTHS, is not in the scope of this study. This will require TRUTHS observations at different viewing angles, achieved with dedicated maneuvers orienting the entire platform and pointing TRUTHS at the calibration targets under the required slanted views. Occasional maneuvers are foreseen to acquire simultaneous off-nadir observations between TRUTHS and other sensors, and hence complement the direct intercalibration study at large angles. This is at this stage foreseen essentially with geostationary missions. Such maneuvers will however be limited, to about one per day, because the associated propellant consumption must be traded against the orbit maintenance and de-orbiting requirements and hence the mission lifetime. Maneuvers also result in data outages, which should be kept to a minimum because nominal nadir series form the backbone of the benchmark climate data record, the other primary mission's objective. Therefore, this study explores and shows the potential of opportunistic near-simultaneous overpasses of both nadir viewing and angle-mismatched observations, without satellite pointing and without radiometric corrections. Stringent collocation (angular and temporal) criteria are applied, with the view that collocation errors at a single match-

up level will statistically reduce by accumulating different matchups (angles and scene types) over the year.

In this manuscript, the selected target satellite is the Copernicus Sentinel 2 (S2). The Copernicus S2 mission currently consists of two satellites (S2A and S2B) that together sample the Earth with better than a five-day revisit. Its main payload instrument measures 13 spectral bands spanning the visible, near-infrared (VNIR), and shortwave infrared (SWIR) at spatial resolutions of 10, 20, or 60 m [19].

The specific study of the angular mismatch supports both the definition of an orbit and the pointing strategy for the TRUTHS mission that optimizes the intercalibration accuracy with minimum impact on the global benchmark accuracy. The continuous development of this simulator is expected to become the basis for the definition of an intercalibration strategy for the TRUTHS mission and/or similar optical instruments.

The manuscript is structured in two sections consisting of methodology (Section II) and results (Section III). Section II is subdivided into a definition of the end-to-end general framework (Section II-A), the orbit definition and match-up data (Section II-B), and the modeling of TOA radiance including both the scene surface and atmosphere (Section II-C). Section III first describes the distribution of sensor-to-sensor match-ups based on parameters such as time differences, latitude, or angular distribution. It then provides the results of the intercalibration uncertainty assessment for each considered scenario.

II. METHODOLOGY

A. General Framework

The general idea of the proposed methodology is that of simulating the end-to-end process of intercalibration at a global scale. That is, we aim to use the orbital projections to generate all the resultant match-ups between two satellites and the associated characteristics of their observations that impact the match-up uncertainty. We could refer to this as an observational digital twin for intercalibration studies.

The logic of this concept is represented in Fig. 1.

The left end of the schema includes the *orbit match-up generator* and the *match-up products database*. The former provides location and angular information at the event (detailed discussion in Section II-B) whereas the second ingests the relevant information to model the surface BRDF and the atmosphere. These two are fundamental information for the module *TOA radiance modeling* used to generate a realistic TOA radiance scene at each sensor-to-sensor match-up (detailed discussion in Section II-C). The following module, *error match-up generator* aims to assess the effect of spectral response mismatch, spatial response mismatch, scene/cloud dynamics, polarization, or angular mismatch. In this study, we have implemented the angular mismatch which is assessed by managing the call to the *TOA radiance modeling*. Specifically, we call the module for each sensor-to-sensor match-up with specific viewing angular information and timestamp for TRUTHS and S2A overpasses, respectively. The result of this process is an error that is iteratively produced

at each sensor-to-sensor match-up and managed by the *global post-processing assessment*. In this first implementation, the global assessment is based on an analysis of the error distribution and the fitting of the radiance curve that are discussed in Section III. The implementation has been applied to three different scenarios defined as follows.

- 1) *Relaxed Scenario* (Section III-B): This scenario only discards sensor-to-sensor match-ups with a sun zenith angle (SZA) higher than 60° or a time difference between sensors larger than 15 min.
- 2) *Intermediate Scenario* (Section III-C): This scenario further filters out the previous match-ups by constraining S2A field-of-view (FoV) [here simplified to 5° viewing zenith angle (VZA)] matching the TRUTHS FoV. It also filters out the matches by considering low-probability cloud events (further info in Section II-C).
- 3) *Restrictive Scenario* (Section III-D): This latter scenario restricts the matches from the previous case by decreasing the maximum delay between sensors to just 5 min and only considers angle matching below 2° .

The tighter criteria for ray-tracing in the third scenario tend toward GSICS collocation practices, where so far larger experience with low Earth orbit (LEO) sensors [17] has been made in the thermal infrared.

B. Orbit Analysis

The initial requirement was that the TRUTHS orbit shall allow observation yearly of the same location with the same geometry and illumination conditions. An average geodetic altitude of 611 km with a repeat cycle (61 days) was chosen to provide an integer number of cycles per sidereal year (366 days), ensuring thus that the illumination condition would repeat year after year. The inclination of 90° (in combination with the repeat cycle) results in a non-sun synchronous orbit, but the 90° ensures that the relative position of the orbital plane with respect to the Sun completes a rotation after one year. Thus, we can think of two different “repetition cycles”: the ground-track repeat cycle (61 days) and the sun-illumination condition repeat cycle (one year, thus six repeat cycles). A benefit of such an orbit is that all mean local solar time (MLST) are sampled along the year, thus allowing intercalibration events outside the pole with sun-synchronous missions with different MLSTs. This orbit was also chosen to provide the climate models with benchmark solar reflected spectrally resolved radiance products sampling the diurnal cycle. Sentinel-2 orbit is sun-synchronous with 10:30 Local Time at Descending Node, an average geodetic altitude of 800.9 km, and an inclination of 98.6° .

Due to the difference in altitude between both satellites, TRUTHS and Sentinel-2 will overtake each other frequently, with a period of about 1.8 days. The TRUTHS orbital plane will rotate with respect to the Sun and will complete a full revolution after one year. During the periods of the year when the orbital plane is close to the orbital plane of sensors in sun-synchronous orbits, co-observations (without maneuvers) may be possible at latitudes other than polar regions. The TRUTHS MLST at Ascending Node Crossing on the first of January

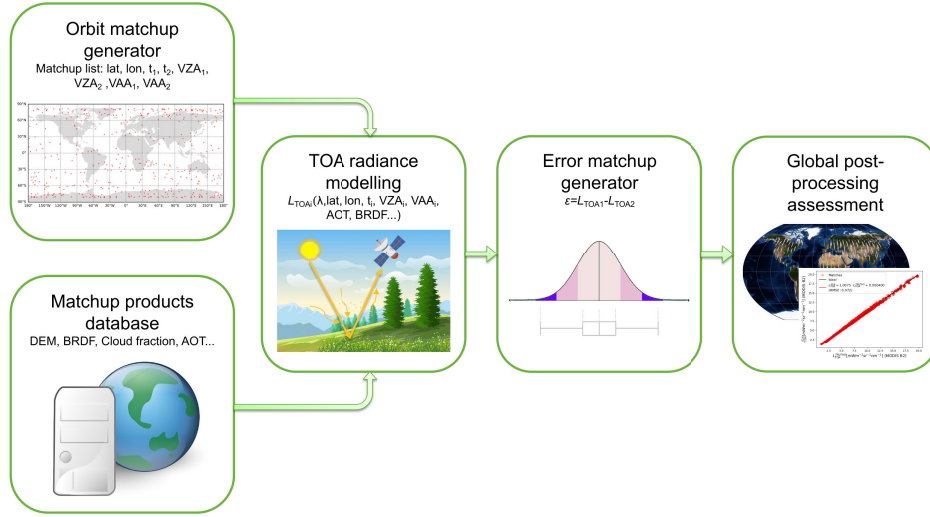


Fig. 1. Workflow schema of the TRUTHS intercalibration assessment based on global realistic simulations.

has been set to 17:00 h, which corresponds to approximately RAAN 356° .

The methodology to identify collocated observations between the TRUTHS sensor with a 100 km-wide swath and Sentinel-2 MSI instrument is outlined below and illustrated in Fig. 2.

- 1) Sentinel-2 swath contour is split with a step of 5 s which approximates 35 km in the along-track direction (green rectangles).
- 2) TRUTHS swath is split in across-track direction with a granularity of 10 km (blue lines).
- 3) The intersection of each intermediate TRUTHS swath line with the rectangular portions of the Sentinel-2 swath will result in two points.
- 4) From those two resulting points, the viewing geometry angles (SAA, SZA, VAA, and OZA) and timestamp to TRUTHS and Sentinel-2 are calculated and used for further analysis.

C. TOA Radiance Modeling

The TOA radiance modeling is generated with the library for radiative transfer (LibRadtran) [20], [21]. We parameterize the scene (surface, atmosphere, and geometry) and obtain an output result that represents the convolved radiance into a spectral response function (SRF). In this implementation, we have selected the SRF of the moderate resolution imaging spectroradiometer (MODIS) bands 2 (approx 841–876 nm spectral interval), 3 (approx 459–479 nm spectral interval), and 6 (approx 1628–1652 nm spectral interval) to keep consistency with the selected BRDF surface products [22].

As mentioned in the previous paragraph, we have selected the MCD43 products [23]. The product describes the BRDF using the RossThick-LiSparseReciprocal kernels obtained from an inversion of a semiempirical model over 16 days of MODIS Terra and Aqua directional surface reflectance data. The three kernel values (fiso, fvol, and fgeo) can be used in LibRadtran to estimate the surface anisotropic effects [24], [25].

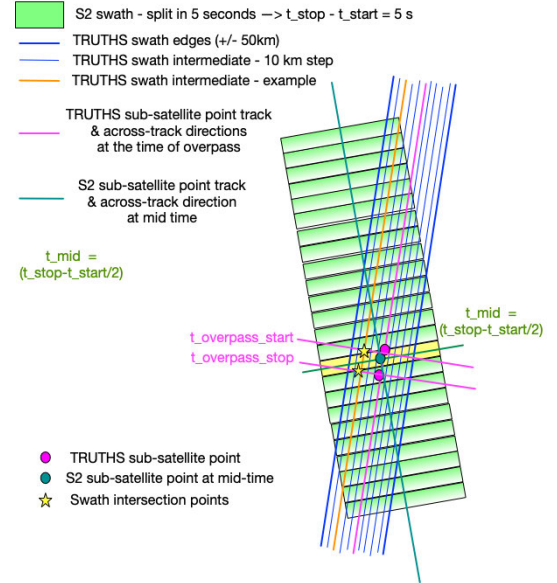


Fig. 2. Schematic representation of the orbit modeling to generate the TRUTHS versus S2A matches across the globe.

Specifically, we have used daily L3 Global 30 ArcSec CMG V006 products for MODIS bands 2, 3, and 6 [26] from the year 2021. The actual orbit sampling represents an approximate 10×35 km and the BRDF pixel is approximately 1 km. These BRDF kernels are then introduced as part of the input parameterization of the Libradtran radiative transfer software. If the product does not contain a retrieval value, we search for and iterate at five-day intervals from the acquisition day up to a maximum of 20 days difference. In case, there is no valid result on any of these days, we use the default BRDF associated with an IGBP landclass in Libradtran. The IGBP landclass is obtained at each sensor-to-sensor match-up from MCD12C products [27] hosted in Google Earth Engine (GEE) [28]. We select the closest pixel to the latitude and longitude

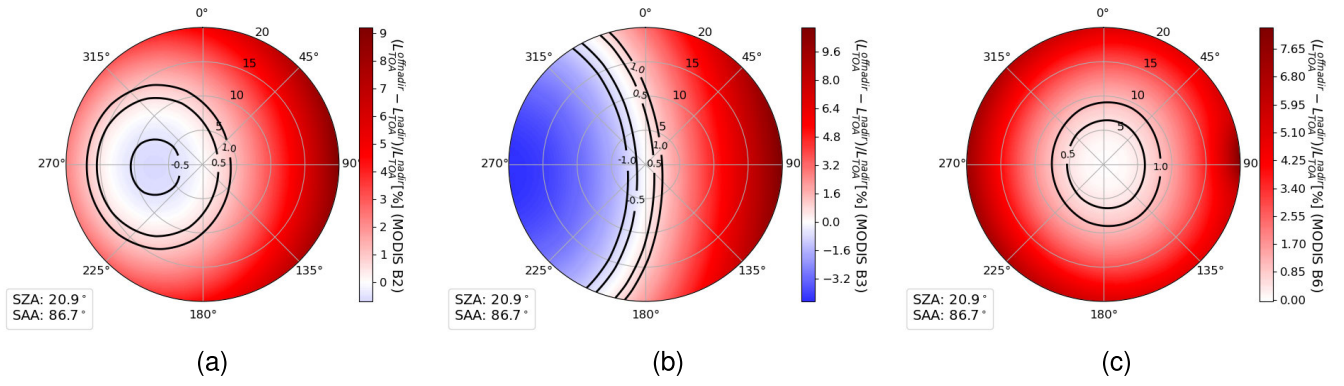


Fig. 3. TRUTHS viewing error modeled for inclinations up to 20° over the Gobabeb site with clear-sky conditions for Terra-MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm).

of the match-up to reduce data processing requirements. Full implementation should consider the TOA radiance propagation and modeling for each BRDF pixel inside the ROI.

The geometry configuration is based on the angular configuration for each satellite overpass at the match-up points given by the orbital simulation (see Section II-B). This information is complemented by the altitude given by a digital elevation model at 0.1° spatial resolution [29].

The aerosol optical thickness (AOT) is modeled from the Copernicus atmosphere monitoring service (CAMS) Global Near-Real-Time [30] from the European Center for Medium-Range Weather Forecasts (ECMWF) and hosted in GEE. The forecast value for the closest hour, day, and location is selected. In case no valid value is found or the connection with the server is lost, the value will be retrieved from an AOT with the monthly average from March 2019 to March 2020 at a 0.1° spatial resolution [31]. In the unlikely scenario that both approaches fail, a default value of 0.2 will be allocated. Other properties of the AOT are modeled with the default values: rural-type aerosol in the boundary layer, background aerosol above 2 km, and spring-summer conditions [20], [21].

The water vapor (WV) is obtained from the global forecast system (GFS) 384-h Predicted Atmosphere Data produced by the National Oceanic and Atmospheric Administration (NOAA) and hosted in GEE. Similar to the AOT, the closest value for the closest 6-h forecast sample is selected. In the absence of a value or invalid retrieval, WV maps with monthly average values from March 2019 to March 2020 at a 0.1° spatial resolution will be accessed [32]. If both the two previous methods report an unsuccessful result, we allocate a value of 1 cm. From the same GFS product, we also extract a forecast value of cloud probability in the pixel area defined as 27830×27830 m. The threshold is set at 20% cloud probability for a pixel area of 27830×27830 m. Since the forecast pixel represents over twice the area of the orbital sampling (approximate 10×35 km), we effectively model both “intermediate” and “restrictive” scenarios with less than 10% cloud probability.

The atmospheric profile is set to mid-latitude summer with a representative wavelength absorption parameterization (REPTRAN model [33]) customized for MODIS bands to be

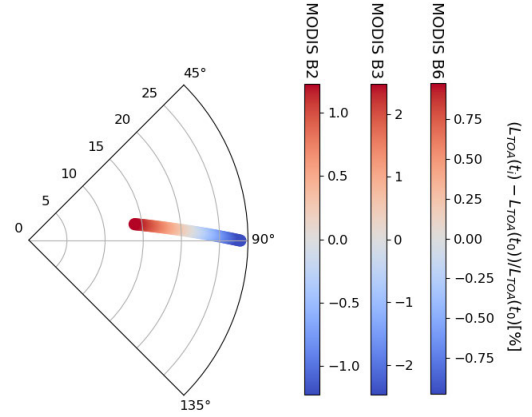


Fig. 4. TRUTHS solar angle evolution and radiometric error modeled for temporal delays up to ± 30 min from the overpass time and MODIS bands B2, B3, and B6. Viewing has been considered as nadir.

consistent with the BRDF products. The radiative transfer runs with 16 streams and the DISORT solver.

Fig. 3 represents the viewing error modeled for inclinations up to 20° for the considered MODIS bands. It also describes the temporal error as a consequence of the sun’s movement with delays of ± 30 min from the overpass time. The overpass represents a typical S2A overpass at latitude -23.6002 and longitude 15.11956 that coincides with the CEOS RadCalNet Gobabeb site [34]. The specific overpass time is 09 h:17 m:02 s for the 25th of November 2021. The atmosphere has been modeled with an AOT of 0.14, WV of 1.694 cm, and altitude of 510 m.

This example indicates the relatively significant level of error, exceeding the 1% value, that occurs for viewing angle differences larger than TRUTHS FoV (5°). This viewing error also varies as a function of spectral band. The directionality of MODIS B3 is dominated by the Rayleigh scattering whereas MODIS B6 shows a nearly symmetric result from nadir with a visible anisotropy due to the hotspot right at the edge of the polar plot. It also shows that these B6 errors have an important azimuthal dependence mostly separated by the backward- and forward-scattering properties of the surface.

Similarly, Fig. 4 illustrates the temporal variations for the same example as in Fig. 3.

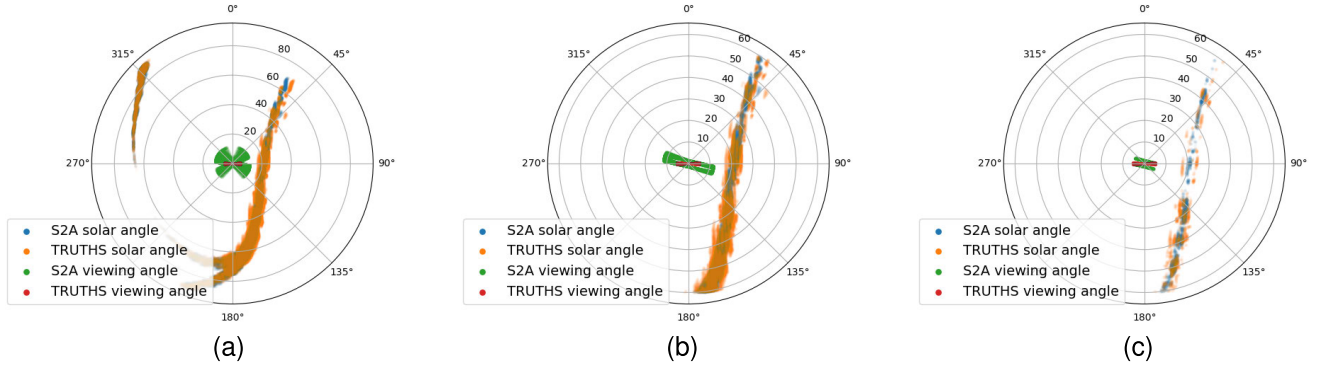


Fig. 5. TRUTHS versus S2A sensor-to-sensor match-up polar distribution of angles for three different scenarios: (a) *all*, (b) *relaxed*, and (c) *intermediate* scenarios. Zenith angle scales for (a) are different from those in (b) and (c).

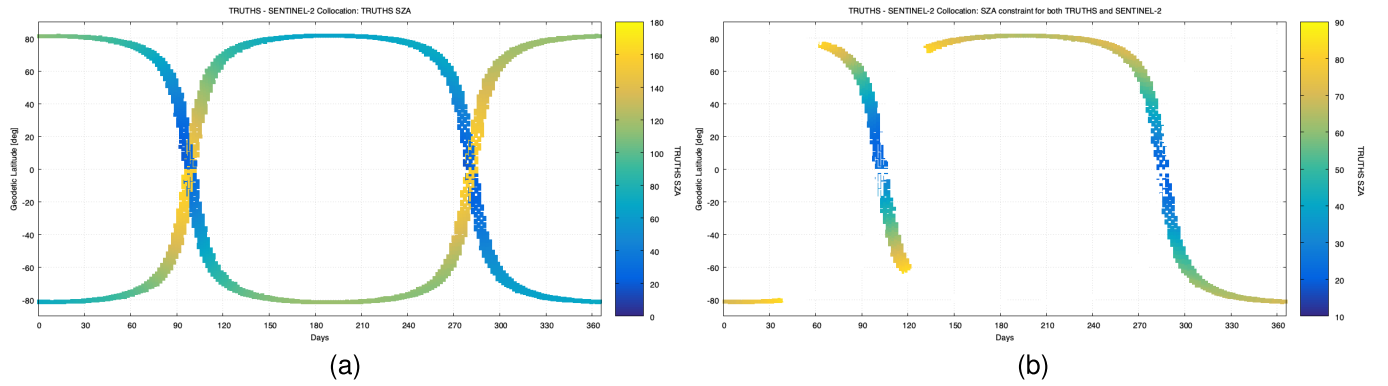


Fig. 6. Collocation opportunities TRUTHS—S2A as a function of the day of the year and considering actual swaths for TRUTHS and S2 where (a) contains the full Earth orbit and (b) is restricted to the daytime orbit.

The solar temporal variations show important variations but to a lesser extent than the viewing impact. The temporal error tends to be highly linear for time delays below 30 min. Again, there is an important difference depending on the spectral band that for the 15 min threshold can range from 0.5% in MODIS B6 to over 1% in MODIS B3 assuming a nadir view. Thus, the coupling of both surface and atmosphere proves very critical to simulate a correct balance between the two effects.

III. RESULTS

A. Orbit Match-Ups and Parameters

The orbit analysis described in Section II-B results in a set of timestamp, location, and angular information for both the S2A and TRUTHS satellites over a year. The analysis is only restricted to 15 min so that further filtering and analysis can select the optimum sensor-to-sensor matches for each scenario.

In general, the time difference between the two satellites shows a nearly uniform and symmetric distribution (mean value below 20 s for all cases). The long repeat cycle of the TRUTHS satellite (61 days; see Section II-B) as compared to the ten days repeat cycle of S2A results in a diverse number of opportunities with different angular and temporal conditions. This potentially leads toward a more symmetric distribution of the time delays between the two sensors in a

match-up area. The *intermediate scenario* produces the most symmetric distribution (mean value below 5 s) likely explained by the constraining of the S2A FoV to 5°, matching that of TRUTHS FoV.

Fig. 5 includes the polar distribution of solar and viewing angles for different scenarios. The location of the sensor-to-sensor match-ups is displayed in Sections 7, 9, and 11. The considered scenarios are: *all*, *relaxed*, and *intermediate*. The former refers to all the sensor-to-sensor match-ups over sunlit land areas whereas the latter two scenarios were defined at the end of Section I.

The polar plot of the angle distribution indicates that without a general restriction on the SZA, nearly half of the crossings would occur at very high SZA over the poles. Specifically, for an *all* scenario, we obtain a total of 95 163 samples whereas for a *relaxed* scenario it is reduced to 51 802 samples (each sample represents approximately 10×35 km as described in Section II-B). The *intermediate* scenario reduces the S2 FoV and includes cloud screening. Thus, it results in a smaller but significant number of 7371 samples. The *restrictive* scenario introduces the most demanding conditions and results in only 34 samples of approximately 10×35 km.

At high latitudes, not only the large SZA would be challenging but also the viewing of azimuthal differences between TRUTHS and S2A. The TRUTHS orbit is designed as a true 90° polar orbit whereas the S2A orbit has a slight inclination of 98.62°. Thus, the restriction to an SZA lower than 60° in the

relaxed scenario significantly reduces both the solar angle and the viewing azimuthal dispersion. The *intermediate scenario* shows that a 15-min threshold between satellite overpasses still results in important solar angle differences between TRUTHS and S2A. However, this is partially compensated because these angular differences do not visually indicate a correlated nature.

The temporal distribution of these opportunities over the year is also an important criterion since any calibration effort ideally requires a continuous effort assessment, dependent on the drift of the target sensor and any sub-orbital variations. Fig. 6 depicts the same sensor-to-sensor match-ups as a function of day of the year and the latitude.

As explained in Section II-B, the rotation of the TRUTHS orbital plane with respect to the Sun results in a yearly pattern. Combined with a general criterion of an SZA threshold of 60° to avoid large angular effects in polar regions, results in an approximate month period of match-ups followed by a five-month period of no valid opportunities. These opportunities occur during the equinox and the match-ups include a full range of regions along the orbit latitudes.

B. Results for a Relaxed Scenario: $SZA < 60^\circ$ and $\Delta t < 15'$

As explained in Section I, this scenario considers all match-ups with the only conditions being that the SZA is lower than 60° and the time difference is lower than 15 min. Fig. 7 presents the match-ups across the globe with a color bar indicating the level of error for each sample. These same errors are presented as an error distribution and radiance linear regression in Fig. 8.

Several of the stripes in the maps are long enough to infer an evolution of the viewing angles through the orbit that is illustrated through a gradient of color at each stripe. The maps show a good distribution of coincidences that cover a range of biomes, latitudes, and longitudes. However, there are specific areas like the Sahara desert or the Amazon forest that are not covered due to the orbit configuration selected for this analysis. Having a simulation covering, e.g., two years would allow for more complete coverage outside the poles. This pattern shift in longitude is due to the changes in the relative orbit phasing position between TRUTHS and S2. The relative position of the orbital planes (i.e., MLST offset) defines approximately the latitudes at which collocation would take place, but the initial phasing (the offset in ascending node crossing at the beginning of the simulation) plays a role in the longitudes of the collocations. Since the S2 cycle is ten days, S2 does not return to the same track after exactly a year (differently to the track of TRUTHS), thus the phasing at the beginning of the year will be different, and hence the longitude of the collocations along the year.

Most of the errors are contained within 5% and the error standard deviation is between 2% and 3%. However, the distribution in all cases presents a slight asymmetric distribution that is translated in mean error values of 0.5%–1%. The fit radiance curve for B2 and B6 shows a slight overestimation that in the case of B6 represents a significant bias. This bias for B6 can be explained by the error resulting

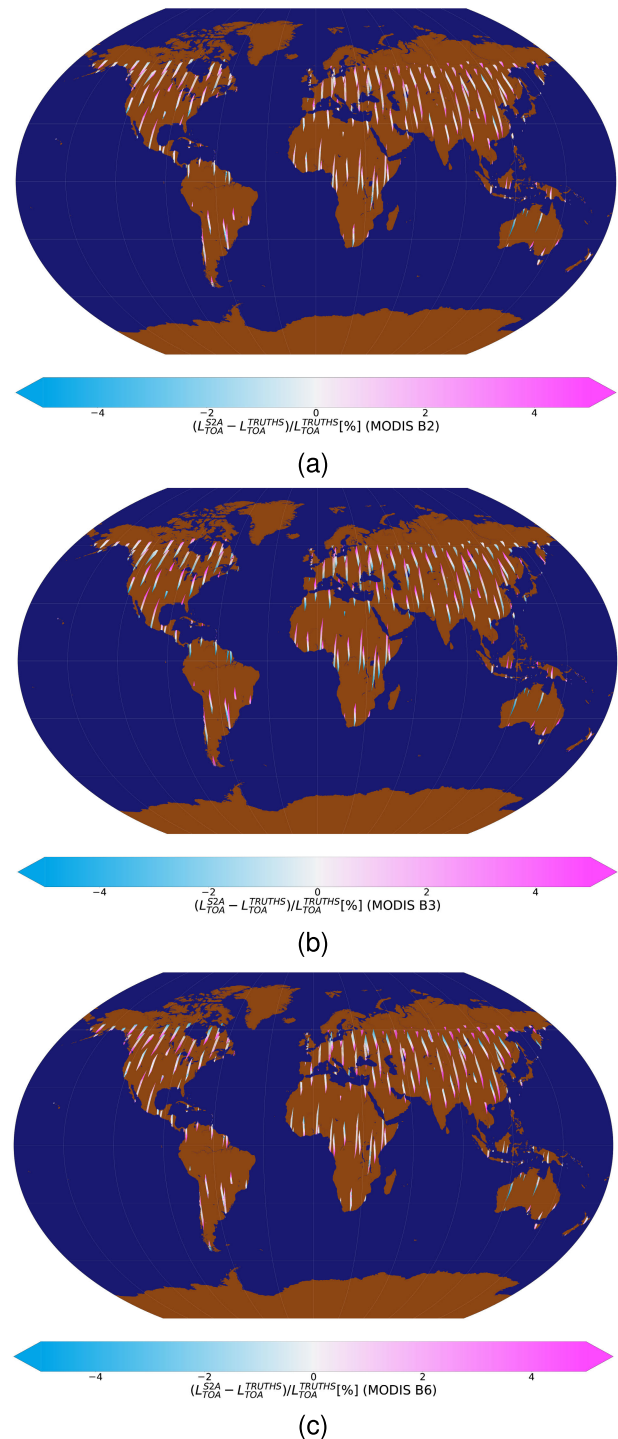


Fig. 7. TRUTHS versus S2A angular error over the Earth projection considering a *relaxed scenario* for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm).

from high radiance values of S2A. High radiance values tend to be close to the swath edge of S2A and the hot-spot area of the surface reflectance [see Fig. 3(c)]. These higher radiance values create an imbalance in the curve fitting that could explain the higher bias. B3 results in a lower bias but a higher offset both in absolute and relative terms. Conversely, this might indicate that the relative angular error is nearly constant through the radiance range likely explained

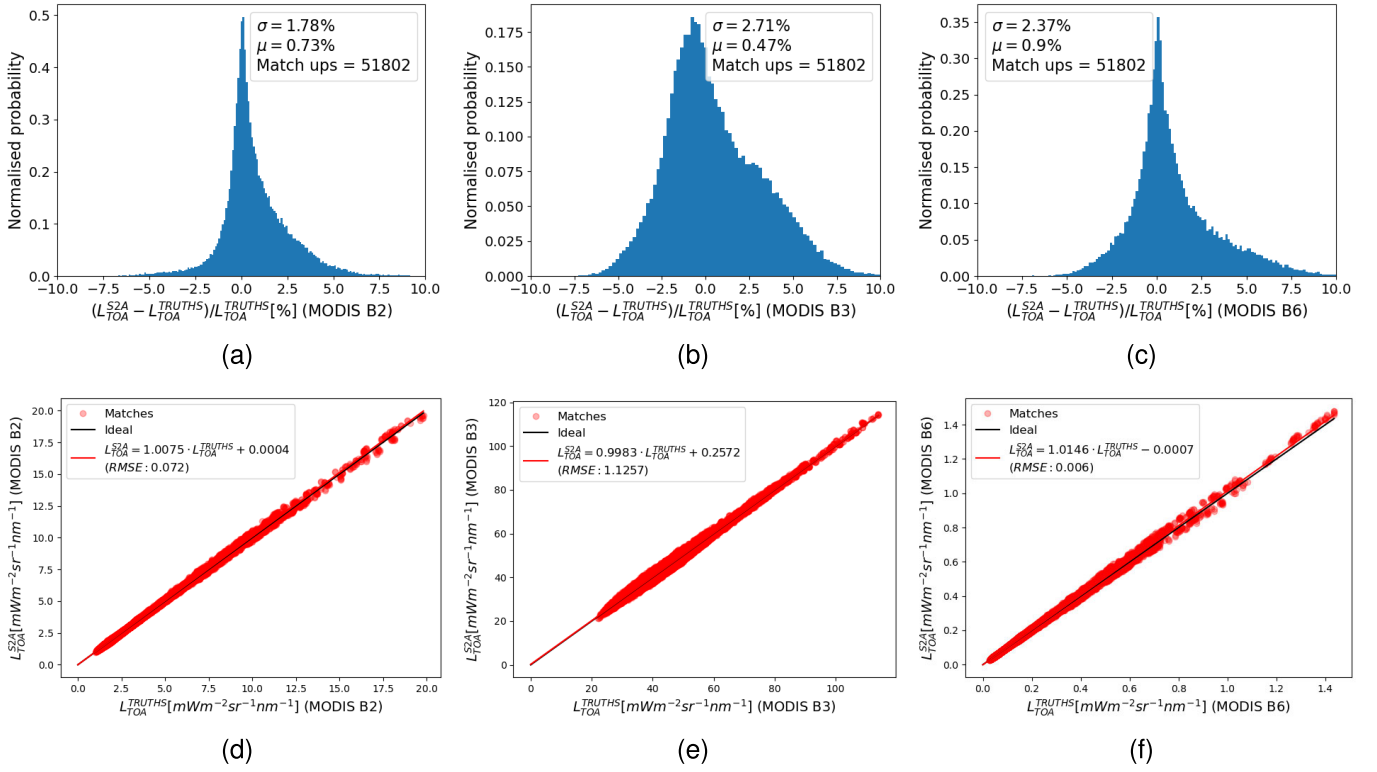


Fig. 8. TRUTHS versus S2A angular error distribution considering a *relaxed scenario* for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), (c) B6 (1640 nm), and (d)–(f) radiance regression the same three MODIS bands.

by the more symmetric nature of the B3 surface error [see Fig. 3(b)]

C. Results for an Intermediate Scenario: Matching FoV and Cloud Screening

This *intermediate scenario* narrows down the number of sensor-to-sensor matches by matching both S2A and TRUTHS FoV and only considering those opportunities that are likely to be cloud-free.

Fig. 9 presents the matches for this scenario.

It is clearly visible that the number of opportunities has significantly decreased. However, it still covers a large number of areas across the globe. It is interesting to note how most of the crossings over tropical regions are mostly not present due to their high cloud probability (e.g., central Africa or Borneo island).

Fig. 10 reports the error distribution and radiance linear regression for this scenario.

The standard deviation of the angular errors has been reduced to the range 1%–2%. More importantly, the error distribution is now almost symmetric with just a small mean error of 0.1% for B3. This can be explained because we are now matching TRUTHS and S2 FoV results in a symmetric and reciprocal angular sampling. Together with a nearly uniform delay distribution, constrains the error propagation and results in a symmetric error distribution of TOA radiance biases.

This has been directly translated in a better fitting for B2 and B6 but not so for B3 [see Fig. 10(d)–(f)]. In the latter

case, the spectral band is highly influenced by atmospheric directionality, and matching FoVs does not represent a significant improvement.

D. Results for a Restrictive Scenario: Matching Angles and Delta $t < 5'$

This scenario sets up highly restrictive conditions to select the “best” sensor-to-sensor matches in terms of angular match.

Following on from the previous *intermediate scenario*, we have further reduced the maximum time delay between satellites to five minutes and selected matching angles with less than 2° . This matching angle is defined as

$$\begin{aligned} & \arccos(\cos(VZA_{\text{TRUTHS}}) \cdot \cos(VZA_{S2A}) \\ & \quad \cdot \cos(VAA_{\text{TRUTHS}} - VAA_{S2A}) + \sin(VZA_{\text{TRUTHS}}) \\ & \quad \cdot \sin(VZA_{S2A})) \leq 2^\circ \end{aligned} \quad (1)$$

where VAA represents the viewing azimuth angle.

Fig. 11 represents the global matches with the associated error to each of them. Note that due to the low number of opportunities and low error value, the scales have been significantly increased and the color bar has been reduced to a range of $\pm 1\%$.

The map indicates that most of the sensor-to-sensor matches have been lost with matches concentrated in nine cluster areas. For example, there are no matches in the entire continents of Africa and Oceania. It should of course be noted that small changes in selected orbit configurations of both TRUTHS and indeed S2 (reflecting small annular changes) can have

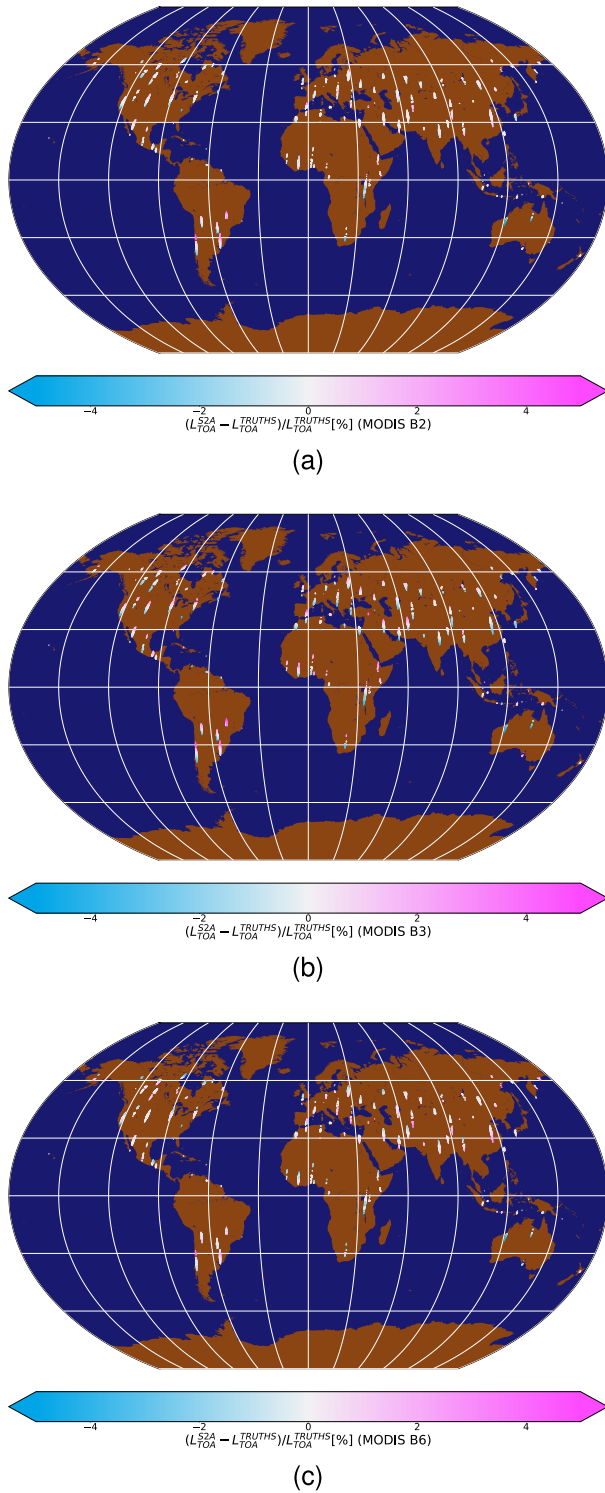


Fig. 9. TRUTHS versus S2A angular error over the Earth projection considering a *intermediate scenario* for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm).

a significant impact on the locations of match-ups and so the above should be seen as illustrative.

Fig. 12 displays the error distribution for this scenario. No curve fitting is provided due to a low number of samples.

The error distribution shows again a very small mean error (below 0.1%) but significantly decreases the error dispersion with a standard deviation of 0.3%. Thus, this scenario

indicates these samples can be used as “golden points” to constrain an intercomparison but are not sufficient for a more detailed characterization, e.g., large radiance range or location dependence.

IV. DISCUSSION

A. General Comments

We have presented a novel study that seeks to define an optimum intercalibration strategy for the TRUTHS mission based on an end-to-end global simulation (or “intercalibration digital twin”). The general methodology described in Section II-A defines an orbit match-up analysis that is the input to a TOA radiance modeling of the event where the combination of different error sources at a global level results in an integrated performance assessment of the intercalibration.

For this first study, we present the error introduced due to angular mismatch (both satellite viewing angles and solar angles) between the TRUTHS satellite and the S2A satellite over land. Here we explore intercalibration events without satellite maneuvers based on angular thresholding and their associated uncertainties. We have defined a general scenario (*all*) and three different scenarios (named *relaxed intermediate* and *restrictive*) that refer to different temporal, angular, or cloud constraints.

Section III-A indicates that the restriction to a SZA lower than 60° significantly reduces both the solar angle and the viewing azimuthal dispersion. However, Fig. 6 suggests that it will also lead to significant periods with no sensor-to-sensor match-ups for the three proposed scenarios.

The results for the *relaxed scenario* report a high number of opportunities but result in a mean error distribution at 0.5%–1%. The fit radiance also presents a significant bias for surface effects as in B6 can be explained by the impact of anisotropic high radiance values of S2A.

The results for the *intermediate scenario* report a lower number of opportunities but still good coverage of different areas across the globe. However, the introduction of cloud probability generates a more realistic simulation of potential match-ups and indicates how crossings over tropical regions mostly disappear. Thus, it suggests that the definition of an orbit (e.g., $RAAN\ 0 \pm 5^\circ$) might result in a majority of crossings over desert areas or tropical forests with a direct consequence on the number of cloud-free opportunities. This scenario clearly improves the mean error distribution to a value below 0.1% which is translated into an improvement of the curve fitting for bands dominated by surface effects (MODIS B2 and B6).

Finally, the results for the *restrictive scenario* result in the lowest angular match-up error (standard deviation below 0.3%) but at the cost of a very small number of opportunities. This is sufficient to broadly check the intercalibration at every event but does not allow a characterization in terms of radiance range, location dependency, or focal plane variations. However, for some sensors which contain their own on-board calibration/monitoring systems, this may still be adequate, particularly if they can also be supplemented by other targets

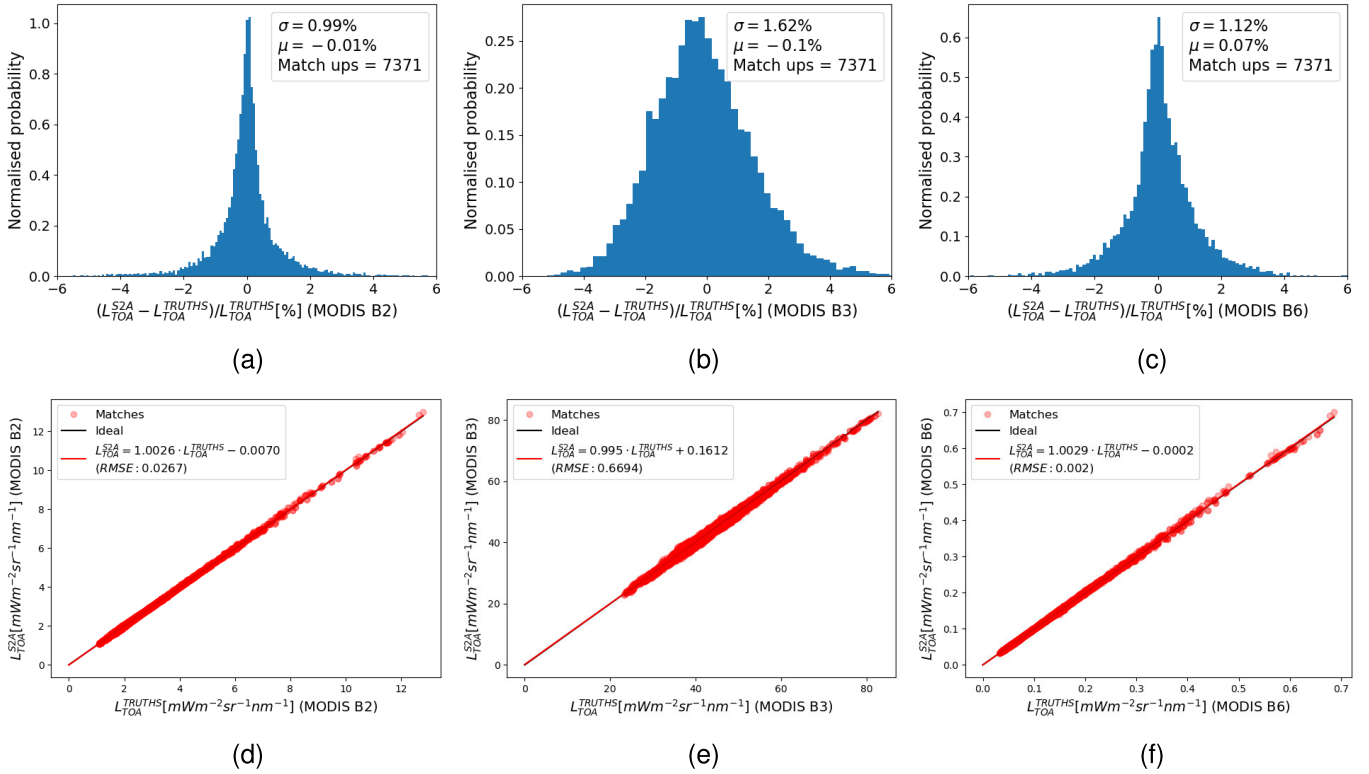


Fig. 10. TRUTHS versus S2A angular error distribution considering a *intermediate scenario* for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm), and (d)–(f) radiance regression the same three MODIS bands.

and/or sensors that may also have been calibrated by TRUTHS independently.

Based on these preliminary findings, a potential optimum global strategy utilizing only this methodology could be that of selecting an *intermediate scenario* as a baseline approach due to its large number of sensor-to-sensor match-ups, large radiance dynamic range and a negligible bias due to angular effects (see Figs. 9 and 10). This can be complemented with a *restrictive scenario* (here they are a subset of an *intermediate scenario*) that could be used as an anchor point. Nonetheless, this approach would result in significant temporal gaps of approximately five months as presented in Fig. 6. To complement these time gaps, dedicated maneuvers could be scheduled during these periods depending on the satellite's needs. Alternatively, the sensor-to-sensor match-ups over these polar regions could be considered at the cost of larger directional errors and/or specific angular corrections.

As indicated above for the full TRUTHS calibration system we will likely have an integrated calibration system of systems, utilizing a range of methods to cover the range of observational conditions, including all those currently in use, summarized on the CEOS CalVal portal [35] but enhanced by a TRUTHS reference calibration from space.

B. Adapting to Other Scenarios

The same code can be adapted to model different scenarios that are not either global or an intercalibration between two sensors in space.

For example, this code has been adapted to model in situ targets such as RadCalNet [34] where TRUTHS will be used

to transfer its high accuracy calibration to anchor the network which in turn will then provide ongoing calibrations to other sensors. The example presented in Fig. 3 has been modeled based on the RadCalNet Gobabeb typical site conditions. Similarly, as for the scenarios presented here, the opportunities throughout the year have been identified and translated into angular mismatch errors. In this specific case, these angular errors might be partially compensated by including a BRDF correction due to its in situ calculation. In the future we will extend the analysis to consider geostationary satellites and of course aircraft sensors or an ad hoc validation campaign. However, in all cases, it is important that we test the validity of these simulations against real data. At the time of writing, there are no hyperspectral sensors with global coverage and full polar orbit. In the absence of perfectly matching data, alternatives such as S2 versus EnMAP or similar combinations could be explored.

This study has only been based on land areas with no consideration of ocean sensor-to-sensor match-ups. By including ocean opportunities we would be distorting the results since most of the sensor-to-sensor match-ups are at extremely low radiance values where effects such as noise, polarization, or stray light will be most relevant. Thus, we consider it best to pursue the ocean case as a separate analysis for specific ocean-focused missions, e.g., those used for Ocean color.

Similar to the ocean case, cloudy scenes have not been considered but filtered out assuming a cloud cover criterion. To consider them for the intercalibration, a specific criterion must be set that is based on the cloud dynamics and scene uniformity. Future studies should look into this specific

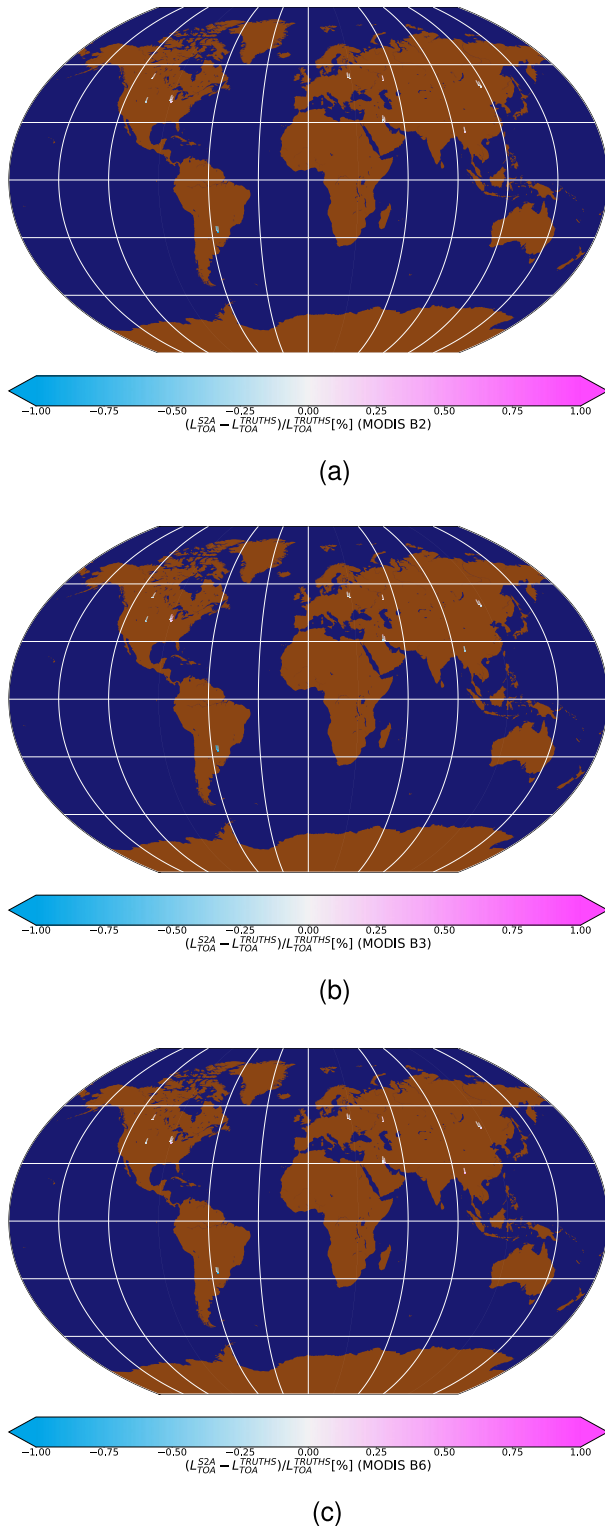


Fig. 11. TRUTHS versus S2A angular error over the Earth projection considering a *restrictive scenario* for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm).

match-up which could enlarge the number of opportunities and the dynamic range of the sensor-to-sensor intercalibration (particularly in the case of a *restrictive scenario* Section III-D).

Finally, we have made the comparison in terms of radiance for the scenarios presented here. This is useful if we are

directly comparing the radiance calibration between TRUTHS and a target sensor over a large radiance dynamic range. However, there is the option to compare these results in terms of reflectance which is straightforward with the code presented here.

C. Further Work

The approach presented here is under continuous evolution and is expected to include several new features and refinements as the mission moves into an operational phase. The obvious next step is to include the other sources of error such as spectral and spatial mismatch but also polarization.

Current modeling of the BRDF relies on the use of MODIS MCD43D products. They are sufficiently realistic to model patterns of surface directionality but improvements will be considered as a trade-off with memory and processing requirements. For example, the use of quality flags in separate products MCD43D31-MCD43D41 would select the best products and also allow alternative BRDF products to be considered if necessary. The atmospheric modeling is mostly based on AOT and WV products. However, other types of information such as the type of aerosol can also be envisaged. Furthermore, we model the TOA radiance by selecting the closest pixel to the latitude and longitude of the 10×35 km match-up. This subsampling is sufficient to provide realistic results in this prototype version. However, a finer orbital sampling, e.g., at 1 km in a more powerful computing system should be considered in subsequent versions.

The current band modeling in terms of REPTRAN MODIS bands significantly reduces the computing requirements. It could be possible to consider a hyperspectral implementation that would imply the parsing of several more BRDF bands and the execution of the radiative transfer with a smaller band resolution. This would not only allow a hyperspectral assessment of the angular effect but would also allow the blend of this effect with the spectral response one [9].

This study has successfully considered the cloud cover by setting a 20% cloud probability threshold based on forecast values in a pixel area of 27830×27830 m. An alternative would be to model the cloud probability based on the closest overpass of Sentinel 2 or Landsat satellites. This approach would provide a high-spatial resolution (20–30 m as compared to 50–100 m of TRUTHS spatial resolution) but other effects might arise such as the quality of the cloud detection algorithm or the constant local time overpass. Even more important is the consideration of cloud dynamics and general scene changes for example by including a simple transport model of the high-spatial resolution cloud.

The current prototype runs on an HP DL380P G9 server with 2 x Intel Xeon E5-2690 V4 (14 cores) and 128GB RAM. This is sufficient to run each MODIS band in approximately 2 h. However, all the potential improvements mentioned here will require an improvement of the processing resources as well as software optimization so as not to exponentially increase the running time.

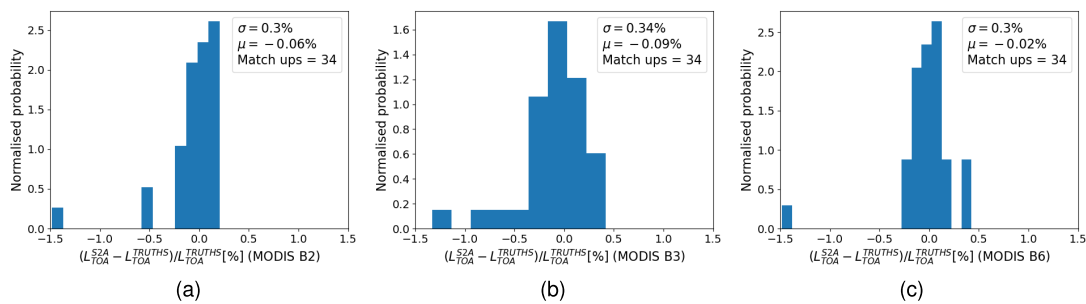


Fig. 12. TRUTHS versus S2A angular error distribution considering a restrictive scenario for MODIS bands (a) B2 (860 nm), (b) B3 (460 nm), and (c) B6 (1640 nm).

D. Conclusion

In conclusion, we have illustrated here through our simulator how the new SITSat class of sensors like TRUTHS will provide the means to revolutionize future decades of satellite Earth observation. Providing, as a free and open service, the capability to improve the performance and interoperability of optical satellite imager data products through in-orbit reference calibration directly traceable to a certifiable SI-traceable reference.

The new system of systems enabled by such calibrations will enhance climate and other science and commercial applications facilitating increased trust in their derived information. The implementation of calibration methodologies illustrated in this article will benefit not only public sector space agencies but also most importantly the “new space” providers where the ability to have their own on-board calibration/monitoring systems is rarely possible.

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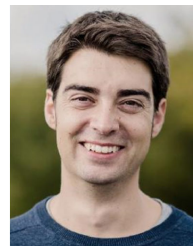


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