A Case Study of Measurement Uncertainty in Field Spectroscopy

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Abstract—In this article, a novel approach to measuring in situ field uncertainties in surface reflectance is presented. This work is an outcome of a national campaign by Geoscience Australia to validate our analysis-ready Landsat 8 and Sentinel 2 surface reflectance products. Various aspects of the field site methodology that were expected to contribute significantly to uncertainties were identified and tested. These aspects included the instrumental uncertainty, the use of a rest to stabilize the spectroradiometer fore-optic, the repositioning of the panel used for calibrating reflectance, and uncertainties introduced by the operator of the equipment, following a standard methodology. Results for two field sites are presented, which consistently show that approximately 95% of the overall uncertainty is a result of inherent variability in the ground surface reflectance. Typically, 5% of the uncertainty is introduced by a combination of the instrumentation and methodology.

Index Terms—Ground-based measurements, Landsat-8, reflectance, Sentinel-2a/b, uncertainty estimation, validation.

I. INTRODUCTION

OVER the last 30 years, satellite instruments, in situ instruments, and calibration and validation (Cal/Val) techniques have improved. Despite this progress, “spectroradiometric measurements still remain one of the least reliable of all physical measures and it is less than helpful to talk in terms of “truth” when it comes to any form of remote- or field-based spectral measurement” [1].

When validating a derived product from a satellite sensor, such as surface reflectance, measurements are made (or calculated) with the understanding that the in situ surface measurements are likely to be closer to “truth” than the corresponding satellite-derived product. It is therefore of the utmost importance to determine the uncertainty of both streams of data: both the validation and validated data.

The science and practice of field spectrometry has been hampered by wide-spread inconsistencies, given the complexities of the measurement methodology itself, as well as the significance of key terms and concepts. Comprehensive reviews into the history and significant issues relating to field spectrometry can be found in [1]–[3].

Field spectroscopy of natural surfaces and materials is a measurement fundamental to the validation of Earth observation science [1], [2], [4]. It is important that these data are gathered using both reliable and well-calibrated equipment together with robust and repeatable sampling methodologies.

There is an increasing recognition of the need to understand the sources of uncertainty in these measurements. Highly reproducible measurements using well-calibrated field spectrometers are essential if the uncertainty arising from the instrument and methods of use is to be separated from uncertainty introduced by the environment [2], [5].

In 2018, Geoscience Australia embarked on a significant national validation campaign of its analysis-ready data (ARD) surface reflectance products for the Landsat 8 and Sentinel 2 moderate resolution multispectral sensors [6]–[8]. The reader is specifically directed to [8] for details of the national validation campaign and methodology therein. However, the methodology used for each field site can be outlined as follows. An area approximately 100 x 100 m was staked out using typically ten 100 m, parallel transects. A reflectance panel is placed close to the starting transect and is used to calibrate the ground radiance such that they can be converted to reflectances. Spectra are recorded using an Analytical Spectral Device Full Range (ASD-FR) for both panel and ground data. Before the operator starts to walk the first transect, multiple spectra of the panel are recorded. The operator then walks the first transect, continually recording surface radiance, and then, back along the second transect before conducting the second panel measurement. This method is continued over the field site and finishes with a final panel measurement. For a field site with ten transects, there are thus six panel measurements. In order to minimize the time taken and the walking distance for the operator, the panel is moved by an assistant two or three times along the edge of the field site, during the transects. Variations to this general methodology have been employed for other field sites in the validation campaign (e.g., walking each transect in the same direction or acquiring panel spectra at both the start and end of each transect), but the aforementioned outline is sufficient for the purpose of identifying where this methodology might introduce uncertainties. One important result found during this campaign is that the reliability of ground measurements can be detrimentally affected if the panel used is too small. A recommendation was to use a panel at least 25 cm in length, as we did for this work.

A priority of this work is to quantify and trace the propagation of uncertainty within the measurement methodology. JCGM-100 [9] stated that while the “concept of uncertainty as a quantifiable attribute is relatively new in the history of
measurements [...] when reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability.”

We recognize four primary sources of variability or uncertainty relating to the measurement methodology. These are as follows:

1) sensor systems (equipment used);
2) measurement model;
3) operator;
4) innate variability in the target surface itself.

This article reports on the results of a range of simple experiments designed to identify and capture the relative sources of uncertainty in the measurement method.

II. EXPERIMENTAL DESIGN

The motivation for our work is to provide insights into the origins and characterization of uncertainties introduced by the methodology used to collect field data for comparison with Landsat-8 and Sentinel 2a/b products. Rather than an exhaustive traceability exercise of uncertainties, the aim is to investigate the practical implications of the methodology when validating the surface reflectance products. An important aspect of this work is to characterize uncertainties under the typical conditions and surfaces used for the national validation campaign.

The field spectra in this study were captured using a nadir-viewing geometry and conform to a hemispherical conical (case-8) reflectance factor (HCRF) in the geometrical optical concepts introduced by [3].

The spectrometer used was a standard resolution ASD-FR FieldSpec 4, covering a spectral range from 350 to 2500 nm. The ASD-FR has three detectors (VIS-NIR: 350–1000 nm, SWIR1: 1001–1800 nm, and SWIR2: 1801–2500 nm). An 8° field-of-view (FOV) fore-optic was fitted to the 1.4-m fiber bundle (Malvern PANanalytical, Boulder, USA). Downwelling irradiance measurements were taken using a tripod leveled 10° Labsphere optical polytetrafluoroethylene (PTFE) reflectance panel (Labsphere Inc., North Sutton, NH, USA), where each recorded spectrum was the average of 25 instantaneous spectra.

True spectral homogeneity is rarely possible at the scale and FOV of the ASD-FR. Consequently, the methodology assumes that the proportions of spectral variation that occur across the sample site are evenly captured by spectrometers [1].

A Labsphere reference panel, while considered to be a Lambertian reflector, is not perfect and even small angular variations in the sampling geometry exhibit differences. The ground target surface is far less likely to be Lambertian, so may exhibit significant differences in reflectance for small differences in the alignment of the ASD-FR to the target. In order to limit errors introduced by incorrect orientations of both the ASD-FR and reference panel, both were fitted with a bullseye-style bubble level. The accuracy of these bubble levels was such that errors of less than 1° are expected. The field measurement methodology described in this study has been refined over time as far as is possible to remove known sources of uncertainty.

Two field sites were chosen for this work. The first site is Mullion, which is situated in a rural location in New South Wales, Australia (latitude = 35.1229° south, longitude = 149.8626° east). The field site is located in a gently undulating improved pasture paddock. On the day of the experiments (April 10, 2019), the indicative cover fractions of photosynthetic vegetation (PV), nonphotosynthetic vegetation (NPV), and bare soil (BS) were 40%, 20%, and 40%, respectively (see Fig. 1). The other site is Lake George, which is also situated in a rural location in New South Wales, Australia (latitude = 35.0925° south, longitude = 149.4624° east). On the day of the experiments (July 2, 2019), the site was located on a dried lake bed, with mottled cracking clay and indicative cover fractions of 2% PV, < 1% NPV, and 98% BS (see Fig. 2). Lake George occasionally is inundated, but was dry from the end of 2017 until after the measurements were taken.

With this in mind, we designed a series of in-field experiments to isolate various sources of uncertainty, which we characterize as uncertainty due to the following reasons:

1) temporal instability (upper limit) in the ASD-FR instrumentation;
2) holding the ASD-FR over the panel on a rest;
3) manually replacing the ASD-FR over the panel on the rest;
4) holding the ASD-FR over the panel without a rest;
5) operator returning to the panel after collecting ground spectra;
6) manually moving the panel location;
7) walking along a transect to collect ground spectra.

The first six items are designed to separate individual contributions to the uncertainty budget, whereas the last item closely resembles the methodology used for a typical field campaign, which can be used to assess the overall uncertainty. For each of the aforementioned steps, an experiment was designed to measure the uncertainty characterized by the random error (see Sections II-A–II-F). We chose to conduct these experiments in the field, so as to closely resemble the field campaign methodology. However, with only the Sun as the source of illumination, it was necessary to model the change in illumination throughout the experimental duration. In order to take into account this changing illumination, we make the general assumption that the illumination intensity is proportional to the cosine of the Solar zenith angle. We then normalized the measured radiances to a standard illumination.

In order to assess the random errors, we chose to collect 50 spectra (each the average of 25 spectra over 2 s) for each experiment, unless otherwise noted. The statistical properties of these spectra could then be used to measure the errors. Each experiment is pictorially represented in Fig. 3 and detailed as follows.

1 All times are quoted in Australian Eastern Standard Time (UTC+1000).
2 This assumption may not be precisely correct, as there may be variability in the incident radiation field. However, expect that such variability will be small compared to the changing Solar zenith angle since the field campaigns were conducted on clear and atmospherically stable days. This is supported by the fact that we do not see any long-term trends in the data presented in this work.
A. Temporal Instability Upper Limit in the Instrumentation and Holding the ASD-FR Over the Panel on a Rest [Experiment (a)]

The first experiment was designed to remove as much operator error as possible, thus only measuring random uncertainties generated by the instrumentation and uncertainties due to changing irradiance that is not already accounted for. We were unable to separate these two contributions to this first experiment. Therefore, we consider the results achieved in this experiment to represent an upper limit on the variability introduced by instrumentation alone. The results for this experiment were achieved by holding the ASD-FR over the panel, using a rest. The rest allows the fore-optic to stabilize approximately 22 cm above the surface of the panel and has a fixed mount point to keep the same viewing location above the panel. At the point where the ASD-FR boom touches the rest, the rest has a v-shaped profile, which restricts sideways movement of the fore-optic. Bubble indicators on both the panel and fore-optic boom are used to achieve a close-as-practicable nadir viewing angle (< 1°). With the ASD-FR mounted on a rest, there should be minimal movement from the operator, and thus, minimal effect from the operator, although it is acknowledged that some operator-generated uncertainty may still occur. We assume that such uncertainties are small, compared to the instrumental uncertainties. Using this setup, 50 spectra were collected, with each spectrum, an average of 25 spectra taken over a 2 s interval. Previous work [10] has shown that the response of an ASD-FR typically changes over time and is sensitive, in particular, to changes in temperature. To minimize such effects, the ASD-FR was switched ON for approximately 30 min before the start of the experiments to allow it to approach thermal equilibrium as close as was practicable. We conducted this experiment at the start of the field campaign, at the start of the random uncertainty measurement experiments and (only for Mullion) at the conclusion of the experiments. Thus, we can compare the relative differences for these times to investigate if there are any long-term effects.

B. Manually Replacing the ASD-FR Over the Panel on the Rest [Experiment (b)]

This experiment was designed to measure the uncertainty introduced by manually replacing the ASD-FR on the rest. The
Fig. 2. Image of the Lake George field site used for these experiments, taken at 1100 (AEST) on the morning of July 2, 2019, facing east. The panel used in the experiments can be seen on the lower half, with the operator resting the ASD-FR probe on the rest mounted on the panel. The ground cover for the field site can also be seen in this image.

panel surface is not perfectly Lambertian and so it is expected to show slight differences in reflectance, depending on the observing angle. A changing observing angle may manifest due to slight errors in placing the ASD-FR on the rest, where each placement may be slightly different, even though a bubble gauge is used to align the ASD-FR vertically. The method used was to place the ASD-FR on the rest, take one spectrum, then lift the ASD-FR up off the rest, and then repeat the procedure 50 times.

C. Holding the ASD-FR Over the Panel Without a Rest [Experiment (c)]

During 2018, many field campaigns were undertaken without a rest. Thus, the operator was required to manually hold the ASD-FR steady over the panel to accumulate spectra. In order to assess the uncertainty introduced with this procedure, this experiment required the operator to hold the ASD-FR steady over the panel and record 50 spectra.

D. Operator Returning to the Panel After Collecting Ground Spectra [Experiment (d)]

In addition to the errors mentioned in the aforementioned experiment (b), additional errors may be introduced by the operator walking away and returning to the panel. For example, an operator may be more accurate in replacing the ASD-FR at the same position and orientation on the rest after just lifting it up [see experiment (b)], than if they were to take a few steps
Fig. 3. Representations of the six methodologies (a)–(f) used in this work. (a) Holding the ASD-FR steady on a rest. (b) Holding the ASD-FR on the rest for one spectrum, then repeatedly removing and replacing the ASD-FR on the rest for subsequent spectra. (c) Holding the ASD-FR without using a rest. (d) Holding the ASD-FR for one spectrum, then repeatedly walking away and returning to the rest for subsequent spectra. (e) Moving the panel and rest together after each spectrum is collected. (f) Full field campaign method.

away from the panel, turn around, and replace the ASD-FR on the rest (this experiment).

E. Manually Moving the Panel Location [Experiment (e)]

During field campaigns, the panel is typically moved along the edge of the field site, in order to minimize the time taken walking to the panel at the end of a transect. To assess how this procedure might introduce further uncertainty, the ASD-FR was placed on the rest, a spectrum was taken, then the panel was moved to a new location, and the procedure was repeated. Care was taken to align the panel horizontally, using a bubble gauge located on the panel stand. Care was also taken to ensure the panel was oriented in the same direction each time and ensured that the rest did not cast a shadow on the panel.

F. Walking Along a Transect to Collect Ground Spectra [Experiment (f)]

In this experiment, a simplified version of the normal transect procedure was adopted. Two panel spectra were acquired, using the rest on the panel. Then, the operator walked along...
TABLE I
WAVELENGTHS OVER WHICH SPECTRA WERE MASKED, CORRESPONDING TO ATMOSPHERIC ABSORPTION FEATURES

| Mask Wavelength (nm) |
|---------------------|
| Start   | End      |
|---------|----------|
| 680     | 700      |
| 710     | 735      |
| 750     | 770      |
| 810     | 840      |
| 880     | 1020     |
| 1080    | 1170     |
| 1300    | 1550     |
| 1760    | 2030     |
| 2250    | 2500     |

Fig. 4. Mean-averaged spectrum for experiment (a) at Mullion, showing the full mean-averaged spectrum in black, with the unmasked parts of the spectrum in blue.

a 25-m line, taking spectra along the way. At the end of the line, the operator walked along the reciprocal heading, keeping the ASD-FR on the same side of his body and attempting to capture the same line. For each transect, the outbound and return journeys together accumulated approximately 20 spectra. The entire procedure, including the two panel measurements and the transect outbound and return along the line, were carried out a total of 50 times.

III. DATA PROCESSING

The workflow described in [8] was used to ingest the raw spectral data. Each DataFrame included columns for the spectrum number, latitude, longitude, date and time of acquisition, Solar zenith angle, wavelength, and radiance. For each experiment, the mean average of all panel spectra was calculated. Then, each mean-averaged spectrum was masked over various wavelength ranges, shown in Table I, to remove those parts of the spectrum that are sensitive to atmospheric absorption features. Fig. 4 shows an example mean-averaged radiance spectrum for experiment (a), at Mullion.

Then, each panel spectrum was divided by the masked mean-averaged spectrum for that experiment. This created a set of normalized, masked panel spectra for each experiment. Fig. 5 shows example normalized, masked panel radiance spectra for experiment (a), at Mullion.

The normalized, masked panel spectra were then averaged along the wavelength axis to yield a single data point for each spectrum. To account for the changing Solar irradiance, the data points were fit against the Solar zenith angle (see Fig. 6) and the resulting fit (red line) was subtracted from all the raw spectra; both panel and ground spectra in the case of experiment (f). Thus, the output of this workflow will be a single point for each spectrum, which is the difference between the spectrum and the expected value. In the ideal case where there are no experimental errors and the atmosphere is perfectly stable, all points should be equal to zero.

IV. RESULTS

Given that we expect ideal data to be equal to zero, we can compare the results to assess the uncertainties that are inherent in each experiment. Here, we treat each experiment individually.

A. Temporal Instability Upper Limit in the Instrumentation and Holding the ASD-FR Over the Panel on a Rest (Experiment (a))

Fig. 7 shows the results for the times this experiment was conducted both at Mullion and Lake George. The standard deviations for the experiments are 0.065%, 0.054%, and 0.042% for Mullion and 0.040% and 0.067% for Lake George, of the mean radiance. The average of these numbers (0.054%) can be interpreted as the upper limit on the typical uncertainty that is contributed by instrumentation alone. Furthermore, the low variability of these numbers indicates that the calculated average is a reliable figure that does not vary greatly on different days or times. This also gives us confidence that contributions due to changing irradiance that is not already accounted for by the Solar zenith angle term will be small, compared to instrumental
Fig. 7. Variability of spectra in experiment (a) for Mullion (left panels) and Lake George (right panels). Experiments were conducted three times during the day for Mullion and twice for Lake George. Times are shown in the upper right corner for each panel. The vertical axis is held constant for each panel in this Figure, as well as for Figs. 8 and 9 so that the relative magnitude of the variations can be easily compared. The uncertainty associated with the variability is similar for all times, with relative uncertainties for Mullion being 0.065%, 0.054%, and 0.042% for 0957, 1054, and 1253, respectively, and uncertainties for Lake George being 0.04% and 0.067% for 1100 and 1151, respectively.

uncertainty. Therefore, we expect that the values derived here are indeed representative of the instrumental uncertainty alone.

B. Manually Placing the ASD-FR Over the Panel [Experiment (b)]

Figs. 8 and 9, top left, show the results for repeatedly placing the ASD-FR on the rest above the panel. The standard deviations of the data points are 0.101% and 0.121% for Mullion and Lake George, respectively. These are about twice the uncertainty reported for experiment (a). Therefore, we can assign typically 0.047% of the uncertainty due to the placement of the ASD-FR on the rest.

C. Holding the ASD-FR Over the Panel Without a Rest [Experiment (c)]

Figs. 8 and 9, top right, show the results for manually holding the ASD-FR above the panel, without using a rest. The standard deviations of the data points are 0.134% and 0.122% for Mullion and Lake George, respectively. The uncertainty for Mullion shows a large increase over that for using the rest, whilst the increase for Lake George is negligible.

D. Operator Returning to the Panel After Collecting Ground Spectra [Experiment (d)]

Figs. 8 and 9, middle left, show the results for the operator walking away from the panel after taking a spectrum, and then, returning to it, to place the ASD-FR on the rest, above the panel. The standard deviation of the data points is 0.145% for Mullion and 0.177% for Lake George. These uncertainties show some increase over those found for experiment (c), implying that the action of repositioning the operator and the aperture of the ASD over the panel does increase the uncertainty budget.

E. Manually Moving the Panel Location [Experiment (e)]

Figs. 8 and 9, middle right, show the results for a helper moving the panel to a new location after each spectrum. The standard deviations of the data points are 0.243% and 0.257% for Mullion and Lake George, respectively. These uncertainties are significantly larger than previous uncertainties, implying that relocating the panel has a significant effect on the uncertainty budget. In comparison to experiment (d), we find that this procedure contributes around 0.09% to the uncertainty budget. We note that any error introduced when the panel is not perfectly leveled will be exacerbated for high Solar zenith angles. To mitigate this, we endeavored to keep the panel as level as possible, using the sight bubble.

F. Walking Along a Transect to Collect Ground Spectra [Experiment (f)]

Figs. 8 and 9, bottom left, show the results for just the panel data, following the methodology in experiment (f). The
Fig. 9. Lake George variability of panel spectra for experiments (b)–(f). Experiment (b) is shown in the upper left, experiment (c) in the upper right, experiment (d) in the middle left, experiment (e) in the middle right, and experiment (f) in the lower left. The vertical axis scale is kept constant for each panel so that the relative magnitude of the variations can be visually compared.

Fig. 10. Mullion variability of ground spectra in experiment (f). The ground spectra were taken during 50 transects, walking forwards and backwards along the same line and include a total of 498 spectra.

standard deviations of the data points are 0.207% for Mullion and 0.278% for Lake George. These uncertainties are slightly larger than the average uncertainty found in experiment (d) but not significantly larger than the average uncertainty found in experiment (e), which suggests that moving the panel does introduce a measurable increase in the uncertainty budget. Note that 100 panel spectra were collected at Mullion, whereas 50 panel spectra were collected at Lake George.

In addition to the results from the panel spectra above, we also analyze the ground spectra that were collected by walking up and down the same 25 m transect, 25 times. The ground data were processed in the same way as the panel data and treated as a separate experiment. Results are shown in Figs. 10 and 11.

G. Transect Random Variability

We note here that the data shown in Figs. 10 and 11 do not appear completely random. For this subsection, we assume the data are randomly distributed and discuss possible causes for any nonrandom variability in the following subsection. The ground data will exhibit intrinsic variability because each spectrum will be taken over different parts of the transect, and thus, will show different amounts of PV, NPV, BS, and shadow. As Figs. 1 and 2 show, significant variability is seen in both sites. In order to characterize the random uncertainties due to the methodology and separate these uncertainties from intrinsic ground variability, we make the assumption that the random uncertainties will be the same as those for the panel data [i.e., experiment (f)]. The variabilities seen in the ground spectra are 8.35% and 6.31% for Mullion and Lake George, respectively. These can be compared to the respective methodological uncertainties of 0.207% and 0.278%.

H. Transect Nonrandom Variability

As mentioned in the previous subsection and as can be seen from Figs. 10 and 11, the variations in the ground spectra appear to exhibit nonrandom behavior. One source of this behavior is likely to come from the fact that the operator walks over the same transect, including spectra over the same surface. Therefore, we might expect to see a repeating pattern of radiances for each transect. We note that it is unlikely that the position of each spectrum in a line will be identical to the same spectrum in a different line, so we expect that any repeating pattern may be at least partially masked by noise. This can be seen in Figs. 10 and 11, as any repeating pattern is not clearly defined.

We decided to investigate further the nonrandom variability, as the structure seen in Fig. 10 does not appear to come from only spectra acquired over the same transect. Fig. 12 shows the ground spectra for Mullion (top) and Lake George (bottom), where all spectral data in one transect have been averaged together into a single data point. Since this data point gives the average over the entire transect, any variation between data points is expected to be purely random. In Fig. 12, odd-numbered transects have been color-coded red and even-numbered transects have been color-coded blue. In this way, we separate out the direction in which the operator walks: red is walking approximately west to east and blue is walking approximately east to west.
The data for Lake George do appear to be randomly distributed, but the data for Mullion show that the surface reflectance generally appears higher for transects walking east to west (blue). On average, the blue points are 0.003 surface reflectance units higher than the red points, equivalent to an average difference of 2.5%. We use a Kolmogorov–Smirnov (KS) test to compare the distributions of the points. The KS test is used to test the null hypothesis that the two samples are drawn from the same distribution. In this case, we find for the Mullion site that the p-value is less than 0.0002, which means that there is a greater than 99.98% chance that there is a real difference between the data points collected when walking west to east, as compared to walking in the opposite direction. In contrast, the Lake George data, when broken into the two directions, show a p-value of 0.915, which means there is a 91.5% chance that they are drawn from the same underlying population. So, there is no evidence that there is any difference in the measured surface reflectance when walking in different directions at Lake George.

V. DISCUSSION

A. Individual Contributions to Uncertainty

Fig. 13 presents the relative contributions of uncertainties and variabilities for both field sites. The smallest contribution to the overall uncertainty is the uncertainty dominated by the instrumentation (0.61% and 0.80% for Mullion and Lake George, respectively). We also found that this uncertainty does not vary significantly during the day (see Fig. 7). This confirms that the method used to prepare equipment for a field campaign is effective in reducing time-dependent variability to insignificant levels. The method we use is to turn on the equipment and leave for at least half an hour before conducting measurements.

Experiments (a) and (c) can be compared to (a) and (b), where we find mixed results when considering if using a rest with the ASD-FR is beneficial. That there is a consistently positive difference when considering uncertainties in both (b)–(a) and (c)–(a) indicates that the action of both holding the ASD-FR without a rest and replacing it on the rest introduces significant variability, but at about the same level.

The difference between experiments (d) and (b) shows that significant variability is also introduced in the action of the operator walking away from the panel. In this case, this is likely to be a result of the operator losing sight of the exact location on the rest previously used, such that the placement of the ASD-FR is less precise, and therefore, introduces more uncertainty.

Experiment (e) shows the largest increase in uncertainty over all the methodological components to this work: 1.12% and 1.20% when compared to experiment (d). This indicates that significant uncertainty is introduced by moving the panel. Furthermore, the data points presented in Figs. 8 and 9 show that the uncertainty is dominated by a small number of points (points 44 and 45 for Mullion and points 24 and 39 for Lake George) in each case. This suggests that poor placement of the panel can occasionally happen and will result in a significantly poorer calibration of results. Thus, it is important that if a panel is to be moved during a field campaign, care should be taken to ensure that the panel is leveled correctly.

B. Uncertainty and Variability Budget

Based on the results above, we can combine them to provide an overall picture of the origins of uncertainty due to the methodology and variability due to the ground conditions. For context, we note that previous work [11] on contact probe leaf data found that generally 3% of their uncertainty budget was due to measurement. Fig. 13 presents the relative contributions of uncertainties and variabilities for both field sites. It is clear that the variability in the ground spectra is the dominant contributor to the uncertainty budget and accounts for around 95%. The uncertainties derived from the panel experiments are all small and together contribute around 5%. Furthermore, given a worst-case scenario, where the operator does not use a rest and moves the panel position after each transect, we would expect no more than 5.0% of the uncertainty budget to come from the methodology. If the operator uses a rest and keeps the panel in the same place, then only 2.4% of the uncertainty budget comes from the methodology. This result compares well with those of [11] mentioned previously. Also, such a small contribution from the methodology gives confidence that measurement errors will not significantly contribute to the Phase 1 results published in [8].

C. Transect Nonrandom Variability

As described in Section IV-H, we find a significant, nonrandom component to the variability while walking the transect. We consider two possible explanations for this effect: first of all is that the presence of the operator may affect the diffuse
radiation field incident on the ground. This may be caused by the operator shadowing diffuse radiation when walking on the Sun side of the transect and/or caused by extra reflectant radiation from the operator when walking on the other side of the transect. However, we believe that the operator did not significantly affect the radiation field because the same operator carried out the experiments and wore the same clothing for each day. Therefore, we would expect to see similar results for both field sites, since this effect is largely dependent on the incident radiation field, rather than the ground characteristics. Yet we do not see a significant effect at the Lake George site.

Another possible explanation is that the ground surface at Mullion was not completely flat and showed a slightly downward incline going from west to east, whereas the surface at Lake George appeared completely flat. Since the operator endeavored to keep the ASD-FR pointed at nadir, using a bubble level, this means that the angle that the ASD-FR made with the surface was not perfectly normal, with the ground tilting slightly toward the Sun when walking west to east and slightly away from the Sun when walking in the opposite direction. This slight difference in orientation could account for the discrepancy we see in the surface reflectance, but further experimentation is required to confirm (or otherwise) this hypothesis, which we intend to pursue in future work.

VI. CONCLUSION

We have performed experiments at two field sites (Mullion and Lake George) used for Landsat 8 and Sentinel 2 validation in Australia. The experiments were designed to estimate random uncertainties in instrumentation and methodology used during field site campaigns, with the intent to identify the best methodology for future campaigns, as well as provide information on the expected contributions of these random uncertainties.

Overall we found that intrinsic variability in the ground surface reflectance dominated the measurements, contributing 94%–96% of the measured variability. The remaining ∼5% is the result of instrumental and methodological uncertainties, which can be broken down as follows.

1) 0.7% due to instrumental uncertainty (experiment (a)—this may include irradiance fluctuations, but we expect this figure to be dominated by instrumental uncertainty alone);
2) 0.8% due to placing the ASD-FR on a rest [experiments (b)–(a)];
3) 1.0% due to placing the ASD-FR over the panel but without a rest [experiments (c)–(a)];
4) 0.7% due to walking away from and returning to the rest [experiments (d)–(b)];
5) 1.2% due to moving the panel to a new location [experiments (e)–(d)];
6) 1.1% due to walking along a transect experiments (f)–(d).

We recommend that future campaigns employ the use of a rest for the ASD-FR above a panel, as well as limiting the number of times a panel is relocated during the work. Furthermore, we advise that all field spectral campaigns undertake similar measurements, as they are a simple and effective means of determining the sources of uncertainty for a given instrumentation, operator, and sampling strategy.

We found that at one field site (Mullion), the measured surface reflectance was significantly brighter when walking east to west, compared to walking in the opposite direction. We did not find a similar pattern at the other field site (Lake George) and conclude that this effect is unlikely to be due to diffuse radiation.
being shadowed by the operator or extra surface reflectance contributed by the operator due to reflected sunlight. We suggest that a more likely reason is that a slight slope in the Mullion site contributes to this difference in surface reflection, but confirmation of this effect will require future experimentation.

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