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Atmospheric Measurement Techniques
Discussions

Interactive comment on "Radiometric calibration of a non-imaging airborne spectrometer to measure the Greenland Ice Sheet surface" *by* Christopher J. Crawford et al.

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The authors appreciate Referee #2's time and effort to review and provide comments on this AMTD paper. The authors are confident that appropriate responses have been drafted to address the comments offered and expect that such revisions have improved the paper's clarity, conclusions, and impact.

The authors realize that the number of acronyms is substantial. We were aware of this when drafting the paper but felt that the acronyms used are found elsewhere in the remote sensing and cryosphere published literature. That said, we re-evaluated the acronyms and reduced where appropriate to enhance the paper's readability and clar-

ity. We also reduced the jargon and removed the term 'benchmarking' from the paper. We also replaced the term MODTRAN 'simulation' to MODTRAN 'prediction' throughout the text to maintain consistency with other published literature on applications of MODTRAN in airborne science.

The authors employed well defined and published methods for evaluating airborne remote sensing VSWIR instrument measurement performance. Use of a radiative transfer model such as MODTRAN is common practice in airborne science, so the authors are not quite certain what it is that they misrepresented. Along those lines, we do accept that the 'accuracy' term and results needed to be re-evaluated against what is reported, and thus, was changed to 'uncertainty' instead. We address this during responses to specific comments below. We do not understand the reference to the 10% uncertainty in the comments. We are careful in the paper to acknowledge variability in uncertainty across the spectrum at an 80% atmospheric transmission level. Our in-flight calibration is absolute because we measured bright and dark targets and then modeled the atmosphere under approximately the same solar illumination conditions with actual observations from the Thule Air Base CIMEL, and well validated satellite sensor retrievals. We used expert knowledge to define the MODTRAN parameterization for the Arctic atmosphere we were measuring and flying through over the Greenland Ice Sheet. We closely examined the below comments to further clarify our approach and results.

The 2% metric comes from the published literature on Polar ice sheet remote sensing using optical instruments. In the paper, we are drawing attention to the fact that it will likely be difficult to achieve that level of measurement uncertainty. Our approach incorporated robust instrument radiometric calibration methods and traceable SI standards coupled with state of the art atmospheric radiative transfer modeling when making these airborne measurements. Without such approach, it would be hard to determine whether a 2% measurement uncertainty of the ice sheet surface is achievable from airborne and/or spaceborne remote sensing.

Regarding model uncertainty and the error budget analysis, if we were to conduct such an exercise, we would have to conduct a sensitivity analysis of MODTRAN parameters spanning both minimum and maximum ranges of each input. This is a separate effort and possible paper that goes beyond the scope of this communication. Error budget analyses of atmospheric radiative transfer models remain largely incomplete across the global domain, so the authors feel that this request is holding this paper to a standard that has yet to be established in the broader remote sensing community and literature. Introducing uncertainty into MODTRAN predictions would reduce the importance and effort in this paper to retrieve actual atmospheric observations during flight and evaluate the measurement performance of the nadir viewing spectrometer.

Please find our responses to specific comments below along with author changes to the paper.

1. p. 2, l. 30: "benchmark"; Instead of using a term like this it is probably better to be speciïňĄc about how you intend to use your simulations of spectral radiance and irradiance. As it currently reads, the measurements are to be tested against the modeled "truth". This begs the question, why are the measurements even needed?

Author Response: We removed the term ‘benchmarking’ from the text and instead, now refer to the process of evaluating MODTRAN predictions of radiance against VSWIR spectrometer measurements as a ‘comparison’. Yes, this is correct. We are treating MODTRAN for this analysis as ‘truth’. MODTRAN radiative transfer predictions are approximations that helped our team (1) evaluate VSWIR spectrometer measurement performance over the Greenland Ice Sheet; and (2) reproduce solar and atmospheric physical processes leading to the remote sensing measurements of reflected surface radiance. We need both remote sensing measurements and radiative transfer models to conduct Greenland Ice Sheet science and applications.

2. p. 3, l. 3: what are "proïňĄle measurements"?

Author Response: Non-imaging profile measurements are defined as along-track radi-

ance spectra of the surface directly below the aircraft within the airborne spectrometer’s Instantaneous Field-of-View (IFOV). This sentence has been added to the paper.

3. p. 3, l 29: "...within infrared wavelengths..." I think you mean "...in the near infrared..." Also, you should be more specific and identify water as the absorber.

Author Response: The remote sensing literature is often ambiguous on whether the ice absorption feature officially falls within the near infrared or shortwave infrared wavelength region. Thus, the authors used infrared wavelengths more generally as it is technically correct and does not place preference. However, the authors agree with the Referee and inserted ‘near’ before infrared. The authors also added absorption by liquid water upon recommendation.

4. p. 4, l. 7: You should state the ïňĄelds-of-view. I note that it is done later but it does not hurt to list them here.

Author Response: Corrected.

5. p. 4, l. 14: "at-sensor" is jargon best used when there is some ambiguity about the vertical location of the radiance: water- or surface-leaving, etc. In this context, where else can a sensor measure radiance other than at-sensor?!

Author Response: We removed the at-sensor jargon from the paper.

6. p. 4, l. 18: spectral response functions of what?

Author Response: The spectral response functions for the nadir viewing spectrometer. We inserted text to clarify this phrase.

7. p. 4 l. 15-18: the list of model input in confusing. Why are standard aerosol proïňĄles and CIMEL measurements (of what? Presumable aerosol optical depths?) both used? What are the assumed state parameters? US standard atmosphere?

Author Response: We clarified the list of MODTRAN inputs. The rationale and specific parameters are described in detail later in the paper under the Methods section. A sub-Arctic geographical and seasonal atmosphere was used as the state parameters, and CIMEL measurements of aerosol optical depth and columnar water vapor were used to parameterize MODTRAN predictions.

8. p. 4 l. 28: "gold standard" is jargon. What characteristics make it the best comparison reference? Does it have the appropriate near-infrared channels for this study?

Author Response: We removed the jargon. Landsat 8 Operational Land Imager (OLI) is being increasingly used to map and monitor ice sheet surface characteristics and change because its coverage has dramatically increased since its launch in 2013. It is an appropriate reference instrument because of its absolute radiometric calibration and on-orbit performance, its medium resolution multispectral VSWIR measurements, and its high latitude temporal imaging frequency. These points are included at appropriate places throughout the paper. The near infrared channel on OLI was not designed to measure the ice sheet surface, but it is an important measurement nevertheless. Landsat has and continues to be used widely in Polar remote sensing studies.

9. p. 4 l..32: "sunlight" should be "sunlit" and change to "... regions with greater than 5...

Author Response: We replaced sunlight to sunlit. We revised the language regarding Landsat 8 OLI solar elevation imaging requirement. One point of clarity. Landsat 8 OLI is a land mission that images near shore coastal regions. Thus, saying all regions is not consistent with mission imaging requirements because we do not nominally measure Oceans.

10. p. 4, l. 33: "... challenges that are a result of ..." Aren't the items that follow actually the challenges? If not, then state what the challenges are.

Author Response: We removed the challenges terminology to more accurately reflect this statement on ice sheet remote sensing.

11. p. 4 l. 34: "longer path": longer than what? "greater atmospheric refraction":

greater than what?

Author Response: This phrase has been removed as a path length and refraction physics are part of low solar illumination angles.

12. p. 5, l. 23: what is the remote cosine receptor? A transmissive or reïňĆective diffuser? Integrating sphere?

Author Response: We added the following sentence to the text to clarify what a remote cosine receptor is. A remote cosine receptor is diffuser optic that transmits incoming irradiance from an 1800 hemispherical view.

13. p. 6, l. 13: The SWIR1 and SWIR2 detectors had not yet been identiïňĄed. After going back, I think I know what they are – you need to state explicitly. This makes already confusing notation even more confusing: sometimes the acronyms use in this paper are longer that what they are meant to represent!

Author Response: We clarified what we mean by SWIR1 and SWIR2 on page 5, Section 2.1.

14. p. 6, l. 13: I have a hard time understanding what "the entire airborne mission that included a dark current subtraction during each ïňĆight" is supposed to mean.

Author Response: We clarified that the entire airborne mission represents all nine science flights. This statement documents that we used the same spectrometer integration time and gain configuration for each science flight to avoid measurement saturation over the Greenland Ice Sheet under different atmospheric conditions. We converged on the optimal spectrometer measurement configuration during the absolute in-flight calibration experiment described in the text. The dark current subtraction reflects the removal of internal noise from the spectrometer when measuring radiance or irradiance.

15. p. 6, l. 28-29: What was optimized? Gains?

Author Response: The integration time and gains were optimized to the integrating sphere NIST traceable source output. This has been clarified in the text.

16. p. 6, l. 28: What is the NIST source? Lamp? Lamp plus integrating sphere? And is it really a NIST source or is it NIST-traceable?

Author Response: The source is NIST traceable and includes lamps plus integrating sphere. This has been clarified in the text.

17. p. 7. l. 2: point out the water vapor absorption bands evident in the stability curve of ïňĄgure 2.

Author Response: The water vapor absorption bands have been identified in Figure 2.

18. pp. 6-7: The ïňĄgures in ïňĄgure 2, especially the linearity curve in the upper left needs to be better explained, either in the text or the caption. The "optimization" in the abscissa is not explained.

Author Response: The linearity test in upper left panel of Figure 2 has been clarified in the caption and the figure description has been revised. The linearity test has also been revised for clarity in the text itself.

19. p. 7, l. 4: Is 1 nm resolution the full-width half-maximum of the slit function, that is, spectral resolution? Or is it sampling resolution? And the wavelength precision of 2%: is that 2% of the wavelength scale (for example, 20 nm at 1000 nm, terrible) or 2% of the sampling resolution (2% of 1 nm, very good). Why not remove such ambiguity and list the precision in absolute units, nm?! And ïňĄnally: the instrument spectral and sampling resolutions must be stated earlier in the text.

Author Response: The spectral resolution of the VNIR detector is 3 nm, and the sampling resolution is 1 nm achieved using an order sorting filter. The spectral resolution of the SWIR detectors is 10 nm with 1 nm sampling resolution. The wavelength scale is 2% of 1 nm, very good. We prefer to report in percentages rather than absolute units as percentages normalize for different radiance levels across the VSWIR range.

We have clarified the text on wavelength precision. We have inserted spectral and sampling resolutions earlier in the text, Section 2.1 to be exact.

20. p. 7, l. 6. Now using Fieldspec 3 or Pro is extremely confusing and requires a scorecard or ïňĆipping back to see which instrument is which. Unless the reader works for ASD or used their products, they won't care. Please use the same identifying notation (how about simpoly zenith and nadir spectrometers?!) throughout?

Author Response: We removed FieldSpec 3 and Pro from the text other than initial description early in the text, Section 2.1 to be exact.

21. p. 7, l. 7: What is the signiïňĄcance of "a PANalytical company"?

Author Response: We removed PANalytical company from the text.

22. p. 7. L. 8-9: "less than 2% for 1 nm resolution". Same comment as above.

Author Response: We revised to match the language used to address Comment 19.

23. p. 7, l. 22: "per manufacture speciïňĄcations." Do you mean "in agreement with manufacture speciïňĄcations"?

Author Response: This statement is what we intended to write, but we did attempt to clarify be adding 'material' to the sentence.

24. p. 7, l. 24-26: I don't understand this sentence. Are you saying that window transmission should be appreciably larger than instrument stability? But this leads to a more important question, relevant to the previous paragraph: why wasn't a calibration made with the window/dome in place?

Author Response: We added sentences to paragraph one of this section to clarify why we were unable to measure transmittance of the nadir viewing optical window. We also clarified why window transmission uncertainty was appreciably larger than instrument stability in paragraph two of Section 3.1.3.

25. p. 7, last paragraph: The listed accuracies are really uncertainties rather than accuracies. How were they derived? Was a correction for window transmittance made? How was the solar zenith angle factored in to the uncertainty? For the zenith measurements (presumably using the cosine receptor) that will likely be the largest source of error, especially if the platform was not actively leveled and in the Arctic where solar zenith angle is quite high.

Author Response: How these uncertainty metrics were derived has been included in the text. We chose not to correct for window transmittance because the uncertainty was within our targeted measurement requirement. The solar zenith problem and its uncertainty is described later in the text including aircraft horizontal stability and low solar illumination angles in the Arctic. It is important to highlight that these measurements were largely experimental, and we describe their intended use and interpretation later in the text.

26. p. 8, l. 6: Is it really an "in-ïňĆight radiance calibration strategy" or a strategy to optimize gain and integration time settings? If it is really in-ïňĆight-calibration, please explain what standard sources or detectors you are using during ïňĆight.

Author Response: We revised the first paragraph in Section 3.2.1 to more accurately describe our absolute in-flight radiometric calibration. With respect to the in-flight description, we consider this absolute because we constrained the upper limits of upwelling spectral radiance under near clear sky conditions while flying over bright and dark targets. Ideally, there would have been a ground campaign to measure reflectance with a standard source, such as a calibrated Spectralon panel, but this was not possible as described in subsequent sections of the text. Our technical approach in this paper is the best attempt given the unavailability of ground measurements in-flight.

27. p. 8, l. 9: same as above.

Author Response: This statement was revised.

28. p. 8, second paragraph: How about the effect of aircraft attitude on solar zenith error and its impact on downwelling irradiance error? (never mind; this is a topic for the next section, but it is not cover there either.)

Author Response: Noted. This comment was addressed in Section 3.2.2.

29. p. 8, last paragraph: what is the threshold for setting the ïňĆag?

Author Response: We removed this statement as this paper does not present science flight data products.

30. p. 9, l 8: You should probably say more about "cloud contamination". Why do cloudslimittheretrievalofsurfacepropertiesfromspectralreïňĆectancemeasurements? After all, since you are measuring incident irradiance (at ïňĆight altitude) it might seem like clouds can be accommodated.

Author Response: We added text regarding cloud contamination and described why identifying these conditions is important for this effort to assess the nadir viewing spectrometer's measurement performance.

31. p. 9, l. 9: "calibration strategy" again. See previous comment.

Author Response: We revised this text.

32. p. 9, second paragraph: I don't understand this – it seems like it defeats the entire purpose of measuring incident irradiance!

Author Response: Our objective for measuring solar irradiance has been clarified in the first paragraph of Section 3.2.2.

33. p. 9, l. 24: By "direct path" do you mean directly transmitted irradiance? A horizontal translation of the aircraft will be insigniïňĄcant compared to pitch and roll offsets! I have yet to see this considered, or the angular response of the cosine receptor presented.

Author Response: Yes, directly transmitted irradiance is what we intended to say. This has been revised. The angular response of the remote cosine receptor was measured and described in Section 3.3.2.

34. p. 9, l. 9: The mysterious NIST-traceable source has yet to be identiïňĄed.

Author Response: We used NIST traceable sources from GSFC's Optics Lab and Radiometric Calibration Lab.

35. Section 3.3.2: I cannot tell ifthe angular calibrations are for azimuthal or zenith response or both. This is very important. On the other hand, if directly transmitted solar irradiance cannot be sensed with the orange can in place it does not matter!

Author Response: The remote cosine receptor angular calibrations were zenith from 00 to 1800. The text has been clarified.

36. p. 11, l. 15-16: What is "direct cloud-sky"? Does that imply a broken cloud ïňĄeld? Cloud optical depth low enough such that direct transmittance is appreciable?

Author Response: The following sentence has been added to clarify what we mean by direct cloud-sky. 'Direct cloud-sky indicates when clouds are fully obstructing the direct path'.

37. p. 11, l. 17: Listing times suggests the window can be nothing other than temporal.

Author Response: This is correct. The real value of these spectral irradiance measurements is found in the temporal domain. We illustrated this in Figure 8 using a short flight segment.

38. P. 11, l. 20: Parabolic corrections for what?

Author Response: A parabolic correction is used to splice together VNIR and SWIR detectors during the conversion from raw counts to radiance. This text is unnecessary as written and is already described earlier in the paper. We removed this statement from the sentence.

39. p. 11, l. 25: Discriminate diffuse sky conditions from what? Or do you mean "identify diffuse sky conditions"?

Author Response: Characterize sky conditions is a more appropriate statement. We revised this sentence.

40. p. 11, l. 31: "...discriminator for sky conditions more broadly..." More broadly than what? I cannot understand, either from the text or ïňĄgure 7, how the zenith measurements can discriminate between different types of diffuse sky sources. Considerably more explanation is required.

Author Response: This comment is well taken. We have revised these sentences to articulate that the OrangeCan spectral irradiance measurements can be used to distinguish between diffuse cloud-sky and diffuse clear-sky based on the amount of irradiance received. This can be visually observed in Figure 7 and detected in the time domain with the Figure 8 illustration.

41. Figure 7: I assume the radiation model was plane-parallel; how did you account for the complex cloud geometries? Nothing was said about the modeling in either the text or the captions.

Author Response: No radiation model was used to derive results shown in Figure 7. In terms of MODTRAN predictions, yes, we assumed plane-parallel and only used 29 July airborne measurements acquired under clear-sky conditions. We used the spectral irradiance data to identify dffuse clear-sky measurements. We assumed direct transmitted clear-sky because the upwelling radiance from the surface exhibited little deviation indicating surface homogeneity with no shadowing. This has been clarified in the text.

42. p. 12, l. 5, ïňĄrst sentence in paragraph: I think you need to be more speciïňĄc about what the science is. I assume you are trying to retrieve surface reïňĆectance. You must state this speciïňĄc application of these measurements. Many other applica-

tions do not require surface reïňĆectance validation.

Author Response: We have revised this paragraph for clarity of the radiative transfer comparison methodology. At this point, we are not trying to retrieve surface reflectance, only compare the nadir viewing spectrometer's measurement performance against MODTRAN. While most remote sensing applications do not demand surface reflectance validation because pixel classification based on feature space is the objective, our view is that validation should be undertaken when specific surface properties are being retrieved from reflectance. This paper is an important step towards establishing surface reflectance uncertainty from airborne measurements during this mission.

43. p. 12, l. 26 (and many other places): Again, the use of the term "benchmark" comes with no qualiïňĄcation. What do you intend to do with the MODTRAN simulations! Of course, compare them to measurements, but toward what end?

Author Response: We removed the 'benchmark' terminology from the entire paper. The end game is to use MODTRAN to atmospherically-correct airborne reflectance from the nadir viewing spectrometer.

44. p. 12, l. 30: Not sure how you can check for changing solar illumination if you cannot see the sun with the orange can!

Author Response: We agree. This phrase has been removed. This is not what we meant to say.

45. p. 13, eq. 3: This equation does not contain the atmospheric transmittance from TOA to ïňĆight altitude or from ïňĆight altitude to ground. Is that what is meant by "apparent" reïňĆectance? After ïňĄnishing the paper, I don't see that this was ever considered. It is either ïňĆawed or you need to explain how it was applied.

Author Response: You are correct. The equation as written does not include transmittance. Apparent reflectance is a widely published term in airborne science and in the remote sensing calibration/validation literature. Because we did not measure ground

reflectance, we treated this low altitude apparent reflectance measurement as a substitute because that is the best possible scenario. We replaced equation 3 in the original paper with equations 3,4, and 5 in the authors changes to the paper. We now completely describe the process we used for retrieving apparent reflectance and have included the proper mathematical notation and supporting citations. MODTRAN is used to simulate these atmospheric quantities during the process of predicting radiance. We have clarified and added text for our radiative transfer method.

46. p. 13, l. 21: "...to parameterize MODTRAN..." makes no sense. Do you mean "...to initialize MODTRAN..."?

Author Response: Yes, we mean parameterize MODTRAN. The use of initialize here would indicate a starting value that will likely change during successive calculations. This is not the case when predicting remote sensing radiance from MODTRAN.

47. p. 14, l. 6: Those are usually called slit functions, not spectral response functions. And ïňĄnally, a mystery solved (from ïňĄg. 11): spectral resolution is 3 nm and 10 nm; 1 nm is sampling resolution. Please state this in the text.

Author Response: Within a MODTRAN environment, slit functions are used to integrate finer spectral resolution radiances to coarse resolution radiances. Spectral response functions were derived specifically for the nadir viewing spectrometer. We describe the spectral resolution of the VNIR and SWIR detectors in the text much earlier now.

48. p. 14, l. 15: Again, poor or confusing usage: "...successfully constrain MODTRAN ..." And as before, do you mean initialize? Or are you really constraining MODTRAN output over a range of input? The caption in Fig. 12 provides no clue. And once again, I think "parameterize" is misused again in the following line.

Author Response: We have revised this sentence. We prefer 'parameterize' over initialize, see response to comment 46 for rationale. In the following sentence, we replace parameterize with 'model'. The caption in Fig. 12 has been clarified.

49. P. 16, l. 4-6: Is accuracy deïňĄned to be the relative difference of measured reïňĆectance from MODTRAN reïňĆectance? This is not accuracy! It is just that, a difference between simulation and measurement. Do the simulations have no error? And if not, why are you even trying to make these challenging measurements!

Author Response: We agree this is not accuracy, instead, we define as uncertainty. We compared radiances not reflectance. The difference is used to quantify uncertainty between MODTRAN and measured radiances. Model predictions are approximations. Our objective is not to investigate MODTRAN error but rather, assess nadir viewing spectrometer measurement performance against a well-tested radiative transfer model using expert knowledge and actual atmospheric measurements. These challenging measurements advance Polar ice sheet remote sensing while relying on a solid methodological foundation in airborne science.

50. p. 16, l. 11: I was hoping this paragraph would quantify uncertainty in the model; alas, it does not. Without it is impossible to assess the signiïňĄcance of comparisons in ïňĄg. 14 and in the OLI comparisons presented on the next paragraph.

Author Response: We address MODTRAN uncertainty in the summary paragraphs prior to responses to specific comments. We are not attempting to assess the significance of comparisons in Fig 14 and for OLI, but rather, draw attention to the fact that more investigation is required based on this paper's results.

51. p. 17, l 13: Spectra is the plural of spectrum, not spectrums.

Author Response: Corrected.

52. P. 17, l. 20-21: Again, what is listed in uncertainty, not accuracy.

Author Response: We agree and have revised accordingly.

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2018-170/amt-2018-170-AC1-

supplement.pdf

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2018-170, 2018.