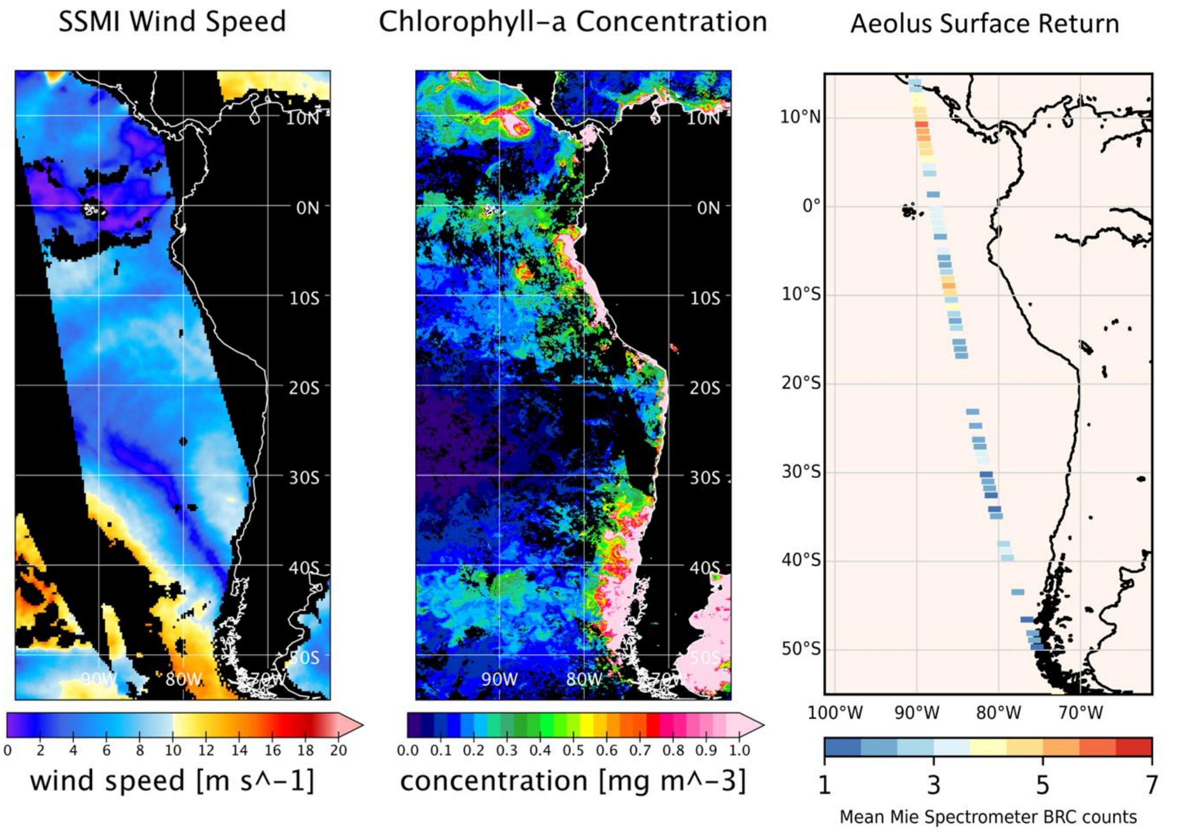
AO 9544 Aeolus + Innovation

SEA-FLECT:
Winds from Aeolus LIDAR
SEA Surface ReFLECTance

Delivery D9

Scientific Road Map



Doc. No.:	AERD/P2466/ESA/AO9544/D9	
Issue. No.:	1	
Version:	1.0.1	
Date:	8 July 2022	
Document prepared under ESA Contract Number: 4000133131/20/I-BG		

Document Change Record

Issue / Revision	Date	Changed pages / paragraphs
1.0.0	01/07/2022	Initial version.
1.0.1	08/07/2022	Suggestions from Final Meeting considered.

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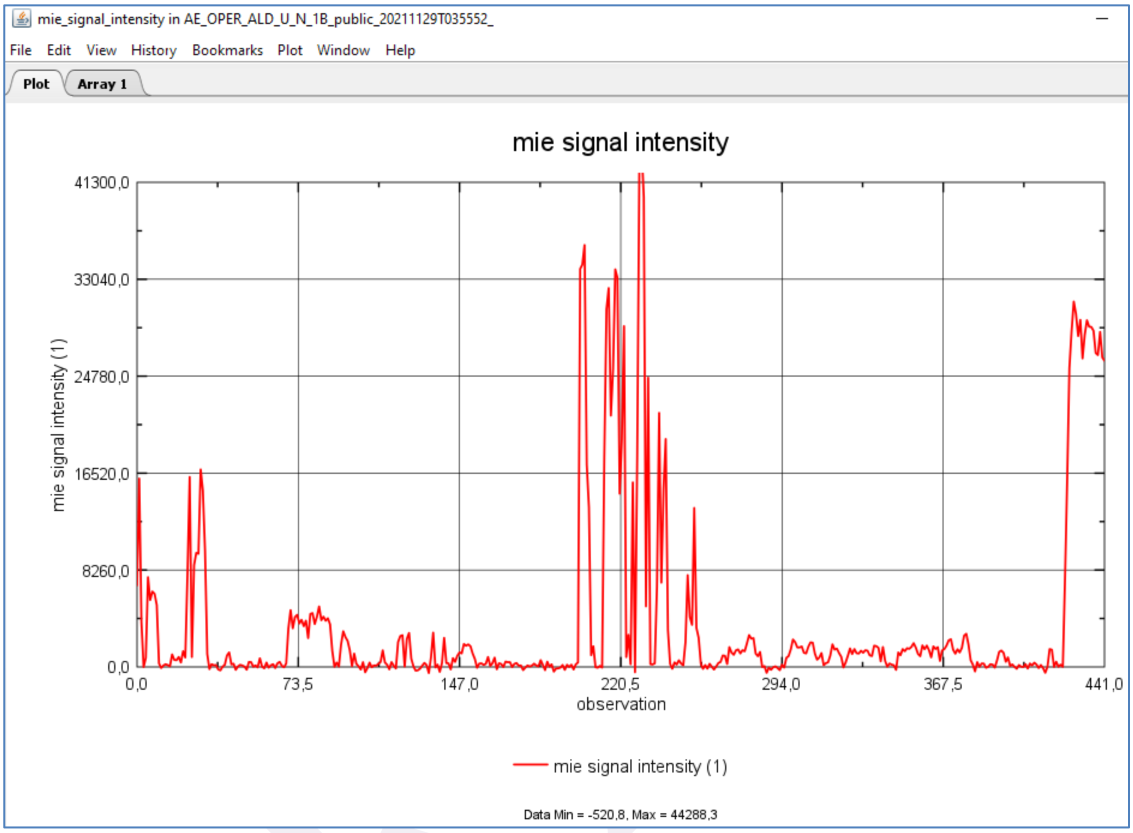
1 MOTIVATION AND OBJECTIVE

The objective of the SeaFlect study was to explore the potential of Aeolus Lidar surface bin observations for the retrieval of the surface wind speed over water surfaces.



Data Min = -520,8, Max = 44288,3

Figure 1: One full orbit of Aeolus observations (29.11.2021, starting 03:55:52 UTC) for the surface range bin (bin 23) of the parameter *"Mie signal intensity"*.

Figure 1 shows one full orbit (29.11.2021 starting 03:55:52 UTC) of the Aeolus L1B "Mie Signal Intensity" product for the surface range bin. No cloud screening has been applied. The following can be observed:

- Observations between ca. 70 and 150 are taken over Africa, with 70 near the Egyptian coast east of Alexandria and 150 on the western South-African coast.
- High Mie signal intensities at observation values between ca. 70 and 90 represent different arid surface types located in the Sahara Desert.
- Observation values from ca. 200-240 represent Antarctica, whereas observation values between ca. 420 to 440 represent the Arctic. This corresponds with high Mie signal intensities, as expected.
- After leaving the Antarctic, the orbit crosses the Pacific with hardly any land interaction. Observation values near 300 represent oligotrophic waters between French Polynesia and New Zealand.

The observed variations in the L1B Mie signal intensity appear plausible and justify the attempt to retrieve the surface wind speed from Aeolus surface range bin observations via a model relating instrumental output to wind speed.

2 RETRIEVAL APPROACH

The proposed retrieval consists of a number of steps as outlined below:

- Generate a database combining Aeolus Level 1b data at 87 km spatial scale (herein referred to as Aeolus L1B observations) together with the required ancillary data (e.g., chlorophyll) for a number of dedicated reference areas.
- Reference areas (clearest waters, high winds, dark ocean) are chosen such that they have a good potential for successfully disentangling the surface contribution from the overall reflectance.
- Identify L1B “Mie signal intensity” observations not affected by clouds or high aerosol loads using the signal-to-noise ration (SNR) and scattering ratio from the Aeolus L1B product.
- Identify the Aeolus surface bin, resp. surface bins in case the surface information is distributed over more than one range bin.
- Convert instrumental output (counts) into reflectance units (e.g., remote sensing reflectance, sr^-1). This is done herein in a simplistic way using ad-hoc scaling to convert counts into “reasonable” reflectance values.
- Estimate the atmospheric contribution to the surface range bin from the (entirely atmospheric) bin above, taking the different geometrical extensions of the atmosphere in the two bins into account.
- Establish an analytical model of the sea surface reflectance as function of wind speed and observation geometry, considering the relevant contributing processes:
    - specular reflection at wave facets,
    - diffuse reflection from white caps.
- Estimate the sub-surface contribution to the upward light field just above the sea surface as a function of chlorophyll-a concentration obtained from external sources (CMEMS operational ocean colour L3 product).
- Invert the analytical model to retrieve surface wind speed from observations.

Please refer to the ➔ SeaFlect ATBD for more information.

3 PRACTICAL EXPERIENCE

Applying the proposed retrieval approach to Aeolus data as described above has revealed a number of limitations with both data and the retrieval scheme. [Suggestions on how to overcome these limitations are given in the section "The way forward" below.]

- The L1B Mie signal intensity is only provided in instrument counts, no conversion into physical units is available.
    - An ad-hoc scaling has therefore been attempted, but this cannot replace a proper vicarious calibration.
    - Calibration is important as this would allow using observations obtained under differing conditions.
- The noise in the L1B signal intensity is significant in relation to the signal expected from the sea surface, limiting the sensitivity of the proposed approach.
    - From the applied geophysical model, we estimate that a reflectance resolution on the order of 10 [%] is required to resolve wind speed at 1 m/s.
    - Due to the Aeolus observation geometry rendering specular reflection at the sea surface highly unlikely, foam coverage appears to be required to provide a measurable signal.
- There is degradation of the Lidar system output over time which would need to be accounted for when converting instrument counts into reflectance.
- The L2A product does currently contain certain parameters required to derive the wind speed via the surface reflectance. In particular the Kmie, Krayleigh, however the exact meaning of these parameters are ambiguous and also actual time rate of change of these parameters might be recorded.
- The surface signal may be distributed over several vertical height bins. If this is the case, then multiple range bins needs to be merged. This might add to retrieval uncertainty, as a precise method to do so is not available, and might require to consider the detector readings and not the L1b data stream, which is contains processed data.
- The surface height bin extension has been changed over the Aeolus lifetime, which constitutes another source of uncertainty.
- It is difficult to separate between the atmospheric, sea surface, and sub-surface contributions to the surface range bin:
    - The geometrical extension of atmosphere and sub-surface inside the surface range bin are not known with high accuracy.
    - There atmospheric contribution to the surface range bin may be significant due to the low vertical resolution (250 m near the surface).
    - The contribution from sea surface is small as compared to the sub-surface contribution in low UV-absorbing waters for low to mid wind speeds.
- The total atmospheric aerosol optical depth (AOD) is unknown.
    - This is further affecting retrieval accuracy since the attenuation of the Lidar signal from/to the satellite cannot be accurately assessed.

  - Information on AOD at the target wavelength could either be obtained from external sources of, optimally, from the Aeolus observations themselves.
- Conditions in the lower atmosphere are implicitly better known from an airborne campaign than from a spaceborne mission.
  - For example, cloud free conditions are required for successful retrieval application from space-borne observations.
  - To reliably identify cloud free conditions may be difficult to achieve from Aeolus observations alone.
  - Therefore, new collocation experiments may have to start with the determination of strong wind/cloud free conditions, requiring a detailed search likely on the basis of fiducial other cloud cover sources.
- Backscatter is determined by the amount of scatterers within a layer.
  - If a layer is optically thin enough, then the backscattering signal is proportional to the geometrical thickness (single scattering approximation).
  - This is not the case for optically thick atmospheric layers with non-negligible multiple scattering, rendering correction procedures more complex.

Please refer to the ➔ **SeaFlect Validation Report** for more information.

4 CONCLUSION

A number of conclusions have been drawn from the SeaFlect results:

- The surface wind retrieval scheme proposed by SeaFlect appears in principle applicable to clear sky and high wind conditions, but its practical use is hampered by several aspects:
  - Due to the Aeolus observation geometry, specular reflection from the sea surface is negligible as the wind-driven surface facets do not reach the required slope of 37.6°.
  - The proposed method is therefore rather suitable to estimate the coverage of isotropically reflecting foam, which in turn may be translated into wind speed. Obviously, such retrieval is limited to wind speeds above ca. 10 m/s.
  - The sub-surface contribution to the surface range bin is dominating in low UV-absorbing waters and would need to be accurately assessed to allow for a satisfactory retrieval accuracy of foam coverage, resp. wind speed.
  - The used L1B signal is only given in instrument counts, which is why a simplistic ad-hoc scaling had to be implemented, adding further uncertainties to the retrievals.
  - Due to the 87-km spatial resolution of the L1B observations, there is frequent contamination by sub-pixel clouds which may be difficult to identify and filter out.
- The lack of instrument calibration and the instability of the laser output would require continuous vicarious calibration to allow for more accurate retrievals.

- Near-nadir LIDAR observations (such as from CALIPSO) appear better suited for the retrieval of small to medium windspeeds above the sea surface.
    - To analyse the existing Aeolus nadir observations in this respect was deemed beyond the scope of SeaFlect.
- Successful application of a method to an airborne instrument does not imply that the same method will work for a spaceborne instrument in a more automated manner. The enlarged substantial uncertainties hamper the detection of a foam (wind speed) dependency even for high wind speeds.

5 THE WAY FORWARD

5.1 Towards an improved Aeolus surface wind retrieval method

Not all relevant aspects and arising questions could be addressed in the context of the SeaFlect project. Therefore, a number of additional analyses could be envisaged to better understand the potential of Aeolus observations for the proposed ocean surface wind retrieval as outlined in the subsections below.

5.1.1 Further analysis of existing data

- Investigate the options for noise reduction. Current analysis is done using the L1B MIE useful product, which is obtained by combining individual measurements at ~3 km resolution over a 28 s period, resulting in observations corresponding to a sensed distance of ~87 km.
    - It is unlikely that the atmosphere is radiometrically stable over such an extended domain (e.g., clouds).
    - Screening for clouds etc. already at the individual 3-km measurement level should result in significantly noise-reduced 87 km observations.
- Comparison of surface bin returns for various surface types of known reflectance (e.g., from other missions operating in the UV, see Annex for an example) to better understand Aeolus instrument performance.
- Related to the previous item: Explore the feasibility for a vicarious calibration of Aeolus L1B data, e.g. from overpasses over Antarctica (bright) and suitable land surfaces (dense tropical forest, arid regions) of known brightness.
    - Investigate the availability of in situ data to support calibration, e.g. through the Aeolus Tropical Campaign.
    - This could be done in conjunction with some of the elements described in section 5.1.2 below.
- Investigate the potential of determining a lower boundary of the oceanic contribution for homogeneous ocean regions from analysing a statistically sufficient number of Aeolus surface returns.
- Investigate the potential of the (few) existing Aeolus nadir observations for the retrieval of surface wind speed and compare the outcome with similar products (e.g., surface wind speed from CALIPSO).

- Investigate the usefulness of the SNR of all range bins for cloud screening. Just looking at the SNR of the three lowest range bins might not be sufficient.
- Gain further insight into behaviour of Aeolus surface range bin observations, e.g. by applying specific stratification strategies such as day-time vs. night-time observations to investigate the potential impact of solar background radiation.
- Investigate the usefulness of the background information (i.e., range bin 24 background radiation measurements) for cloud detection. It could also be investigated in how far the background information could be used for a vicarious calibration.
- Investigate the need to correct Mie channel measurements for possible Rayleigh signal contamination.
- Normalise the Mie ACCD counts by the distance to the satellite. However, due to the low eccentricity (e = 0.0013009) of the Aeolus orbit, this should only have a very minor impact on signal intensity.

5.1.2 *Further improvements of the proposed retrieval scheme*

- Consolidate the applied retrieval processing in terms of
    - Scene classification,
    - Surface identification,
    - Use of ancillary data to characterise the sub-surface contribution.
- Investigate the existence of advanced foam reflection models. For example, is there a dependence of wind speed on foam reflective properties?
- Detailed analysis of the return signal to identify observations with the highest likelihood of no contamination by aerosol or clouds.
- Apply the retrieval in specific areas, e.g. for waters that are highly absorbing in the UV such as encountered in the Baltic Sea as to minimise the impact of the in-water contribution to the surface bin signal.
- Related to the previous item, also global analyses could be envisaged, using the sub-surface characterisation from independent sources (e.g., satellite-derived maps of UV-absorbing coloured dissolved organic matter) to stratify the input.
- Rigorously determine an atmospheric correction on the basis of a simplified radiative transfer code in combination with atmospheric information taken from the aux-met data or external data sources.
- Investigate the crosstalk between the Mie and Rayleigh observations, or even investigate the potential to combine the individual observations to improve SNR.

5.1.3 *Radiative transfer simulations*

- Apply RT simulations to better understand the relative importance of atmospheric, sea surface and sub-surface contributions for typically occurring environmental conditions, as well as their interaction. This could be done in a two-phased approach:

  - Principle insight could be gained by studying an idealised Rayleigh case, where scattering in atmosphere an ocean is assumed to be entirely or at least predominantly Rayleigh-based.
    - This would allow for the use of computationally efficient RT models such as Matrix-Operator.
    - The closest representation of such Rayleigh case on Earth would be a very clear atmosphere above a hyper-oligotrophic ocean.
  - Due to the Aeolus observation geometry, Monte Carlo / ray tracing RT models would be required for situations involving significant particle backscattering (i.e., most real-world conditions) as these allow to accurately simulate the backscattered light field at angles very close to 180°.
- Investigate whether polarization plays a significant role in the attempted surface wind retrieval. For example, polarization may be used to better define the vertical position the sea surface within the surface bin.
- Use of synthetic data sets obtained from RT simulations to derive surface wind retrieval schemes (various approaches could be explored from simple regression to NN-based solutions).

5.2 Towards an improved Aeolus surface wind observation capability

Some of difficulties encountered are also due to mission specific choices. The proposed ocean surface wind retrieval scheme would likely benefit from a number of optimisations in the observation approach. *Note that we herein do not discuss in how far the sketched ideas are compliant with the Aeolus main mission goals:*

- Better vertical resolution to reduce the atmospheric and oceanic contributions to the surface bin.
- More accurate vertical localization of the surface bin with respect to the sea surface to facilitate accurate estimation of both the atmospheric and oceanic contributions to the surface bin.
- More stable laser output, resp. continuous accurate monitoring of laser output intensity fluctuations.
- Instrument calibration to provide L1B data in physical units (radiance or reflectance) instead of digital numbers.
- Adding a multi-channel imager to the platform or flying in tandem with a multi-channel imager to support the scene analysis (e.g., cloud cover, aerosol load, …).
- Adding another laser wavelength. For example, observations at 1,064 nm would have several advantages for Lidar-based wind speed retrieval:
  - Very low sub-surface signal due to high water absorption.
  - Limited atmospheric Rayleigh scattering: lower atmospheric contribution to the surface bin and higher transmittance through the atmosphere.
- Dual observation geometry approach:
  - Slanted observation angle (e.g., as is) for atmospheric wind profiles,

    - Near-nadir observations for other purposes (e.g., aerosol, surface wind, ..., see e.g. the products offered by CALIPSO).
- Several of these suggestions will be implemented through the upcoming (2023?) EarthCare mission:
    - ATLID (UV LIDAR) will provide a vertical resolution of ca. 100m near the sea surface.
    - ATLID will be flown jointly with MSI (Multispectral Imager), the latter allowing e.g., for an accurate cloud identification.
    - ATLID will likely also offer higher instrumental stability and a better instrumental characterisation (i.e., calibration).

5.3 Suggestion for an end-of-life experiment

Several of the aspects mentioned in Sections 5.1 and 5.2 could be studied in detail through a dedicated End-of-Life (EoL) experiment with the following main characteristics:

- Near-nadir observation geometry,
- Data collection for at least one week.

The near-nadir observation geometry (< 10°) would result in a significantly enhanced contribution from specular reflection at the sea surface, leading to a stronger signal from the sea surface which would in turn allow to study the performance of the proposed approach also for lower windspeeds. A near-nadir geometry would also slightly reduce the percentage of cloud-affected measurements.
Running the experiment over a period of ca. one week (equiv. to ca. 100 orbits) should provide sufficient cloud-free observations to apply the evaluation procedures that have been developed in the context of the Aeolus activities. Optimally, different observation geometries could be applied (e.g., 5°, 20°).
The outcome of the proposed EoL experiment would be an assessment on the performance of the proposed wind speed retrieval as a function of the observation angle.

6 ANNEX

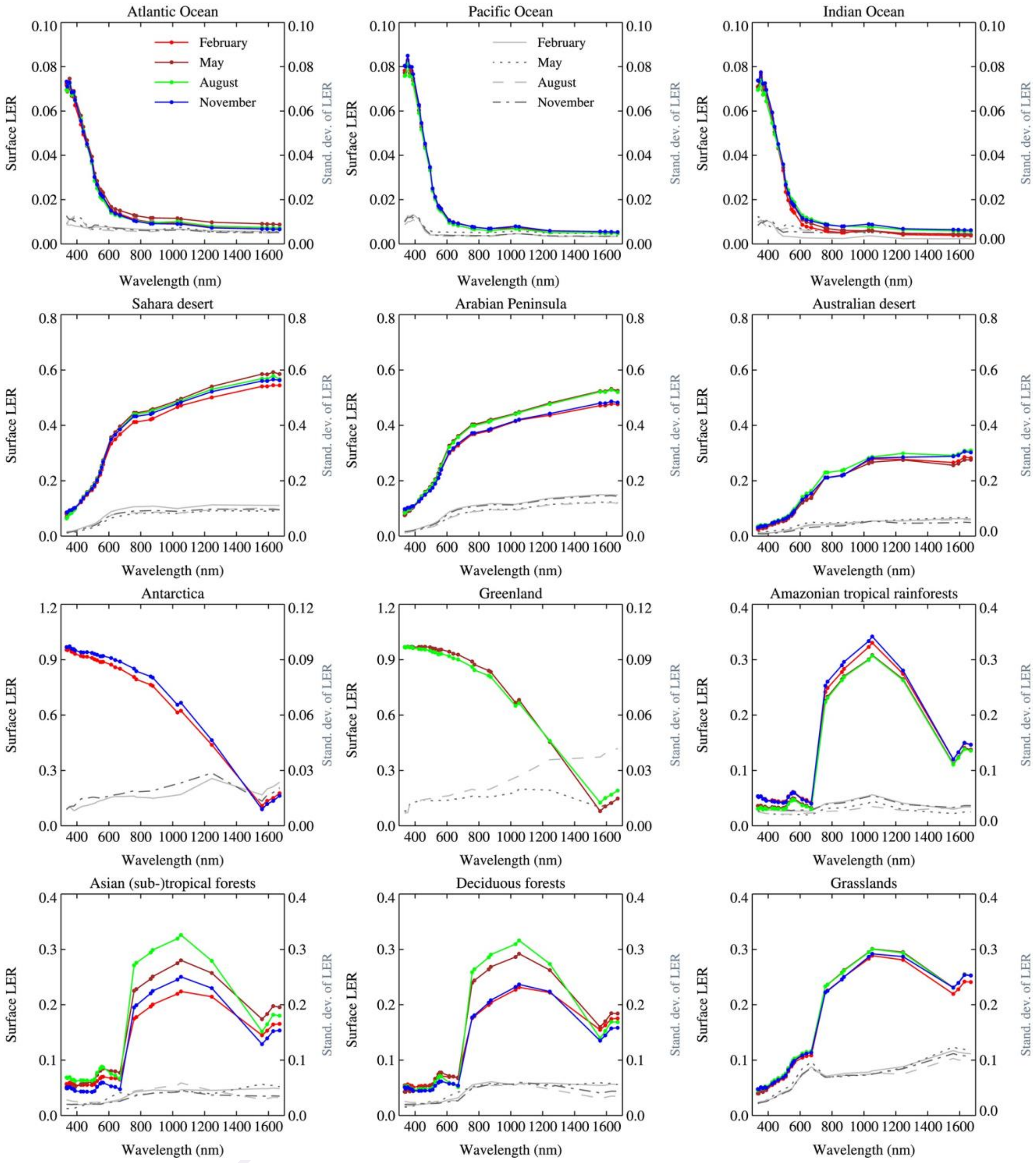


Figure 2: Surface reflectivity climatologies from UV to NIR determined from Earth observations by GOME-2 and SCIAMACHY. The grey lines indicate the standard deviation. Source: Tilstra et al. [2017].

Figure 2 shows reflectance spectra for different surface type regions derived from SCIAMACHY observations. A number of aspects of relevance to the proposed activities can be drawn from those:

- Reflectance values on the order of 0.08 in the UV are confirmed for oligotrophic waters,
- Desert targets cannot be considered being bright at the target wavelength (actually, they are dark in the UV!),
- Both Greenland and Antarctica are suitable as bright targets in the UV,
- Vegetation is generally dark in the UV.

See Tilstra et al. [2017] for further details.

7 REFERENCES

Tilstra, L. G., Tuinder, O. N. E., Wang, P., and Stammes, P. (2017), Surface reflectivity climatologies from UV to NIR determined from Earth observations by GOME-2 and SCIAMACHY, J. Geophys. Res. Atmos., 122, 4084– 4111, doi:10.1002/2016JD025940.