Look-Up table approach for uncertainty determination for operational vicarious calibration of Earth imaging sensors

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Abstract: Understanding the uncertainty of a vicarious calibration is essential for any application to Earth imaging sensors. RadCalNet provides SI-traceable spectral top-of-atmosphere (TOA) reflectance from a network of ground sites and uses a Look-Up Table (LUT) approach for uncertainty determination. The uncertainty LUT was derived using Monte Carlo techniques applied to the relevant solar geometry, surface, and atmospheric variables. While the surface reflectance is typically the dominant uncertainty source, atmospheric contributions do play an important role depending upon the exact scenario and conditions. This approach allows knowledge of the TOA reflectance uncertainty to within 0.5%.

1. Introduction

The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) formed a working group as part of the Infrared and Visible Sensors (IVOS) Subgroup to develop a network for data from ground-based, automated radiometric test sites. The goal was to provide a resource for the inflight absolute radiometric calibration for imagers in the reflected solar part of the spectrum with known, SI-traceable uncertainties. The result was the Radiometric Calibration Network (RadCalNet) that began providing beta-level top-of-atmosphere (TOA) spectral reflectance in 2016 and publicly available data from four test sites in 2018 [1]. RadCalNet data are freely available to registered users via a web-based portal (www.radcalnet.org).

Appreciation of the need for accurate radiometric calibration in terrestrial remote sensing has grown steadily from the early days of Landsat [2,3] through the NASA's Earth Observing System sensors [4-6] to more recent missions [7-9]. Increased interest in combining data from multiple sensors, larger numbers of sensors from both government and commercial operators, and the push towards smaller and lower cost sensors operating without on-board calibration pointed towards a greater need for on-orbit radiometric calibration options.

The key element to successful absolute radiometric calibration is providing an SI-traceable result with demonstrated error budgets to place the calibration on a recognized metrological scale. Developing the error budgets and demonstrating SI-traceability for in-situ based vicarious results is a key element to allowing results from multiple groups and test sites to be combined to provide a more comprehensive understanding of the imager. Round-robin activities and joint field campaigns have provided a basis for developing and verifying the error budgets for these vicarious methods [10-12].

The vicarious methods on which RadCalNet is based have been used successfully since the 1980s for the absolute radiometric calibration of earth imaging sensors. Work at multiple sites showed that automated instrumentation could provide SI-traceable, absolute radiometric calibration of on-orbit sensors with known, and peer-reviewed, uncertainties. The results also showed that they can achieve uncertainties similar to collections made with on-site personnel
The willingness of several test site operators to provide a portion of their data made the RadCalNet concept possible. The RadCalNet Working Group did not define the specific instruments and methods to be used by RadCalNet members. Instead, the working group developed a set of data protocols for the test sites and a single processing stream while working with the sites to evaluate and document a site's SI-traceability and absolute uncertainties. RadCalNet takes the data provided by the sites to compute nadir-viewing TOA reflectance at 30-minute intervals from 0900-1500 local standard time. A more detailed description of the RadCalNet data and processing is provided in Section 2.

Thus, the success of RadCalNet depends heavily on the site owners providing data with a clear SI-traceability that is followed through the RadCalNet processing to the data product provided to the user. An equally important goal of RadCalNet is to provide uncertainties for each data point. Understanding the uncertainty is necessary when using vicarious calibration data for Earth imaging sensors [2]. Each member site has the responsibility for their own quality assurance and to derive and provide the uncertainties of the parameters that they provide to RadCalNet. The RadCalNet team then uses these inputs to determine an uncertainty for each TOA reflectance as a function of wavelength for each time.

The current work describes the approach that was developed to provide the TOA reflectance uncertainty for each output data point (both in time and spectrally) for the RadCalNet data products. The next section provides background on the RadCalNet processing to provide context for the look-up table (LUT) uncertainty approach. Section 3 describes the Monte Carlo methods used to populate the LUT along with the methods used to determine the input parameters for the Monte Carlo runs. Section 4 shows the results demonstrating that the LUT approach to RadCalNet uncertainties is providing values with errors in the uncertainty <0.5%. This last section also describes efforts that are underway to ensure that RadCalNet uncertainties can be accurately provided for any possible new sites that join the network as well as potential improvements in the uncertainty generation methodology.

2. RadCalNet background

A description of the RadCalNet data product is provided here for context. The reader is directed to Bouvet et al. (2019) for details of RadCalNet [1]. Participation in RadCalNet is on a voluntary basis and as part of membership in RadCalNet, the instrumented sites agree to provide their data and uncertainties in a specific format and undergo peer review evaluation of the uncertainties associated to their data.

2.1 RadCalNet input product

RadCalNet requires site operators to provide a nadir-viewing surface reflectance at 10-nm intervals from 400 nm to 1000 nm from 9 am to 3 pm local standard time at 30-minute intervals. Several sites also provide spectral reflectance data from 1000 nm to 2500 nm and the RadCalNet processing includes those data when provided. The area for which the reflectance is representative of the given test site is determined by each site with the smallest area allowed being 45m × 45m. Atmospheric data needed by RadCalNet is an aerosol optical depth at 550 nm (AOD), an Angstrom coefficient, column water vapor, and column ozone. An aerosol type corresponding to one of the standard inputs that are part of the MODTRAN radiative transfer code [16] is also needed. In addition, the sites provide a surface pressure and temperature for each data point. The site operators also provide RadCalNet with their site elevation, latitude and longitude that represents the center of the area that is valid for their provided BOA reflectance.

2.2 RadCalNet processing

The site operators perform quality assessments on their data to evaluate which data are suitable for inclusion in the RadCalNet processing and archive. All input data provided by the
sites are assumed valid for processing and to have uncertainties as reported by the site operator. The input parameter uncertainties are based upon the expertise of the site operators with their specific instrumentation, processing methods, and site characteristics.

The input data from each site is submitted to a central processing system that generates the Top-of-Atmosphere (TOA) reflectance using the MODTRAN V5.3.3 radiative transfer code (RTC). During initial setup for data processing, an input file for all site-specific default MODTRAN parameters is generated. It is not expected that the values of these parameters will change, but the file is provided so that the MODTRAN input file for any data run can be recreated. MODTRAN is configured for RadCalNet processing to run in multiple scattering mode using the eight-stream option for the DISORT (discrete ordinates) computations [16]. Gaseous absorption is calculated using the MODTRAN band-model as opposed to correlated-k option. Vertical profile information is based on the mid-latitude summer model for all sites scaled according to surface temperature, pressure, and column water vapor.

The multiple scattering calculations are done for a vertical slant path to space. The surface is assumed to be lambertian and no adjacency effects are included. The spectral resolution used for the MODTRAN calculations is a triangular shaped response with 10 nm full-width, half maximum. Spectral sampling is 400 nm to 1000 nm at 10 nm intervals for all sites with additional spectral bands available at those sites providing inputs beyond the required RadCalNet spectral range. The Chance/Kurucz solar irradiance spectral model is used but has no impact on the predicted TOA reflectance for RadCalNet since the same solar irradiance is used to scale the MODTRAN results to reflectance.

The given Angstrom coefficient and 550 nm AOD are used within MODTRAN to compute the spectral variation in AOD. The aerosol model is set by the site operator based on one of six standard MODTRAN types. To date, all the sites rely on a Rural with 23 km visibility model scaled by the spectral AOD at each wavelength. The result is a TOA spectral radiance for each time and date for which the site owners provide a complete set of input parameters. The spectral radiance is converted to reflectance using the incident solar irradiance used by the multiple scattering calculations and a Lambertian reflectance. Figure 1 shows an example of the surface, or bottom-of-atmosphere (BOA), reflectance input and TOA reflectance output for one measurement at the Railroad Valley Playa site.

![Graph](image.png)

Fig. 1. Surface (BOA) and Top-of Atmosphere (TOA) reflectance at Railroad Valley Playa for measurement on Sept 28, 2020 at 1830 UTC.
There is no requirement on the accuracy of the BOA reflectance provided by each site, but sites must demonstrate that the data are SI-traceable with a verified uncertainty. RadCalNet relies on the expertise that each site owner has with their site and instrumentation to provide QA of the data being provided to RadCalNet. Any data provided should be of sufficient quality to warrant processing by RadCalNet. As mentioned above, there are currently four locations in operation with five RadCalNet sites.

2.3 RadCalNet test sites

The longest operating automated site of the current five sites is the La Crau site in France (LCFR) that has been in use since 1997 when an automatic photometric station was placed at the site [17]. The site is a 400 m × 400 m area in south-eastern France (longitude: 4.87°E, latitude: 43.50°N, altitude 20 m) [18]. The area has a dry and sunny Mediterranean climate, and the soil is mainly composed of pebbles and is sparsely covered by a low vegetation. The Railroad Valley Playa site in Nevada, USA (RVUS) has been used for reflectance-based vicarious calibration since the mid-1990s [19] and fully automated data collections began in 2011. The 1 km² area of the Radiometric Calibration Test Site (RadCaTS) at Railroad Valley Playa is centered at 38.497° N and 115.690° W at an altitude of 1435 m. The site is in a remote area with limited access. The surface is a clay-based playa that is generally invariant under dry conditions but changes due to periodic rain and snowfall events. The Baotou Site has two instrumented areas with one site consisting of four gravel targets 48 × 48 m² in size (BTCN) and the other being an extended sandy area (BSCN) [20]. The sites are located approximately 50 km from Baotou City, China at latitude 40.84° N and longitude 109.46° E, with an altitude of 1270 m. The fifth site is in Gobabeb, Namibia (GONA) and was developed during the RadCalNet prototype phase and has been providing data from July 2017 [21, 22]. The site relies on an identical instrumentation approach as the La Crau site. It is the only site of the four to be selected through a global search relying primarily on quantitative assessments of spectral characteristics, spatial uniformity, probability of clear skies, and other key site parameters. Gobabeb is centered at 23.599° S and 15.119° E at an altitude of 510 m, with the defined instrumented 30m radius surface area representative of the extended surrounding area.

All RadCalNet sites take the same basic approach of measuring surface and atmospheric parameters using the reflectance-based vicarious method [23] from which they can derive the required RadCalNet inputs. The measurements themselves and the instrumentation used vary from location to location. Details of the specific instrumentation, measurement approaches, and processing specific to each site are provided on the RadCalNet portal (www.radcalnet.org).

2.4 RadCalNet data collection

All of the sites rely on multispectral measurements of directly transmitted solar irradiance to characterize the atmospheric aerosols in terms of their column amounts related to AOD and the aerosol sizes in terms of a power law parameter (also known as Junge or Angstrom parameter) [24]. Solar transmittance measurements or numerical weather prediction data are used to provide column amounts of gaseous absorbers such as ozone and water vapor. Ancillary information such as surface pressure measurements, site altitude, or numerical weather predictions provide the information needed to derive molecular scattering optical depths. Sky radiance measurements made at the sites are used to provide improved aerosol size information while others use the data to assess the quality of the solar transmittance data.

All sites deploy downward-looking multispectral and/or hyperspectral non-imaging radiometers to retrieve the upwelling radiance near ground level. Two locations use fixed, vertically viewing sensors while the other two make use of multi-angle scans. The upwelling radiance is converted to a nadir-viewing, bottom-of-atmosphere (BOA) reflectance using the
ratio of the upwelling radiance to a downwelling total irradiance derived from radiative transfer calculations and atmospheric conditions. Spectral models of the sites provide the conversion of multispectral data to the required spectral sampling of RadCalNet.

2.5 RadCalNet uncertainty product

Early in the RadCalNet development process, it was decided that uncertainties would be determined for each RadCalNet data point, both in time and spectrally, rather than a constant value. Providing uncertainties specific to a selected output gives the user an additional tool to evaluate the quality of data sets from multiple sites and dates. A Monte Carlo approach was selected as the means to determine the uncertainties in order to allow for the impact of co-dependent effects of the input uncertainties rather than assuming independence and a root-sum-squared methodology.

The time, date, and test site coordinates for a selected RadCalNet point is used by the RadCalNet processing to determine a solar zenith angle for the RTC calculations that provide the TOA reflectance. The site owner, as stated above, provides the aerosol type, BOA spectral reflectance, column ozone, and column water vapor. The spectral AOD for the RTC calculation is determined in the RadCalNet processing based on the 550-nm AOD and the Angstrom exponent provided by the site owner for that RadCalNet point. The test sites also provide uncertainties for all of their inputs.

The uncertainties for a selected RadCalNet data point are based on the standard deviation of TOA spectral reflectance outputs from a series of RTC runs based on randomized inputs. The randomized inputs are found by assuming a gaussian distribution about the given input of the RadCalNet point and using the supplied input uncertainty as the variance. The ideal method would be to do this computation individually for every RadCalNet point, but, while the Monte Carlo approach does not assume variable independence, it is a time consuming method to produce results with low statistical variability.

Based on the computational load of the Monte Carlo method, the RadCalNet Working Group opted to rely on a look-up-table (LUT) approach with a nearest-neighbor look-up scheme. The LUT entries are generated from Monte Carlo simulations as described in the previous paragraph. The table is organized in terms of two "base" variables and five "seed" variables. The two base variables are solar zenith angle and aerosol type, and these variables are not randomized in the Monte Carlo runs. The five input variables of column ozone, AOD at 550 nm, Angstrom coefficient, site altitude and BOA reflectance are the seed variables and are randomized to determine the TOA reflectance outputs. The inclusion of altitude is a surrogate for variability in atmospheric pressure and thus the impact of molecular scattering. The TOA reflectance uncertainty in spectral regions containing water vapor absorption features will typically exceed 10%, thus for simplicity only a constant water vapor column of 1.0 g/cm is used.

The resolution of the input parameters was selected to ensure a <0.5% impact from the LUT approach on the determined TOA reflectance uncertainty. That is, the LUT-based uncertainty would need to be between 2.5% and 3.5% if the Monte Carlo based uncertainty is 3.0% for a specific set of inputs parameters. The approach was developed to be applicable to all RadCalNet sites and ranges of inputs while providing a computationally efficient solution both in generating the LUT as well as production of the RadCalNet products. Details of the LUT generation are provided in the next section.

3. Methodology

To generate a useful LUT, the initial step is an understanding of the expected range of atmospheric and surface inputs for the RadCalNet sites. This ensures the LUT includes the typical atmospheric conditions expected at the RadCalNet sites and determines the resolution
of variable step sizes within the LUT. Table 1 displays summary statistics for relevant variables to the uncertainty analysis from each site’s start date to end of 2020. For each site the total number of individual measurements that are submitted in all the input files is listed as ‘N’.

The zenith angle range (Min/Max) shows that only the site closest to the equator, GONA, experiences solar angles less than 15°. The largest zenith angles observed at any of the sites are over 80°. Zenith angles greater than 70° present challenges for RTC results due to longer atmospheric paths and strong sensitivities to small changes in angles.

The mean AOD values indicate generally low aerosol loadings for the sites, in particular the RVUS and GONA sites. The maximum AOD of 0.16 at RVUS is due to a QA process which filters out high AOD cases from the input files. The Angstrom coefficient values are generally similar for all the sites and related to the predominant size of aerosol particles distribution. Higher Angstrom values indicates predominantly smaller aerosol particles and vice versa. The Angstrom coefficient can have a negative value and are representative of a coarse mode aerosol with dust or particle hygroscopic growth.

The ozone column amounts are typical for the midlatitudes. The BTCN and BSCN sites use a constant climatological value for an ozone column of 280 DU. The water vapor column amounts show the difference between remote higher altitude desert sites (RVUS, BTCN, and BSCN) and those near or on the coast and at lower altitudes (GONA and LCFR).

Table 1. Summary statistics for atmospheric variables at the 5 RadCalNet sites.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>N</td>
<td>14472</td>
<td>10110</td>
<td>10326</td>
<td>2826</td>
<td>1245</td>
</tr>
<tr>
<td>Zenith</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ G0</td>
<td>41.64 (15.01)</td>
<td>46.11 (15.91)</td>
<td>37.11 (14.71)</td>
<td>44.66 (15.99)</td>
<td>42.29 (12.46)</td>
</tr>
<tr>
<td>Min/max</td>
<td>15.36/77.87</td>
<td>20.28/81.64</td>
<td>0.23/64.53</td>
<td>17.63/82.10</td>
<td>17.68/77.36</td>
</tr>
<tr>
<td>AOD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ G0</td>
<td>0.055 (0.03)</td>
<td>0.11 (0.12)</td>
<td>0.081 (0.08)</td>
<td>0.152 (0.07)</td>
<td>0.16 (0.07)</td>
</tr>
<tr>
<td>Min/max</td>
<td>0.004/0.16</td>
<td>0.008/2.38</td>
<td>0.002/1.92</td>
<td>0.004/0.30</td>
<td>0.001/0.33</td>
</tr>
<tr>
<td>Angstrom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ G0</td>
<td>0.03 (0.43)</td>
<td>1.03 (0.39)</td>
<td>0.85 (0.50)</td>
<td>0.84 (0.39)</td>
<td>0.90 (0.36)</td>
</tr>
<tr>
<td>Min/max</td>
<td>0.001/3.78</td>
<td>-0.087/2.20</td>
<td>-0.065/3.34</td>
<td>-0.97/1.72</td>
<td>-0.31/1.72</td>
</tr>
<tr>
<td>Ozone (DU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ G0</td>
<td>299 (28.55)</td>
<td>318 (31.7)</td>
<td>286 (21)</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>Min/max</td>
<td>223/448</td>
<td>239/467</td>
<td>221/347</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WV (g/cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ G0</td>
<td>0.79 (0.41)</td>
<td>2.36 (1.53)</td>
<td>1.24 (1.11)</td>
<td>0.67 (0.50)</td>
<td>0.83 (0.51)</td>
</tr>
<tr>
<td>Min/max</td>
<td>0.11/2.65</td>
<td>0.07/10.3</td>
<td>0.06/3.11</td>
<td>0.06/3.11</td>
<td>0.07/2.15</td>
</tr>
</tbody>
</table>

Figure 2 shows the mean BOA reflectance from each of the 5 sites and is representative of the spectral shape seen at each site. The two Baotou sites only provide the spectral range of 400 to 1000 nm and both LCFR and GONA have gaps due to masking longer wavelength absorption regions. RVUS provides spectral data covering the full 400 to 2500 nm range. The two dashed line curves are the spectra that have the overall maximum and minimum observed values for BOA reflectance at 850 nm. The maximum value occurs for RVUS and overall minimum observed value at LCFR and the minimum and maximum BOA reflectance spectra indicate the general envelope within which all the spectra fall.
Using this summary information, the LUT input variable ranges and steps were determined to balance as wide a range as needed to cover the majority of situations and limiting the number of RTC calculations to a feasible number. Table 2 displays the RTC input variable seed values used to generate the RadCalNet uncertainty LUT. The uncertainty of the input variables used in the randomization process are listed in each column header. As mentioned previously, only water vapor column amounts of 1.0 g/cm were included with no randomization. Strong atmospheric absorption features, such as by water vapor, can result in large uncertainties that typically exceed 10%. The individual variable increments were determined after careful consideration of the relative contributions to the overall uncertainty and the ability to distinguish differences in the RTC output for increasingly smaller increments. As future needs warrant, additional seed values or increments can be added to the LUT.

Table 2. Variable seed values that define the dimensions and interval steps of the uncertainty LUT. Values in parentheses indicate the 1σ uncertainty for that parameter.
The interval choices were made to encompass the conditions typically seen at any of the sites. The atmospheric pathlength is defined by the cosine of the solar zenith angle. A 5° interval for angles up to 45° is sufficient to capture the effect of the increasing pathlength. Above 45° the pathlength changes more rapidly, so intervals of 0.05 in cosine of zenith angle were used. Only GONA experiences zenith angles less than 15° for brief periods during their summertime and the atmospheric pathlength differences between nadir and 10° are less than 1.5%.

The majority of AOD cases were concentrated in the lower range of the scale so intervals of 0.04 were used to differentiate these situations. AOD values greater than 0.25 tend to be excluded by the site operator QA processes generating the inputs so the AOD interval at 0.4 is applicable to the high aerosol loading cases. The Angstrom exponent uses regular intervals of 0.25 and it is expected that larger particle sizes (lower Angstrom values) will have smaller impact on uncertainty, thus the lowest interval was selected for the initial LUT as 0.5.

As will be seen in Section 4, the ozone column amounts have minimal impact on the resulting TOA uncertainty and only 3 intervals were selected. The two altitude intervals were selected to be representative for the difference between low- and high-altitude sites. The 0.5 km interval is applicable to RadCalNet sites with altitudes from 0 to 1 km (LCFR and GONA) and the 1.435 km interval for RadCalNet sites with altitudes greater than 1 km (RVUS, BTCN and BSCN).

As can be seen by comparing the min/max values of the variables in Table 1 and Table 2, the ranges do not capture all observed data to date. Table 3 shows the percentage of cases for each site (out of the total number N in Table 1) that are outside the minimum and maximum bounds of the LUT variable ranges. The large percentages seen for the number of cases below the minimum LUT AOD of 0.05 is not a concern as low AOD means less atmospheric scattering and thus a lower contribution to the overall uncertainty. Additionally, an AOD of 0.05 approaches the minimum allowable value of AOD that can be used as input in MODTRAN. Out of all the variables an additional value for Angstrom coefficient of 0.25 is under consideration for inclusion in a future updated LUT to include those cases for which Angstrom values are < 0.50.

Table 3. Percentage of data from each RadCalNet site that are outside the upper and lower uncertainty LUT variable limits

<table>
<thead>
<tr>
<th>Zenith Angle</th>
<th>Angstrom (0.3)</th>
<th>AOD (0.02)</th>
<th>O3 (DU) (11)</th>
<th>BOA (4%)</th>
<th>H2O (g/cm) (0.1)</th>
<th>Altitude (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.50</td>
<td>0.05</td>
<td>280</td>
<td>0.05</td>
<td>1.0</td>
<td>0.500</td>
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<tr>
<td>15.0</td>
<td>0.75</td>
<td>0.09</td>
<td>300</td>
<td>0.10</td>
<td>1.435</td>
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<tr>
<td>20.0</td>
<td>1.00</td>
<td>0.13</td>
<td>320</td>
<td>0.15</td>
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<tr>
<td>25.0</td>
<td>1.25</td>
<td>0.17</td>
<td>0.20</td>
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<tr>
<td>30.0</td>
<td>1.5</td>
<td>0.21</td>
<td>0.25</td>
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<td>35.0</td>
<td>1.75</td>
<td>0.25</td>
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<td>40.0</td>
<td>1.95</td>
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<td>45.0</td>
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<td>69.1</td>
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<tr>
<td>72.1</td>
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</table>

The interval choices were made to encompass the conditions typically seen at any of the sites. The atmospheric pathlength is defined by the cosine of the solar zenith angle. A 5° interval for angles up to 45° is sufficient to capture the effect of the increasing pathlength. Above 45° the pathlength changes more rapidly, so intervals of 0.05 in cosine of zenith angle were used. Only GONA experiences zenith angles less than 15° for brief periods during their summertime and the atmospheric pathlength differences between nadir and 10° are less than 1.5%.

The majority of AOD cases were concentrated in the lower range of the scale so intervals of 0.04 were used to differentiate these situations. AOD values greater than 0.25 tend to be excluded by the site operator QA processes generating the inputs so the AOD interval at 0.4 is applicable to the high aerosol loading cases. The Angstrom exponent uses regular intervals of 0.25 and it is expected that larger particle sizes (lower Angstrom values) will have smaller impact on uncertainty, thus the lowest interval was selected for the initial LUT as 0.5.

As will be seen in Section 4, the ozone column amounts have minimal impact on the resulting TOA uncertainty and only 3 intervals were selected. The two altitude intervals were selected to be representative for the difference between low- and high-altitude sites. The 0.5 km interval is applicable to RadCalNet sites with altitudes from 0 to 1 km (LCFR and GONA) and the 1.435 km interval for RadCalNet sites with altitudes greater than 1 km (RVUS, BTCN and BSCN).

As can be seen by comparing the min/max values of the variables in Table 1 and Table 2, the ranges do not capture all observed data to date. Table 3 shows the percentage of cases for each site (out of the total number N in Table 1) that are outside the minimum and maximum bounds of the LUT variable ranges. The large percentages seen for the number of cases below the minimum LUT AOD of 0.05 is not a concern as low AOD means less atmospheric scattering and thus a lower contribution to the overall uncertainty. Additionally, an AOD of 0.05 approaches the minimum allowable value of AOD that can be used as input in MODTRAN. Out of all the variables an additional value for Angstrom coefficient of 0.25 is under consideration for inclusion in a future updated LUT to include those cases for which Angstrom values are < 0.50.

Table 3. Percentage of data from each RadCalNet site that are outside the upper and lower uncertainty LUT variable limits

<table>
<thead>
<tr>
<th>Zenith Angle</th>
<th>Angstrom (0.3)</th>
<th>AOD (0.02)</th>
<th>O3 (DU) (11)</th>
<th>BOA (4%)</th>
<th>H2O (g/cm) (0.1)</th>
<th>Altitude (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVUS</td>
<td>&lt; 10</td>
<td>0 %</td>
<td>0 %</td>
<td>5.1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>&gt; 72.1</td>
<td>1.7%</td>
<td>5.5%</td>
<td>0%</td>
<td>3.1%</td>
<td>0.7%</td>
</tr>
<tr>
<td>LCFR</td>
<td>&lt; 0.05</td>
<td>54%</td>
<td>31%</td>
<td>38%</td>
<td>4.8%</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.4</td>
<td>0%</td>
<td>2.4%</td>
<td>1.2%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>GONA</td>
<td>&lt; 0.5</td>
<td>17%</td>
<td>11%</td>
<td>30%</td>
<td>23%</td>
<td>16%</td>
</tr>
<tr>
<td>BTCN</td>
<td>&gt; 1.75</td>
<td>2.5%</td>
<td>2.1%</td>
<td>5.1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>BSCN</td>
<td>&lt; 280</td>
<td>27%</td>
<td>8.1%</td>
<td>34%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>&gt; 320</td>
<td>19%</td>
<td>40%</td>
<td>1.2%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
A total of eight input variables in the MODTRAN RTC describe the atmospheric state, surface reflectance and solar geometry and are used to define the dimensions of the LUT: 1) solar zenith angle, 2) aerosol type, 3) Angstrom coefficient, 4) aerosol optical depth at 550 nm, 5) total ozone column, 6) surface reflectance, 7) total water vapor column, and 8) altitude. The aerosol type uses the MODTRAN definitions [16] and to date all RadCalNet sites have used the ‘Rural’ type. The initial uncertainty LUT thus only has one dimension for the aerosol type of ‘Rural’. As mentioned previously only the case of water vapor column amounts of 1.0 g/cm was included so it also has a single LUT dimension. The other six variables have multiple dimensions of the total number of intervals as listed in Table 2. The LUT is a compilation of all possible combinations of the variables, for a total of 40,320 individual combinations or scenarios.

For the Monte Carlo uncertainty calculations, the input variable values in Table 2 were used as seeds to generate sets of MODTRAN input files for each scenario. A set of 100 input files per scenario was generated with randomized inputs for Angstrom coefficient, AOD, ozone, a spectrally flat surface reflectance, and altitude. The randomization process assumes a gaussian distribution about the given input seed value and using the supplied input uncertainty as the variance. For example, for the given scenario using the first line of values in Table 2, randomized variables are defined as an Angstrom seed of 0.5 with variance 0.3, AOD seed of 0.05 with variance of 0.02, ozone seed of 280 with variance of 11, surface reflectance of 0.05 with variance of 0.002, and altitude seed of 0.5 with variance of 0.1. The zenith angle is considered known exactly and is not randomized and a constant water vapor column of 1 g/cm is used. The resulting set of 100 MODTRAN input files were then processed in the same manner as RadCalNet data to generate TOA reflectance. The uncertainty was calculated as the standard deviation divided by the mean of the 100 TOA reflectance values and is assigned in the LUT as the uncertainty value for that given scenario. This process is then repeated for each scenario to populate the LUT, which required over four million RTC runs.

The choice of 100 input files per scenario was determined to be a reasonable trade between accurately assessing the repeatability of results while keeping computation time reasonable. Figure 3a-c shows the uncertainty result for 3 selected wavelengths as the number of random samples used in the computation increases. The solid line is the uncertainty derived for a set of 2000 randomized samples and the dotted lines are +/- 0.5 of that value to represent the goal of knowledge of the TOA uncertainty at the 0.5% level. The data points represent the repeatability of the uncertainty as derived using the indicated number of samples and repeated 30 times for each selected number, e.g. 5, 10, 15, 20, 30, 40, 50, etc. As expected, the lower the number of samples used to derive the uncertainty increases the spread and possibility of outliers influencing the uncertainty. As the number of samples increases the retrieved uncertainty approaches the ‘true’ uncertainty defined as that from 2000 samples. It is seen that the choice of 100 random samples will lessen the impact of any outliers in the dataset and return a value of the uncertainty within 0.5% of the expected value.
Fig. 3. TOA reflectance uncertainty derived using an increasing number of randomized samples, 2, 3, 4, 5, 10, etc., repeated 30 times for step. The solid line is the ‘true’ uncertainty as derived for 2000 random samples with the dotted lines indicating the +/- 0.5% envelope. The red points are the 100 random samples cases. Results for three wavelengths are shown a) 400 nm, b) 800 nm, and c) 1600 nm.

Figure 4 illustrates the derived uncertainty for the 30 n=100 cases corresponding to the 30 red dots in Figure 3. The solid black line is the uncertainty for the n = 2000 case and the black
dashed lines define a +/- 0.5% uncertainty envelope. It is evident that all 30 cases fall within that envelope and thus meet our defined expectation for knowledge of the uncertainty. The water vapor absorption regions are spectral regions with low signal and challenging to derive an uncertainty. As a caveat to RadCalNet data users, a flag in the reported uncertainty data indicates that the uncertainty for specific wavelength regions is greater than 10% and should be used with caution.

Fig. 4. TOA reflectance uncertainty spectrum for the 2000 random samples case (solid black line), +/- 0.5% uncertainty envelope, and the 30 100 random sample cases shown in blue.

4. Results and Discussion

The dominant uncertainties for TOA reflectance predictions arise from errors in the atmospheric and surface characterizations. The Monte Carlo process to generate the RadCalNet uncertainty LUT includes both the individual uncertainties for each variable but also captures correlated uncertainties. To understand the contributions of the individual uncertainties to the total uncertainty a dataset was generated using the mean RVUS variable values from Table 1 as seed values. Similar to the RadCalNet LUT generation process, five sets of 100 input files each was created by randomizing each of the five variables individually while holding the other four constant at the seed value. A sixth set of 100 input files included randomization on all five variables. The considered variables are Angstrom exponent, AOD, ozone column, BOA reflectance and altitude.

Figure 5 clearly shows that the surface reflectance (BOA) uncertainty far outweighs the contributions of the individual atmospheric uncertainties and can be considered the driver of the resulting TOA reflectance uncertainty. This result is not surprising given the low aerosol loading and relatively high surface reflectance at the RVUS site. Generally, any other site considered for vicarious calibration, including the other RadCalNet sites, have similarly low aerosol loading and relatively high reflectance so the surface reflectance uncertainty will be the largest contributor to the TOA reflectance uncertainty. Combining the individual uncertainty contributions in Figure 5 using a sum of squares method will result in a total TOA uncertainty that is slightly higher than the ‘All’ case. This is expected as the Monte Carlo process includes correlated uncertainties which can reduce the total TOA uncertainty compared to including only the isolated impact of each variable.
The component contributions to the TOA uncertainty shown in Figure 5 are typical for low aerosol loading, high surface reflectance sites at zenith angles less than about 60°. Situations with larger zenith angles, low surface reflectance and/or high aerosol loading will experience increased uncertainty contributions from the atmospheric parameters and decreased uncertainty dependence on surface reflectance. This is particularly true for low surface reflectances as the measured TOA signals under these dark surface conditions will primarily be from atmospheric scattering/emission and more susceptible to variations in atmospheric properties.

With over 40,000 individual spectra included in the LUT covering the wide range of surface and atmospheric conditions the RadCalNet sites may experience, it is a challenge to summarize the results in a limited number of plots. Only a few examples of interesting observed features in the LUT entries will be presented here to illustrate nuances in the effect the input variables can have on the TOA uncertainty. A deeper analysis, such as data mining the LUT to identify combinations of atmospheric conditions that yield the lowest TOA uncertainty for a given RadCalNet site, is an intended follow-up research activity. Such efforts can provide guidance to the RadCalNet user community in selecting datasets for sensor comparisons.

A straightforward example of TOA uncertainty differences is the impact of solar zenith angle. For the representative atmospheric conditions of AOD = 0.09, Angstrom exponent = 0.75, ozone column of 300 DU, and a spectrally flat BOA reflectance of 0.2, the TOA uncertainty for a zenith angle of 40° is shown as the black line in Figure 6. The TOA uncertainty for the same atmospheric and surface scenario for zenith angles of 10° and 72.1° are shown in red and blue, respectively. The impact of the increased atmospheric pathlength for the larger zenith angles is readily apparent. The 10° and 40° cases have essentially the same spectral shape, but the uncertainty is increased slightly for the 40° case. The situation is a bit more complex for the 72.1° case as the atmospheric pathlength along the solar path is over 3 times longer compared to the 10° case. For these longer pathlengths, the uncertainty becomes dominated by the atmospheric scattering which itself is wavelength dependent.

The AOD, Angstrom exponent and the interaction of the two drive the sensitivity at shorter wavelengths. Due to the handling of these aerosol parameters in MODTRAN, the uncertainty...
for Angstrom exponent approaches zero at 550 nm as this is the wavelength at which AOD is defined, and thus leads to lower uncertainties at shorter wavelengths. An additional factor to consider at shorter wavelengths is the strong spectral dependence of molecular scattering which can lead to Rayleigh optical depths that are greater than that of a low AOD scenario, such as an AOD of 0.05.

**Fig. 6.** TOA reflectance uncertainty for three solar zenith angles, 10° (red), 40° (black), and 72.1° (blue) with identical surface and atmospheric conditions.

The three uncertainty cases shown in Figure 6 differ due to only changing one variable, the solar zenith angle. A second example of observed features in the LUT involves changing multiple variables simultaneously and to illustrate the impact of aerosol loading. Figure 7 shows three LUT uncertainty spectra, the black line is the same combination of atmospheric and surface conditions as shown in Figure 6 (AOD = 0.09, Angstrom exponent = 0.75, ozone column of 300 DU, BOA reflectance of 0.2, and zenith angle of 40°). The blue line is the case with low aerosol loading, predominantly large aerosol particles and low surface reflectance (AOD = 0.05, Angstrom exponent = 0.50, ozone column of 300 DU, BOA reflectance of 0.05, and zenith angle of 40°). The red line is the contrasting scenario of high aerosol loading with predominately small sized aerosol particles (AOD = 0.40, Angstrom exponent = 1.75, ozone column of 300 DU, BOA reflectance of 0.05, and zenith angle of 40°).

The low surface reflectance cases were selected to highlight atmospheric impacts. At longer wavelengths the molecular scattering impact is small so the low AOD cases (black and blue) show a similar uncertainty which will be predominantly due to the surface reflectance uncertainty. The high aerosol case in red has larger uncertainty due to the additional AOD uncertainty on top of the surface reflectance uncertainty. At short wavelengths the molecular scattering uncertainty will dominate and mask any surface reflectance effects. The AOD is large enough for the red case that the impact of its uncertainty is noticeable. The red case uncertainty decreases from 400 nm because AOD is decreasing and thus the AOD uncertainty also decreases. The inflection point occurs when AOD and molecular scattering are small enough that the surface reflectance uncertainty then becomes the dominant uncertainty contributor. By about 1000 nm, the surface reflectance becomes the dominant uncertainty source with an additional contribution from AOD. AOD uncertainty is relatively flat at longer wavelengths.
These two uncertainty examples briefly illustrate the complexity in understanding the shape and structure of each entry in the LUT. An extensive study of the LUT would quickly get bogged down in understanding and explaining the minutiae of any individual uncertainty spectra. Fortunately, the RadCalNet sites generally have low aerosol loadings which results in the surface reflectance uncertainty being the dominant contributor in most situations. Thus, the resulting TOA uncertainty will be on the order of the uncertainty of the surface reflectance determination.

Figure 8 shows a subset of the 1260 possible LUT uncertainty spectra for a zenith angle of 40°. Three sets of 180 colored lines each are for the LUT values with AOD’s of 0.05 (light blue), 0.17 (orange), and 0.40 (black). Each set of 180 lines contains all possible combinations of Angstrom Exponent (6), Ozone Column (3) and surface reflectance (10).

For any one set of AOD cases, the correlations with the other variables can cause a spread in the retrieved uncertainties. For the scenario of low AOD (0.05) the uncertainty is generally in the range of 3-4% over most of the spectral range. The curvature at short wavelengths is due to the decreasing dominance of surface reflectance uncertainty. The uncertainty, as expected, has spikes in absorption regions (e.g. 1300 nm, 1800 nm) and is accordingly flagged in the RadCalNet output data as a caveat to users. The moderate AOD cases (0.17) in orange show similar spectral shape and range of results as the low AOD data set. The large AOD (0.40) cases however start to show increased uncertainty for longer wavelengths for an increasing number of variable combinations. A review of uncertainty results for the other zenith angles shows similar spectral shapes but generally a tighter spread and overall lower uncertainty for low zenith angles and vice versa for high zenith angles.
Fig. 8. TOA reflectance uncertainty for solar zenith angle of 40° for all AOD = 0.05 scenarios (light blue), AOD = 0.17 scenarios (orange) and AOD = 0.4 scenarios (black).

The following provides a practical demonstration of how the LUT is implemented within the RadCalNet data processing. The BOA reflectance spectra and its associated uncertainty from the LCFR input file provided by the site operator for June 22, 2021 at 11:30 UTC is shown in Figure 9. Note that the uncertainty values included in the input files are in reflectance units, not percentage. The atmospheric conditions at 11:30 UTC are also provided in the input file as AOD of 0.089, Angstrom Exponent of 1.175, ozone column of 331.73 DU, water vapor of 2.12 g/cm, and surface temperature of 302.8 K. The LCFR altitude is 20 m and based on the date, time, latitude and longitude the solar zenith angle is calculated to be 20.29°.

Fig 9. BOA reflectance (black) and uncertainty (blue) extracted from a RadCalNet input file from LCFR for June 22, 2021 at 11:30 UTC. Uncertainty is in terms of reflectance units.

This information is packaged into the proper format and run through MODTRAN to compute the TOA reflectance. The associated TOA reflectance uncertainty is then extracted from the LUT at each spectral wavelength. For the atmospheric and zenith angle LUT dimensions, the nearest larger neighbor entry is used. For this example, the selected LUT values are for the scenario of zenith angle of 25, AOD of 0.09, Angstrom exponent of 1.25, ozone column of 320 DU and an altitude of 500 m. At each wavelength, the uncertainty is determined by linear interpolation between the two BOA LUT entries that bracket the BOA reflectance. In this example, at 850 nm the BOA reflectance is 0.2849, so the interpolation uses the LUT entries for BOA of 0.25 and 0.30. A scaling factor is also applied to account for the LUT being...
derived for BOA reflectance uncertainties of 4% and the actual BOA reflectance uncertainty in the input files. In this instance, the reported BOA reflectance uncertainty at 850 nm is 3.43%. The scaling factor is applied as 3.43/4.0 = 0.8599.

Figure 10 shows the extracted spectral TOA uncertainty in percentage after the interpolation and scaling. The gaps seen are in atmospheric absorption regions where the uncertainty can exceed 10% and are flagged in the output data. In addition, if for a given scenario any of the zenith angle, AOD, Angstrom or BOA reflectance values exceed their largest respective LUT table interval, e.g. a AOD greater than 0.4, the uncertainty is written to the output as a negative number as a caveat to the users that the TOA uncertainty may be an underestimate.

The uncertainty values as seen in Figure 10 are then applied to the TOA reflectance and included in the RadCalNet output files. Figure 11 shows the resulting TOA reflectance and its associated uncertainty for our LCFR example case. To be consistent with the input files, the uncertainty is provided in units of reflectance, not percentage. It is seen that in general the uncertainty mimics the shape of the TOA reflectance spectra and is on the order of 3-4% of the reflectance.

5. Summary & Conclusions

Knowledge of the uncertainty of remote sensing measurements is fundamentally important particularly for applications that combine data from multiple sensors. The RadCalNet initiative from CEOS leverages the resources of participating vicarious calibration field sites to provide SI-traceable BOA and TOA spectral reflectance with documented error budgets and
uncertainties. The uncertainty for the TOA reflectance product was derived using a Monte Carlo approach that considered the correlated interactions of the contributing atmospheric and surface parameters. While the surface reflectance uncertainty is typically the dominant contributor to the resulting TOA reflectance uncertainty, scenarios with large zenith angles and/or high aerosol loading will result in the atmospheric parameter uncertainties being the main contributors. The Monte Carlo calculations over a range of input variables were used to generate a Look-Up Table of uncertainties that covers the majority of atmospheric and surface conditions experienced by the five currently operating RadCalNet sites. The technique allows knowledge of the uncertainty to within 0.5%.

As RadCalNet expands to other sites, additions to the LUT are under consideration. Given the number of cases in the current dataset with an Angstrom exponent less than 0.5, including a new Angstrom interval at 0.25 is warranted. This is not a trivial undertaking though as to completely populate the updated LUT will require 672,000 RTC runs. A new site under consideration for joining RadCalNet is a brighter surface and can have peak surface reflectances near 0.70. To accurately provide the uncertainty would require the addition of at minimum 4 new BOA reflectance LUT dimensions to extend from the current maximum of 0.50 to 0.70.

An option to generate an uncertainty ‘on-the-fly’ during processing by applying the Monte Carlo technique to each individually submitted RadCalNet input case is under consideration. The computational runtime required to implement this was not realistic for the current processing version using MODTRAN 5. However, improvements in the efficiency of MODTRAN 6 make implementation feasible and an alternate version of the processing is under development for consideration as RadCalNet evolves.

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Data Availability. Data underlying the results presented in this paper are not publically available at this time but may be obtained from the authors upon reasonable request.

References


