

Proposal for Simultaneous Sea Surface Wind Speed and Water Vapor Observations by Spaceborne IPDA-DIAL

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Abstract: Water vapor data over the ocean is especially useful for numerical weather predictions of localized heavy rains and typhoons. We have proposed the spaceborne water vapor DIAL using the OPG/OPA transmitter with absorption lines in the 1350nm band and the IPDA-DIAL method to measure water vapor just above the sea surface. In this paper, we propose the IPDA-DIAL method with a smaller laser power and telescope aperture to provide flexibility in platform selection. Measurement error simulation results show that the IPDA-DIAL observes water vapor from sea level to an altitude of 600 m with an error of 7%. Furthermore, we proposed a method to simultaneously measure water vapor and wind speed over the sea surface by measuring the backscatter coefficient at the sea surface using the IPDA-DIAL. To confirm the usefulness of this method, wind speeds obtained using CALIPSO 1064nm sea surface backscatter coefficient data were validated for the ocean near a typhoon. This enables us to observe the latent and sensible heat fluxes over the ocean in a snapshot.

1. Introduction

In recent years, the occurrence of heavy rainfall and the increase in strong typhoons due to global warming have become major social problems. In Japan, the number of heavy rainfall disasters is increasing year by year, and disaster prevention and mitigation actions are urgently needed. Although these disasters can be mitigated by improving the accuracy of forecasts, it has been pointed out that information on the profile of water vapor in the lower troposphere over the ocean is particularly important for forecasting purposes. Spaceborne lidar observations of water vapor over the ocean and its assimilation into numerical weather prediction models are expected to improve the accuracy of rainfall forecasts.

Currently, water vapor is observed by radiosondes, infrared and microwave sensors on satellites and GNSS, but there are problems with spatial and temporal resolution. Passive satellite observations have a wide horizontal coverage but insufficient vertical resolution, and since DIAL has no bias error, it can be used to calibrate passive remote sensing equipment and is expected to have a synergistic effect with satellite sensor observations.

We have proposed a two-beam spaceborne water vapor DIAL using an OPA (Optical Parametric Amplifier) transmitter with a 1350 nm absorption band [1]. The OPA system using QPM (Quasi Phase Matching) devices is a one-pass amplifier [2]. Compared with conventional phase-matching OPO (Optical Parametric Oscillator), it has no resonator structure, which is advantageous for spaceborne applications.

2. IPDA DIAL

In addition to the vertical profile of water vapor, the measurement of water vapor near the sea surface is important for predicting heavy rainfall and estimating the flux between the ocean and the atmosphere. Therefore, without significantly changing the specifications of the proposed DIAL mission, we proposed to use IPDA (Integrated Path Differential Absorption) technology [3] to measure water vapor near the sea surface using both atmospheric backscattered and sea surface scattered signals, as shown in Fig. 1 [4]. In this study, the average power of the laser was halved, and the telescope aperture was set to 50 cm to provide flexibility in the platform as shown in Table 1.

Table 1. Parameters of the space-borne water vapor IPDA-DIAL and DIAL

Parameter	IPDA-DIAL (Current Proposal)	DIAL (Original proposal)
Pulse Energy	10mJ (One-beam)	10mJx2 (Two-beam)
Repetition Rate	500Hz (on/off pair)	500Hz (on/off pair)
Wavelength	1336nm	1336nm
Telescope Aperture	0.5m	0.8m
Quantum Efficiency	50%(APD)	50%(APD)
Platform Altitude	400km	250km
Ground Track Speed	7.7km/s	7.8km/s

specification are shown in Fig. 2. The vertical line indicates the IPDA integration range. A summer mean profile over Japan is used as the water vapor model, with a horizontal resolution of 50 km, and daytime observations are assumed. Error simulation results show that water vapor from sea level to an altitude of 300 m can be observed with an error of 15%, and water vapor from sea level to an altitude of 600 m can be observed with an error of 7%.

3. Estimation of latent heat fluxes from sea surface wind speed and water vapor observations

As with the vertical profile of water vapor, measurements of near-surface water vapor are particularly important for predicting heavy rainfall and estimating fluxes between the ocean and the atmosphere. Although latent heat flux is smaller than radiative flux, it is synonymous with the water vapor supply from the ocean to the atmosphere and is an important parameter for cloud and rain formation and atmospheric radiation, especially in the tropics and subtropics. However, it has been pointed out that there are large differences among products in products with estimated global distributions and large errors with the measured values (true values) from buoys at sea [5]. The latent heat flux Q_{lat} is obtained from the following bulk equation, which is widely used.

$$Q_{lat} = \rho L_v \langle wq \rangle \approx \rho L_v C_E S \Delta Q \quad (1)$$

where ρ is the atmospheric density and L_v is the latent heat of evaporation. $\langle wq \rangle$ is the variation of vertical wind and specific humidity, which is approximated by the product of the latent heat transfer coefficient C_E wind speed S over sea level, and the specific humidity difference ΔQ between atmosphere and ocean. ΔQ can be calculated from the amount of water vapor near the sea surface determined by IPDA-DIAL and the saturated water vapor density determined from the sea surface temperature obtained from satellite data. Furthermore, the sea surface wind speed can be obtained by applying the method for estimating sea surface wind speed from the sea surface backscatter coefficient measured by the spaceborne lidar CALIPSO [6] to the IPDA-DIAL off signal. Combining these parameters with temperature information such as objective analysis data, it is possible to calculate the latent

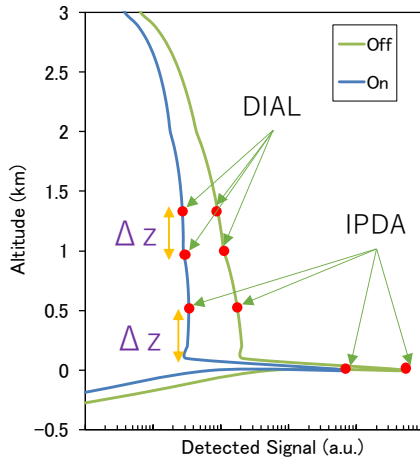


Figure 1. Comparison of the space-borne DIAL and proposed IPDA-DIAL

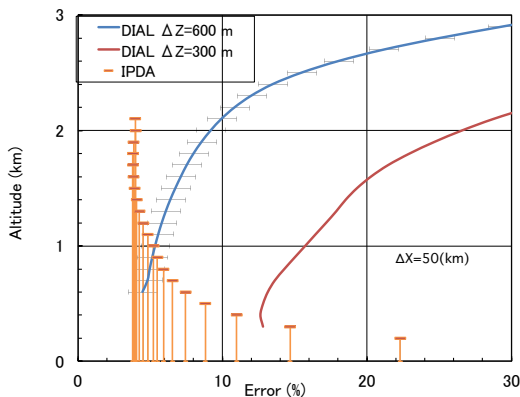


Figure 2. Random error of water vapor density for the space-borne DIAL with vertical resolutions of 300m/600m and IPDA DIAL

The random errors of water vapor density for IPDA and DIAL calculated with this

and sensible heat fluxes on a snapshot-by-snapshot basis.

The principle for determining sea surface wind speed from the sea surface backscatter coefficient is as follows from Hu et al.[6] The stronger the wind, the higher the wave height and the larger the wave-slope variance (σ^2).

In the case of satellite lidar, the sea surface backscatter coefficient of lidar is

$$\gamma = \frac{\rho}{4\pi\sigma^2} \quad (2)$$

where ρ is the Fresnel reflectance and $\rho = [(n - 1)/(n + 1)]^2$ from the refractive index n of seawater. On the other hand, the relationship between wind speed and σ^2 is as shown in Eqn. 3.

$$\begin{aligned} \sigma^2 &= 0.0146\sqrt{U} && (U < 7\text{m/s}) \\ \sigma^2 &= 0.003 + 0.00512U && (13.3 > U \geq 7\text{m/s}) \\ \sigma^2 &= 0.138 \log_{10} U - 0.084 && (U \geq 13.3\text{m/s}) \end{aligned} \quad (3)$$

The Cox-Munk model (linear relationship) is used for wind speeds from 7 to 13.3 m/s, the Wu model (log-linear relationship) is used for wind speeds above 13.3 m/s, and for wind speeds below 7 m/s the wave gradient distribution is considered as a one-dimensional Gaussian distribution. These relations were compared with the wind speeds derived from the CALIPSO backscatter coefficients averaged over 10 km using one month of global data and the AMSR- E wind speeds (20 km resolution), and the rms difference was reported to be 1.2 m/s. The relationship between the sea surface backscatter coefficient and wind speed obtained using Eqn.2 and Eqn. 3 is shown in Fig. 3.

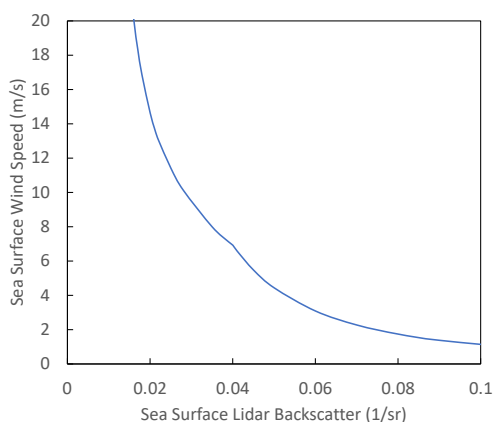


Figure 3. Relation between sea surface wind speed and sea surface backscatter

4. Comparison of sea surface wind speeds

To confirm the usefulness of this relationship in measuring sea surface wind speeds in southern Japan during the summer months when typhoons occur, wind speeds obtained using CALIPSO's sea surface scattering coefficient data were validated.

Wind speeds along the track were obtained using CALIPSO's attenuated backscatter coefficient data at 1064 nm. The procedure was based on reference [6], and sea surface wind speed was obtained from the sea surface backscatter coefficient with atmospheric attenuation correction. For verification, we compared the L3-sea surface wind speed data from the AMSR-2 microwave radiometer [7] and the meteorological observation data from the meteorological observation vessel Keifu Maru.

Fig. 4 shows the comparison results of these three data. The trajectory of CALIPSO on the comparison date (30 July 2018) crosses the east side of Typhoon No. 12 as shown in the weather map in Fig. 5. In the range of 20-24°N, both satellite data and vessel measurements agreed well, which verifies that sea surface wind speed can be correctly estimated from the sea surface scattering coefficient. However, in the range of 24° to 33°N, the microwave radiometer wind speed values are lower and less variable than the wind speeds obtained from CALIPSO. One possible reason for this difference is the effect of inhomogeneous wind speed distribution due to the difference in the measurement FOV: the footprint of CALIPSO is as narrow as 70 m, whereas the FOV of the AMSR-2 microwave radiometer is about 15 km, which is significantly different. Another possible factor is the effects of multiple reflections of microwaves due to tall and strong rainfall areas, since the spiral band around Typhoon 1812 can be seen in meteorological satellite images in this latitude range.

Large wind speeds may increase the water vapor observation error because the backscatter intensity from the sea surface is reduced when the wind speed is high.

From Fig. 3, for example, the backscatter intensity from the sea surface at a wind speed of 10 m/s decreases to 24% compared to a wind speed of 2 m/s. However, since the water vapor

measurement error by the IPDA~DIAL method depends on the atmospheric scattering intensity, which is weaker than the sea surface backscattering intensity, the influence on the error is negligible.

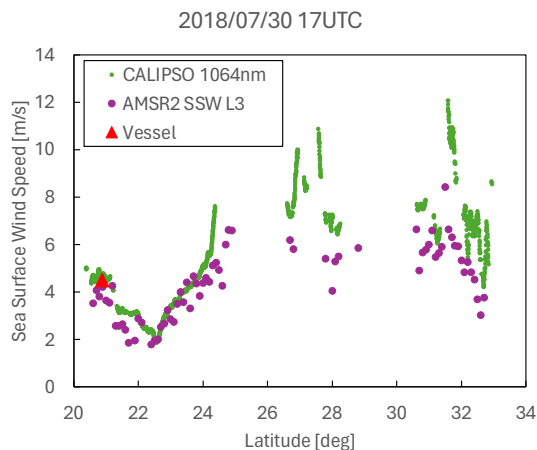


Figure 4. Sea surface wind speeds derived from CALIPSO 1064nm (green dot), collocated AMSR2 wind speed (purple dot) and meteorological observations by research vessel (red triangle)

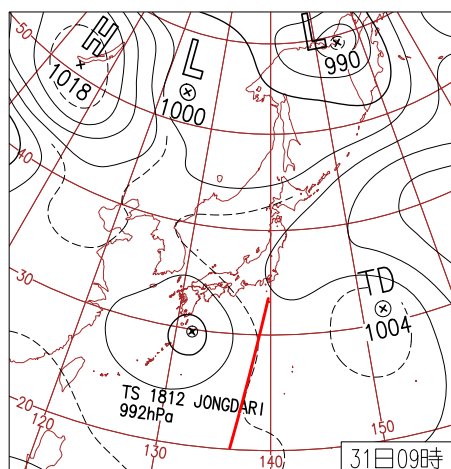


Figure 5. Orbit track locations (red line) of CALIPSO and AMSR-2 on weather map

5. Conclusion

To provide flexibility in platform selection, we proposed the IPDA-DIAL with half the original laser power and a telescope aperture of 50 cm instead of 80 cm. Error simulations show that IPDA-DIAL can observe water vapor from sea level to an altitude of 300 m with an error of 15% and from sea level to an altitude of 600 m with an error of 7%, assuming a horizontal resolution of 50 km and daytime observations.

Furthermore, by applying the method of determining sea surface wind speed from the sea surface backscatter coefficient to the off signal of the IPDA-DIAL, we proposed a method of simultaneously measuring water vapor and wind speed over the sea surface. To confirm the usefulness of this method, wind speed was verified over the Pacific Ocean where typhoons occur using CALIPSO 1064nm sea surface backscatter coefficient data. This demonstrated the potential of the method for snapshot observations of ocean-atmosphere latent and sensible heat fluxes over the ocean.

6. References

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