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The DOI for this manuscript is
DOI:10.2151/jmsj.2017-017

J-STAGE Advance published data: June 19, 2017

The final manuscript after publication will replace the preliminary version at the above DOI once it is available.
Feasibility Study for Future Space-Borne Coherent Doppler Wind Lidar, Part 1: Instrumental Overview for Global Wind Profile Observation

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6 June 2017

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Abstract

A working group is studying the feasibility of a future Japanese space-borne coherent Doppler wind lidar (CDWL) for global wind profile observation. This study is composed of two companion papers: an instrumental overview of the space-borne CDWL for global wind profile observation (Part 1) and the wind measurement performance (error and bias) investigated using a full-fledged space-borne CDWL simulator (Part 2). The objective of this paper is to describe the future space-borne CDWL in terms of technical points and observation user requirements. The future mission concept is designed to have two looks for vector wind measurement with vertical resolutions of 0.5 (lower troposphere: 0-3 km), 1 (middle troposphere: 3-8 km), and 2 km (upper troposphere: 8-20 km) and horizontal resolution of <100 km along a satellite. The altitude and orbit of the satellite are discussed from a scientific viewpoint. The candidate altitude and orbit of the satellite are 220 km and an inclination angle of 96.4° (polar orbit) or 35.1° (low-inclination-angle orbit), respectively. The technical requirements of the space-borne CDWL are a single-frequency 2-μm pulse laser with an average laser power of 3.75 W, two effective 40-cm-diameter afocal telescopes, a wide-bandwidth (>3.4 GHz) detector, a high-speed AD converter, and a systematic lidar efficiency of 0.08. The space-borne CDWL looks at two locations at a nadir angle of 35° at two azimuth angles of 45° and 135° (225° and 305°) along the satellite track. The future space-borne CDWL wind profile observation will fill the gap of the current global wind observing systems and contribute to the
improvement of the initial conditions for NWP, the prediction of typhoons and heavy rain, and various meteorological studies.

**Keywords**  Doppler wind lidar; Earth observation satellite; global wind profile observation; numerical weather prediction; lidar simulator; observing system simulation experiment

1. Introduction

Severe weather-related disasters are becoming increasingly serious in many parts of the world, and people are more in danger than ever because of weather-related disasters or climate change. Improvements of numerical weather prediction (NWP) are important for disaster prevention or disaster risk reduction. Wind is one of the fundamental meteorological variables describing the atmospheric state (pressure, temperature, and humidity). Global wind profile observation is crucial to significantly improve the initial conditions essential for global and regional NWP, air quality forecasts, climate studies, and various meteorological studies. The World Meteorological Organization (WMO) organizes various observing networks and systems in order to provide a wide range of meteorological descriptions. WMO has many scientific and technical programs in order to solve present and future problems. Current space-borne observing systems are biased to temperature- and water-vapor-related measurements in comparison with wind measurements (Baker et al. 2014). The WMO Integrated Global Observing System technical report (WMO, 2012) states, “Development of satellite-based wind profiling systems remains a priority for the
Tables 1(a) and 1(b) respectively show current user requirements of wind profile observation for global NWP (WMO, online) and a summary of current global wind observing systems. While these requirements are for globally homogeneous wind profile observation, current global wind observing systems do not always satisfy these requirements. Automatic weather station networks, buoy networks, and ships provide surface meteorological information with a large coverage but provide few meteorological profiles. Ground-based wind profilers provide wind profiles, but the wind profilers are installed only in Japan, Western Europe, and North America. Wind profiles are provided mainly by radiosonde networks and also by aircraft measurements. The radiosonde and aircraft measurements are mainly performed over populated regions in the northern hemisphere but not in the southern hemisphere. The number of weather stations observing the upper atmosphere has been decreasing. A lack of wind observations over oceans, the southern hemisphere, and other sparse areas causes nonuniform errors in NWP and subsequent analysis. Single-layer vector wind can be measured by satellite-borne microwave scatterometers and polarimetric microwave radiometers, and multiple-layer vector wind, called the atmospheric motion vector (AMV), can be retrieved from cloud and water vapor motions derived from geostationary and polar-orbit satellite images. As discussed in our previous study (Ishii et al., 2016), the AMV achieves a large coverage area and high temporal and horizontal resolutions (2.5 and 10 min, 0.5°×0.5°) but has low vertical resolution (2-4 km). The bias and root-mean-square (RMS) vector difference of the AMV
retrieval verified against radiosonde wind observations shown in previous studies (e.g., Hayashi and Shimoji 2013; Otsuka et al. 2015) are relatively large (bias of less than 2 m s\(^{-1}\) and RMS vector difference of worse than 4 m s\(^{-1}\)). The AMV can hardly retrieve vector winds under thick clouds, over dry regions, clear-sky regions or regions with few clouds, the atmosphere near Earth’s surface over inland area, and low-wind-speed regions. The height assignment of the AMV remains very inaccurate and it causes significant vector wind errors (RMS vector difference of 4-8 m s\(^{-1}\)) (Velden and Bedka 2009). There are 30-60 hPa differences in the height assignment between the AMV and other instruments (Velden and Bedka 2009; Folger and Weissmann 2014).

Doppler wind lidar (DWL) provides us wind profile with high vertical resolution, low bias, and good precision and it is necessary to fill the gap of current observations. The impacts of space-borne DWL wind observations on NWP have been assessed by OSSEs (Riishøjgaard et al. 2004; Stoffelen et al. 2006; Marseille et al. 2008; Masutani et al. 2010; Ishibashi 2014; Atlas et al. 2015(a), 2015(b)). The European Space Agency is planning to launch the first space-borne DWL called ADM-Aeolus for obtaining global wind profiles (ESA 1999; Stoffelen et al. 2005) in 2017 (ESA, online). ADM-Aeolus uses a single-frequency UV laser and a direct-detection system. ADM-Aeolus will provide profiles of a single line of sight (LOS) wind speed. In the United States, NOAA and NASA conducted several feasibility studies of shuttle- and space-borne CDWLs (Huffaker 1978; Huffaker et al. 1980, 1984; Menzies 1986; NASA 1987, 1989; Petheram et al. 1989; Kavaya and Emmitt 1998).
The Global Wind Observing System (GWOS) mission concept was proposed to the National Research Council (NRC 2007), which was planned to demonstrate the potential of wind vector measurements with a hybrid DWL (Emmitt 2001). The Winds from the International Space Station for Climate Research (WISSCR) mission study was conducted in late 2010 and early 2011 (Hardesty et al. 2011; Baker et al. 2014). The Optical Autocovariance Wind Lidar (OAWL) is composed of a 0.355 μm (or 0.532 μm) single-frequency laser and a direct-detection DWL with a Mach-Zehnder-type interferometer (Grund et al. 2009; Tucker and Weimer, 2014). The OAWL measures signal intensities simultaneously at several fixed phase delays after passing the Mach-Zehnder-type interferometer and determines the optical autocovariance functions of the outgoing laser and backscattered signals. The phase difference between the two functions provides us the Doppler-shifted frequency, and then wind speed is given by the Doppler-shifted frequency.

In Japan, studies on the feasibility of the International Space Station (ISS)-borne coherent DWL (CDWL), called JEM-CDWL, were conducted in late 1990s (Iwasaki 1999). NICT, Tohoku University, The University of Tokyo, Meteorological Research Institute (MRI), and JAXA organized a working group for a future Japanese space-borne CDWL in 2011 and are studying the feasibility from the technical and scientific viewpoints in order to enhance the feasibility of the space-borne CDWL. The space-borne CDWL is proposed to be carried on a super-low-altitude satellite (SLAS; Nagano et al. 2009). The SLAS is a new satellite with ion propulsion technologies being developed by JAXA, which will fly in a circular orbit at
altitudes of 180-250 km. Because more fuel is needed to keep the satellite in the low orbital altitude from descending owing to air drag of atmospheric friction, the operation period of the SLAS may be limited. However, more importantly, the low orbital altitudes allow us to reduce the pulse energy of the laser, the diameter of the telescope, and the electrical power consumption required for space-borne active remote sensing systems, which is a promising approach for next-generation Earth observation satellites. The objectives of the future space-borne CDWL are to demonstrate multi-looking LOS wind profiling observations, the retrieval of vector wind, compensation techniques for the Doppler shift due to the satellite speed, and the advantages of Earth observation at low altitudes. Preliminary results of the measurement performances of a space-borne CDWL simulator and the concept of an OSSE study were described previously (Ishii et al. 2016). The latest results show that the percentage of wind profiling observations with good-quality estimates is 40% below 8 km over the latitudes except for the equatorial region in the southern hemisphere, and that the expected LOS wind speed error for good-quality estimates is 0.5 m s$^{-1}$ below 8 km. The results of the OSSE study show that the forecast improvement rates for the wind speed at 850 hPa for a 36-hour forecast are apparent, especially in the middle and high latitudes of the southern hemisphere. The results suggest that global wind profile observations could have additional positive impacts on the NWP system. This paper is composed of two companion papers. In Part 1, we provide an overview of global wind profiling observation and technical strategies for designing the space-borne CDWL. In Part 2, the measurement
performances using a space-borne lidar simulator will be discussed by characterizing the retrieved LOS wind speed and the LOS wind speed error and bias under various atmospheric conditions (Baron et al. 2017). As a future companion paper of Part 1 and 2, full OSSEs will be discussed to determine the potential impacts of global wind profiles simulated using the space-borne CDWL simulator for NWP (Okamoto et al. 2017) in accordance with the flow shown in Fig. 1. This paper is arranged as follows. In the next section, we describe coherent and direct-detection DWL and wind measurement principle of a CDWL. The global wind profiling observation geometry of the space-borne CDWL is shown in section 3. Key technologies required for the space-borne CDWL are described in section 4. A summary of this paper is presented in section 5.

2. Doppler Wind Lidar

2.1 Technical comparison of coherent and direct-detection Doppler wind lidar

Doppler wind lidar (DWL) is an active remote sensing system providing wind profiles. Coherent- or direct-detection DWLs have been developed by research groups for a long time. A CDWL uses the Doppler-shifted frequency of infrared (IR) laser light backscattered mainly by coarse-mode aerosols (Mie scattering) (Seinfeld and Pandis 1988) moving with the wind. On the other hand, most of the direct-detection DWL types use ultraviolet (UV) laser light backscattered by small aerosols or molecules (Rayleigh scattering), or both types of scattering. Both IR and UV lasers are in the eye-safe region. The target atmosphere
of a coherent DWL is the atmospheric boundary layer, the lower and middle troposphere due to dependence on aerosol abundances. A direct-detection DWL is used for
tropospheric wind measurement with the Mie and/or Rayleigh scattering and stratospheric wind measurement with the Rayleigh scattering. The development of an IR laser capable of meeting the requirements of a space-borne DWL system is technically feasible (Sato et al. 2017). Nd:YAG lasers are a matured laser technology. There are many challenges (e.g., laser-induced damage, contamination) in developing a space-qualified UV laser meeting the requirements of a space-borne DWL. Such instrument with an average laser power of 5 W has not yet been achieved in Japan. In a CDWL, a coaxial configuration is employed, while in a direct-detection DWL both coaxial and biaxial configurations are employed. In a CDWL, a portion of a single-frequency continuous-wave laser beam described in section 2 must be matched with the backscattered light beam to maximize the signal-to-noise ratio (SNR), which means that a CDWL uses a receiver with a very narrow bandpass. A CDWL can be used to make daytime and nighttime wind measurements. A direct-detection DWL uses an m-class diameter and a lightweight telescope with a narrow field of view, an interferometer (e.g., Fabry–Pérot etalon, Mach–Zehnder), and narrow-band optical bandpass filters to maximize the signal-to-noise ratio by reducing the background radiation. Although a direct-detection DWL also perform nighttime and daytime wind measurement. The use for the narrow-band optical bandpass filters in the daytime measurement results in the degradation of observable range due to the decrease of
A coherent DWL does not require such a large-area telescope. A CDWL can directly measure a Doppler-shifted frequency without bias (in principle) and with random wind error better than 1 m s\(^{-1}\) (Ishii et al. 2010; Iwai et al. 2013; Baron et al. 2017). The precision of CDWL wind measurement depends on the aerosol abundance and speckle (Rye 1979; Frehlich and Kavaya 1991). Speckle has temporal and spatial components and it is considered in heterodyne efficiency. Performance of direct-detection DWL required for space-borne DWL wind measurement has a bias of 0.4 m s\(^{-1}\) and a precision of 0.6–1.7 m s\(^{-1}\) (ESA 2001). It depends on sensitivity curve of receiver for wind speed. It is very important to make bias-free wind measurements with and high precision, especially for NWP over a weak wind region or for comparison and validation with the AMV. There are sinks and sources of various substances in the lower troposphere. Wind measurement with low bias and high precision is also necessary for estimating the flux of materials. For a future SLAS mission, the CDWL was selected as result of many considerations (difficulties of using UV laser, diameter of telescope, bias and precision, and so on). A comparison of the SLAS-borne CDWL and space-borne direct-detection DWL is summarized in Table 2.

### 2.2 Principle of coherent Doppler wind Lidar

The basic principle of a CDWL is described in Fig. 2, which is similar to that of a Doppler radar, but not the same. The basic components of the CDWL are a single-frequency
continuous wave (CW) laser, a pulse laser, a telescope, two heterodyne detectors, optical components, and signal processing components. The single-frequency CW laser passes through an acoustic optical modulator (AOM), and the AOM shifts the frequency of the single-frequency CW laser. The frequency-shifted CW laser is used for both injection seeding to achieve a single-frequency pulse laser and heterodyne detection. The single-frequency laser pulses are sent into the atmosphere at a nadir angle. The backscattering coefficient of atmospheric molecules (Rayleigh scattering) is inversely proportional to the fourth power of the wavelength. In the 2-µm region, the backscattering coefficient of atmospheric molecules is negligible relative to that of aerosols. The backscattering coefficient of aerosols (Mie scattering) is assumed to depend on the wavelength with a power law of a negative Ångström exponent (Ångström 1964), where the Ångström exponent is related to the size distribution of aerosols. The Ångström exponent at the 2-µm region is approximately 0.3 to 2 (Srivastava et al 2001). The CDWL mainly detects signals backscattered by moving aerosol particles to measure the Doppler-shift frequency of the LOS wind speed. A portion of the nonfrequency-shifted single-frequency CW laser is photomixed with the frequency-shifted CW laser on one detector and with the backscattered signals on the other detector. Each detector converts the frequencies of the outgoing laser and backscattered signals down to an intermediate frequency (IF). The detection process is called heterodyne detection. In general, the heterodyne detection is performed under a shot-noise-limited condition where the detector noise due to the non-
frequency-shifted single-frequency CW laser power dominates all other noise. The IFs of
the two signals are determined by frequency analysis. The Doppler-shifted frequency $\Delta f$ is
then given as the difference frequency between the mean IFs of the two signals:

$$\Delta f = (f_L + f_{\text{shift}} + \Delta f_{\text{shift}}) - (f_L + f_{\text{shift}}).$$

The Doppler-shifted frequency directly determines the LOS wind speed of a vector wind. The LOS wind speed $V_{\text{LOS}}$ is obtained as

$$V_{\text{LOS}} = \frac{\lambda_L}{2} \cdot \Delta f,$$  (1)

where $\lambda_L$ is the laser wavelength. At a $\lambda_L$ of 2 $\mu$m, $\Delta f$ of 1 MHz corresponds to an LOS wind speed of 1 m s$^{-1}$. The LOS wind speed depends on the vector wind components $u$, $v$, and $w$. $V_{\text{LOS}}$ is given by

$$V_{\text{LOS}} = u \cdot \sin \theta_{\text{LOS}} \cdot \sin \varphi_{\text{LOS}} + v \cdot \cos \theta_{\text{LOS}} \cdot \sin \varphi_{\text{LOS}} + w \cdot \cos \varphi_{\text{LOS}},$$  (2)

where $\theta_{\text{LOS}}$ is the azimuth angle from north and $\varphi_{\text{LOS}}$ is the nadir angle of the laser beam.

The effective number of coherent signal photons $\Phi$ detected per range gate ($\Delta r = c \cdot M T_s/2$) per shot for target range $r$ (m) is given as (Frehlich 2004)

$$\Phi = \eta_Q \cdot \eta_H \cdot \eta_O \cdot E_T \cdot \frac{A_R}{r^2} \cdot \beta(r) \cdot T_{R}^{2} \cdot \frac{\Delta r}{h f_L},$$  (3)

where $c = 2.998 \times 10^8$ is the light speed (m s$^{-1}$), $M$ is the number of sampling points, $T_s$ is the sampling interval (s), $\eta_Q$, $\eta_H$, and $\eta_O$ are the quantum efficiency of the detector, the heterodyne efficiency, and the optical efficiency, respectively, $E_T$ is the pulse energy of the laser (J pulse$^{-1}$), $A_R$ is the telescope area (m$^2$), $\beta(r)$ is the backscattering coefficient of the target atmosphere (m$^{-1}$ sr$^{-1}$), $T_{R}(r)$ is the one-way transmission between the lidar and the
target atmosphere, and \( h = 6.626 \times 10^{-34} \) (J s) is Planck’s constant.

The optical signal current \( I_S(t) \) (A) on a linear detector is expressed as (Frehlich and Kavaya 1991)

\[
I_S(t) = I_{DC}(t) + I_S(t) + I_{DK}(t) + I_T(t) + i_{IF}(t), \quad (4)
\]

where \( I_{DC}(t), I_S(t), I_{DK}(t), I_T(t), \) and \( i_{IF}(t) \) are the direct current (A) caused by the single-frequency CW laser, the direct-detection signal current caused by the backscattered signal (A), the dark current (A), the thermal noise current (A), and the IF signal current (A), respectively. \( I_{DC}(t) \) and \( I_S(t) \) are expressed as

\[
I_{DC}(t) = G \cdot \frac{\eta Q e h f L}{h f_L} \cdot P_{\text{single-frequency CW laser}}, \quad (5)
\]

\[
I_S(t) = G \cdot \frac{\eta Q e h f L}{h f_L} \cdot P_{\text{direct-detection signal}}, \quad (6)
\]

where \( G \) is the amplifier gain (dimensionless), \( P_{\text{single-frequency CW laser}} \) and \( P_{\text{direct-detection signal}} \) are the single-frequency CW laser power (W) and the direct-detection signal power current (W), respectively, and \( e = 1.602 \times 10^{-19} \) (C electron\(^{-1}\)) is the electronic charge. \( P_{\text{direct-detection signal}} \)

signal current is expressed as the following equation using \( \Phi \):

\[
P_{\text{direct-detection signal}} = \frac{h f_L}{\eta H M T_s} \Phi. \quad (7)
\]

If the signal current \( i_{IF}(t) \) for a homogeneous range gate (\( \Delta r \)) with a constant SNR and stationary wind is expressed as the discrete time series of backscattered signals (Zrinč 1979; Rye and Hardesty 1993; Frehlich and Yadlowsky 1994), \( i_{IF}(t) \) is expressed as

\[
i_{IF} = \sqrt{2} \left( \frac{e \eta Q}{h f_L} \right)^2 \eta H Q \cdot P_{\text{single-frequency CW laser}} \cdot P_{\text{direct-detection signal}} \cdot \sum_{k=-M}^{M} \exp \left( -2 \pi^2 (w k T_s)^2 + i \frac{4\pi (f_{\text{shift}} + \Delta f) T_s}{\lambda L} \right), \quad (8)
\]

where \( w \) is the spectral width of the backscattered signal (Hz). The wideband signal-to-
noise ratio (SNR) of the CDWL is the ratio of the average signal power to the average noise power and defined as

\[
\text{SNR} = \frac{\langle i_{DF}(t)^2 \rangle}{\langle i_{DC}(t)^2 \rangle + \langle i_S(t)^2 \rangle + \langle i_{DK}(t)^2 \rangle + \langle i_T(t)^2 \rangle},
\]

(9)

where <> denotes the ensemble average over time. We assume that the average noise powers, \(\langle i_{DC}(t)^2 \rangle\) and \(\langle i_S(t)^2 \rangle\), caused by the single-frequency CW laser and the backscattered signal, respectively, obey the Poisson statistics. \(\langle i_{DC}(t)^2 \rangle\), \(\langle i_S(t)^2 \rangle\), \(\langle i_{DK}(t)^2 \rangle\), and \(\langle i_T(t)^2 \rangle\) are expressed as

\[
\langle i_{DC}(t)^2 \rangle = 2GeB\langle I_{DC} \rangle = 2G^2e^2B\frac{\hbar Q}{hf_L}\langle P_{\text{single-frequency CW laser}} \rangle, \quad (10)
\]

\[
\langle i_S(t)^2 \rangle = 2GeB\langle I_S \rangle = 2G^2e^2B\frac{\hbar Q}{hf_L}\langle P_{\text{direct-detection signal}} \rangle, \quad (11)
\]

\[
\langle i_D(t)^2 \rangle = 2GeB\langle I_D \rangle, \quad (12)
\]

\[
\langle i_{DK}(t)^2 \rangle = \frac{4K_B^2Te^2}{R_L}, \quad (13)
\]

where B (Hz) is the bandwidth of the detector and amplifier, \(K_B = 1.38054 \times 10^{-23}\) (J K\(^{-1}\)) is Boltzmann’s constant, \(T_e\) (K) is the absolute temperature of the detector, and \(R_L\) (\(\Omega\)) is the load resistor of the detector. We substitute Eqs. (10)–(13) into Eq. (9). For a typical CDWL, the shot noise power due to the single-frequency CW laser power is much larger than all other noise powers, which is called the “shot-noise-limited condition”. Then, the SNR is expressed as

\[
\text{SNR} = \frac{\eta_H}{hf_L B}\langle P_{\text{direct-detection signal}} \rangle. \quad (14)
\]

The relation SNR=\(\Phi/M'\) (\(M'=M/2\)) is for real number time series (Frehlich et al. 1997).
The theoretical lowest LOS wind speed error \((dv)\) (m s\(^{-1}\)) is given by the Cramer–Rao lower bound (CRLB) (Scharf 1991; Rye and Hardesty 1993):

\[
dv_{CRLB,K} = \frac{\lambda_c F_S}{2} \sqrt{\frac{f_2^2}{K M} \left[ \int_{-0.5}^{0.5} \left( \frac{(f/f_2)^2}{\sqrt{\pi f_2}} \right) \left( \frac{\text{SNR}}{\sqrt{2f_2}} \right)^{-1} df \right]^{-1}}, \tag{15}
\]

where \(f_2\) is the spectral width normalized by the sampling frequency \(F_S\) (Hz), and \(K\) is the number of accumulated pulses. \(f_2\) is given by the spectrum width of the laser for the homogeneous atmosphere. Note that the CRLB in Eq. 15 is for complex number time series signal \(\sqrt{2}\) smaller than for the real number time series signal. By using the nadir angle \(\phi\), the theoretical horizontal LOS wind error per range gate becomes \(dv_{HLOS} = dv / \sin \phi\). When we use the same algorism as that of Part 2 to make wind retrieval of the CDWL data (Baron et al. 2017), \(dv_{K=1}\) for a single pulse (\(K=1\)) and \(\text{SNR} < 1\) follows that the CLRB is approximately proportional to \(1/\text{SNR}\):

\[
dv_{CRLB,K=1} \propto 1/\text{SNR}, \tag{16}
\]

Typically, \(\text{SNR}\) for good wind retrieval at 2-\(\mu\)m and at a height of 200 km is in the range between \(10^{-3}\) and \(10^{-2}\) (Baron et al. 2017). We assume that \(dv\) is independent random variable with a Gauss distribution. \(dv_{CRLB}\) for \(K\) pulses is given as

\[
dv_{CRLB,K} \propto 1/(\sqrt{K} \cdot \text{SNR}), \tag{17}
\]

Using Eqs. (14), (16), (17), and pulse repetition frequency (PRF) instead of \(K\), we have

\(\sqrt{\text{PRF} \cdot E_T} = \text{constant}\).
3. Global Wind Profiling Observation Geometry

The altitude and orbit (inclination, period) of a satellite are key parameters for studying the performances of space-borne remote sensing. Electric power, mass, and volume are also key parameters for designing the structure of a satellite, the size of a solar array panel, and the size of a radiator. In general, the observation altitudes of Earth observation satellites are in the range of 400–700 km. A polar-orbit satellite and the ISS fly in a circular orbit at an attitude of 400 km at inclination angles of 98° and 52°, respectively. The light power detected by a lidar is proportional to the pulse energy of the laser, the area of the receiver (telescope), and the optical efficiency, which is inversely proportional to the square of the distance between the lidar and the target atmosphere as described in Eq. (3). If the orbital altitude of a future candidate satellite were half that of the ISS, the pulse energy of the laser or the diameter of the telescope would be four times smaller. The target orbital altitude of the future SLAS is 220 km, which means that the pulse energy meeting the requirements of future space-borne CDWL would be four times smaller than that of the ISS-borne CDWL. The target design life of this satellite is 5 years due to the fuel of the ion engine, and the target operation of the space-borne CDWL observation is 3-5 years. We are considering two candidate orbits for the future space-borne DWL: a sun-synchronous polar orbit (96.4°) and a low-inclination-angle orbit (35.1°). The electrical power consumption for maintaining the bus and running the sensor depends on the size of the solar array panel (SAP), the angle of cant of the SAP, and the inclination angle of the SLAS. Detailed considerations
are necessary for choosing the size and designing the structure of the SAP. Figure 3 shows the sun-synchronous polar and low-inclination-angle orbits. A comparison of the platform parameters for the future space-borne CDWL, ISS-borne JEM-CDWL, and ADM-Aeolus is summarized in Table 3.

Figure 4 shows the relationship between the horizontal line of sight (HLOS) wind speed error and the nadir angle for various altitudes (surface, 2, 5, 8, and 10 km) and for the configuration depicted in Fig. 4. The HLOS wind speed error is calculated using Eqs. (3), (7), (14), and (15), the nadir angle, the enhanced aerosol model of the target atmosphere based on Global Backscatter Experiment (Bowdle et al 1991) for use in the 2-µm CDWL concept study (Emmitt et al., 2001), and the parameters described in a previous study (Ishii 2009). The HLOS wind speed error depends on target range $r$ and a sine of $\varphi$. The HLOS wind speed error depends on the SNR. In general, the HLOS wind speed error is low in the lower troposphere. Since the SNR is slightly higher at the altitude of 5 km than at 2 km, the HLOS wind speed error for 5 km is lower than that for 2 km. The HLOS wind speed error decreases from nadir angles of 20° to 30°, decreases slightly from 30° to 35°, and increases above 40°. The range between the lidar and the target atmosphere increases with the nadir angle, and the SNR decreases with the square of the target range. It is necessary to consider the horizontal resolution required by current users for wind profile observation. A nadir angle of 35° is selected for future space-borne CDWL observations. The horizontal wind direction is obtained by DWL observation of the same air mass from two
directions (i.e., two LOS wind measurements). The LOS wind speed versus azimuth angle at the same altitude yields a sinusoidal curve. The LOS wind speed is 0 m s\(^{-1}\) for a laser beam direction perpendicular to the wind direction and it is a maximum speed for a laser beam direction parallel to the wind direction. As the separation angle of the two laser beam directions decreases, difference of the LOS wind speed becomes small, which results in degradation of accuracy in vector wind measurement. Although the LOS azimuth angle relative to the satellite speed is fixed, the angle with respect to zonal or meridional components varies over 360° during a full orbit. However, the zonal or meridional components of the winds can be constructed from any LOS orientations since the two LOS are always perpendicular. When the two laser beams are projected into a horizontal plane, the optimum configuration for reconstructing the wind vector is when both LOS are perpendicular. Azimuth angles of 45° (forward) and 135° (backward) (or 225° and 315°) are selected for vector wind measurement to the right of the orbit ground track (0° is the satellite flight direction and a positive angle is in the clockwise direction). Figure 5 shows a schematic down-looking wind observation geometry and a swath of the SLAS-borne CDWL. The location of the laser footprint with a diameter 2 m is determined by the combination of the nadir angle, azimuth angle, and orbital altitude, and the laser footprint track is about 110 km away from the satellite ground track. The spacing between two laser footprints is determined by the ground track speed of the satellite and PRF. The Earth’s rotation causes a successive satellite ground track spacing of 2370 km at 0° and 2030 km.
at 35° latitude. The ground track speed of the satellite is 7.5 km s\(^{-1}\); a horizontal resolution of 100 km corresponds to about 13.3 s. The separation between a pair of orthogonal LOS wind is 12.8 s. The forward and backward laser directions are alternately switched.

4. **Key technology required for space-borne coherent Doppler wind lidar**

The power backscattered from the atmosphere decreases with the square of the range to the target atmosphere. The pulse energy of a laser required for an ISS JEM-CDL flying at 400 km altitude was 0.5 J (Ishii 2009) at a PRF of 10 Hz. The low orbital altitude of the SLAS-borne CDWL allows the pulse energy of the laser of 0.5 J to be reduced fourfold (0.125 J). The average laser power required for the SLAS-borne CDWL is 1.25 W at 2 \(\mu\)m. NICT developed a 2-\(\mu\)m single-frequency Q-switched Tm,Ho:YLF laser operating at 30 Hz with a pulse duration of 150 ns\(_{\text{FWHM}}\) (FWHM: full width at half maximum) (Ishii et al., 2010; Mizutani et al. 2015). JAXA developed a 1.5-\(\mu\)m optical fiber laser for airborne application emitting 0.0019 J at 4000 Hz (average power = 7.6 W) (Inokuchi and Tanaka, 2009; Inokuchi et al., 2014). By using Eqs. (3), (7), (14), and (17), average powers of 40W and 19W for Ångström exponent of -0.3 and -2 respectively are required at the 1.55-\(\mu\)m CDL with 0.01J pulse energy to obtain the same LOS wind speed error \(dv\) as that of a 2-\(\mu\)m CDWL with 0.125J pulse energy at 30Hz. In this study, the laser designs for 1.5 and 2 \(\mu\)m permit a pulse energy of 0.01 J and a PRF of 1700 (Ångström exponent = -2.0) to 4700 Hz (Ångström exponent = -0.3), and a pulse energy of 0.125 J and a PRF of 30 Hz, respectively. The pulse
width for both lasers is 200 ns.

A CDWL requires a single-frequency Q-switched laser. A single-frequency Q-switched laser pulse is achieved by the injection seeding with a single-frequency CW laser beam matched to a pulse laser by the ramp-and-fire technique (Henderson et al. 1986). The single-frequency CW laser is critical for the injection seeding and heterodyne detection. It is important to develop a reliable single-frequency CW laser for the future SLAS-borne CDWL. The single-frequency CW laser needs to have a small frequency jitter, which means that it does not change the frequency during the round-trip time between the CDWL and the target atmosphere. Technical requirements for the target 2-μm laser are the TEM₀₀ mode, wavelength tuning, an output of >30 mW, long power stability, linear polarization, and a frequency jitter of <10 kHz ms⁻¹. Figure 6 shows two candidate laser systems for the 2-μm Q-switched pulse laser with a noncomposite Tm,Ho:YLF laser rod: (a) a one-oscillator configuration and (b) a master oscillator power amplifier (MOPA) configuration. For the current laser-diode-pumped (LD-pumped) 2-μm single-frequency Q-switched Tm,Ho:YLF laser developed at NICT, it has been shown experimentally that the average laser power increases at a rate of 0.1 W/°C with the cooling of the laser rod. The Tm,Ho:YLF laser rod should be cooled to lower than roughly -100 °C to achieve an average laser power of 3.75 W (0.125 J/pulse, 30 Hz). A cooling system would require a large amount of electrical power to cool the Tm,Ho:YLF laser rod to such a low temperature. The MOPA configuration is another approach because it is not necessary to cool the Tm,Ho:YLF laser
rod to such a low temperature. We constructed a new laser model for the design of the Tm,Ho:YLF laser (Sato et al. 2014), which is a major improvement on previous laser models (e.g., Walsh et al. 2000). We are theoretically and experimentally investigating the feasibility of the MOPA-configured 2-μm laser operating at a laser rod temperature higher than -40 °C. Preliminary results of the simulation using the new laser model show the possibility that the MOPA-configured 2-μm laser could emit a laser pulse of 0.125 J at a PRF of 30 Hz. The MOPA-configured 2-μm laser could also use thermoelectric cooling systems for cooling two Tm,Ho:YLF lasers. We understand that the laser configuration has a trade-off between the laser power and the power required for heat removal and electrical power consumption. A high-power laser is the component with the highest risk in a lidar system. High-power laser diode arrays (LDAs) are used to pump a laser rod in the pumping laser module. NASA (2006) studied the reliability of LDAs for space-borne laser application and established guidelines for the qualification and screening testing of LDAs. Currently, another high risk for the space-qualified laser is laser-induced damage (LID) due to outgas from the adhesion material. Preventing LID requires special attention to the design of a high-pulse energy laser system. We conducted destructive tests to evaluate the performances of various optical coatings at 2 μm and obtained the high damage threshold for the 2-μm optics with ion-beam sputtering coating.

Figure 7 shows a candidate 1.5-μm optical fiber laser with the MOPA configuration. The 1.5-μm optical fiber laser consists of a small-power laser source, an AOM used for
generating a pulse waveform, and erbium-doped optical fiber amplifiers. The 1.5-μm optical fiber applications rely on well-developed materials and well-established telecommunication devices. The technology of the 1.5-μm optical fiber laser has advantages for lidar applications, such as weight, size, robustness, and free optical alignment. However, there are also challenges in realizing a light source to meet the requirements of the future SLAS-borne CDWL: a high PRF (1700 to 4700 Hz), a single frequency, high-energy pulse (0.01 J), laser beam quality, the amplified spontaneous emission (ASE) effect, and polarization-maintaining operation. New glass rare-earth host materials will enable the development of a highly doped optical fiber amplifier with a short length and large mode area. A highly doped optical fiber amplifier produces high pulse energy. The high pulse energy indicates a nonlinear process in the optical fiber, especially for stimulated Brillouin scattering (SBS). The SBS restricts the input optical power and it is a limiting factor for the achievable pulse energy. To reduce the nonlinearity of the process, a planar waveguide is being developed using glass rare-earth host materials. The planar waveguide laser has attractive features such as high efficiency, high beam quality, and so on. To the best of our knowledge, the highest average power of an Er-doped fiber laser with a planar waveguide is 7.6 W with a pulse energy of 1.9 mJ and a pulse width of 580 ns (Sakimura et al. 2012). A laser pulse with a log pulse width has a narrow linewidth in the frequency domain. The narrow-linewidth laser pulse is useful for frequency analysis with a high frequency resolution, leading to wind measurement with high precision.
Sakimura et al. (2012) reported gain saturation due to the ASE effect. A 1.5-μm optical fiber laser with an average power of 10 W has not been demonstrated even at the laboratory level. Further technical studies are necessary in order to develop a 1.5-μm optical fiber laser meeting the requirements of the future SLAS-borne CDWL. The 2-μm laser technology for a space-borne lidar has been matured in Japan (Ishii et al. 2010; Mizutani et al. 2015; Sato et al. 2016). Therefore, the 2-μm laser is a better approach for the future SLAS-borne CDWL than the 1.5-μm laser system. Hereafter and in Parts 2, we focus on the space-borne CDWL with a 2-μm laser.

A key requirement for a coherent receiver is a telescope with diffraction-limited performance. NICT has developed afocal telescopes for a 2-μm coherent lidar. The afocal telescopes have a two-mirror off-axis Mersenne design in order to minimize wavefront aberrations and have excellent wavefront accuracy. The afocal telescopes are coaxial systems with a beam-expanding collimator and a receiving telescope. We are accumulating knowledge and technologies to design and fabricate an afocal telescope with a large aperture. Since the motion of a scanning device causes scanning-induced momentum and affects the altitude determination and control of a satellite, the space-borne CDWL described in previous studies (Iwasaki 1999; Ishii 2009) uses two fixed off-axis telescopes with a 40-cm clear aperture. Reducing the mass and size of the mirror and telescope allows a longer operation by reducing the fuel consumption.

The SLAS will fly at a track speed of about 7.8 km s⁻¹. We assume that the SLAS track
were parallel to Earth rotation direction. Earth rotation speed is about 460 m s\(^{-1}\). For a wind speed of 100 m s\(^{-1}\) (i.e., the upper limit measurement requirement for the velocity) and Earth rotation speed of 460 m s\(^{-1}\), the Doppler-shifted frequency at 2 μm is 8.4 GHz (\(\pm 7.8\) GHz + 0.1 GHz + 0.5 GHz). The laser pulse will be sent into the atmosphere at azimuth angles of 45° and 135° and at a nadir angle of 35°. The Doppler-shifted frequency is about 3.4 GHz \([\approx 8.4 \cdot \cos(45°) \cdot \sin(35°)]\). A detector with a bandwidth of >3.4 GHz is necessary for the space-borne CDWL wind measurements. An InGaAs detector is one of the candidate detectors. The electrical characteristics of an InGaAs detector can be affected by proton radiation with increasing number of protons (Garden 2000). The InGaAs detector must be designed and fabricated in accordance with the orbital type and altitude of the SLAS, the mission duration with respect to the solar activity, and the shielding of the SLAS. The Doppler-shifted frequency due to the satellite speed can be compensated by hardware-based onboard frequency calibration and down-converted to the IF frequency center of 100 MHz. Fluctuations in the frequency of the outgoing laser pulse due to short-term frequency drifting of the mechanical fluctuations of the piezoelectric translator (PZT) motion, long-term frequency drifting of the single-frequency CW laser, and other types of frequency drifting can be corrected by an algorithm proposed by Frehlich et al. (1997). Analog-to-digital (AD) conversion from an analog signal to a discrete signal is commonly used in data processing. Both the sampling frequency and the number of sampling points of an AD converter determine the frequency and range resolutions in DWL wind measurement. There are
some space-qualified, high-speed, and high-resolution AD converters (e.g., Texas Instruments ADS5463-SP (12-bit resolution, 500 MHz sampling frequency) and ADS5474-SP (14-bit resolution, 400 MHz sampling frequency)). The range and frequency resolutions are determined by the sampling frequency and the number of sampling points. The two resolutions have a trade-off relationship with each other. To accurately investigate the uncertainty of wind measurement due to the frequency fluctuation in the outgoing laser pulse, different numbers of sampling points are used for frequency analysis. An AD converter with a high bit resolution is useful for estimating the power of the backscattered signal and retrieving the backscattering coefficient from the target atmosphere. In this study, we selected an AD converter with 14-bit resolution and 400 MHz sampling frequency. If 4096-point and 256-point FFTs are used for the frequency analysis of outgoing laser pulses and backscattered signals, the frequency resolutions for the 4096-point and 256-point FFTs are 0.10 and 1.56 MHz, respectively, and the 256-point FFT corresponds to a range resolution of 96 m. The space-qualified, high-speed, and high-resolution AD converters will be sufficient to meet the WMO observational user requirements. The concept of the space-borne CDWL is summarized in Table 4.

Table 4

5. Summary

Wind profile observation is important to improve NWP, climate studies, and various meteorological studies. Current space-borne observing systems are biased to
temperature- and water-vapor-related measurements. The AMV can hardly retrieve vector wind with a high vertical resolution and precise height assignment. A space-borne DWL is a promising remote sensing technique for global wind profile observation and will solve the issues facing current space-borne observing systems. In this paper, we described the concept of a future space-borne CDWL. Our working group is studying the feasibility of a future Japanese space-borne CDWL from technical and scientific viewpoints. An instrumental overview of the space-borne DWL is described in this paper. The future mission concept described here will be the first space-borne DWL with heterodyne detection and it is designed to have two LOSs for vector wind measurement from a new super-low-altitude satellite (SLAS). The SLAS will be a challenging innovative technology for next-generation Earth observation satellites. There are two candidate orbits, 96.4° (a polar orbit similar to that of ADM-Aelous) and 35.1° (low-inclination-angle orbit similar to that of TRMM). The satellite orbit and altitude are under discussion from the scientific viewpoint. The CDWL uses an eye-safe transmitter with a single frequency, high pulse energy, and long pulse width. The development of a space-qualified single-frequency pulse laser will provide opportunities for future space-borne lidar, such as high spectral resolution lidar or differential absorption lidar. Heterodyne detection is a challenging technique to be carried out under diffraction-limited and shot-noise-limited conditions. Heterodyne detection is a novel technique allowing daytime and nighttime wind measurements without considering solar background noise. The technical requirements of the SLAS-borne CDWL are an
average laser power of 3.75 W (0.125 J at a PRF of 30 Hz) at 2 μm, two effective 40-cm-
diameter afocal telescopes, a wide-bandwidth (>3.4 GHz) detector, a high-speed AD
converter, and a systematic lidar efficiency of 0.08.

The SLAS-borne CDWL will provide a full vector wind profile with high vertical resolution,
low bias, and high precision at along-track horizontal and vertical resolutions better than 100
km, and <0.5 km for the altitude range of 0–3 km and <1 km for the altitude range of 3–8
km, respectively, in the presence of moderate- or enhanced loaded aerosol and cloud and
it will fill the gap of the current global wind observing systems. Note that it is true when
moderate- or enhanced-loaded aerosol and cloud are present. By providing global wind
profiling and intercalibration between the SLAS-borne CDWL and other global wind
observing systems, the SLAS-borne CDWL will be complementary and offer insights into
the improvement and development of algorithms for passive sensors. Synergistic wind
measurements using the SLAS-borne CDWL and other global wind observing systems
should improve the initial conditions for NWP, the prediction of typhoons, heavy rain, and
atmospheric transport, and meteorological studies.
Acknowledgments

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper. The authors wish to thank Tatemasa Miyoshi of the RIKEN Advanced Institute for Computational Science; Masakatsu Nakajima, Hamaki Inokuchi, Maki Hirakata, and Hirokazu Hoshino of JAXA; Kazuhiro Asai of Tokyo Institute of Technology; and Kazumasa Aonashi of JMA/MRI for supporting the research activity of the working group. The authors wish to thank Yoshiaki Sato of JMA; Munehiko Yamaguchi of JMA/MRI; Fumio Hasebe of Hokkaido University; Hirohiko Masunaga of Nagoya University; Masato Shiotani, Tetsuya Takemi, and Eriko Nishimoto of Kyoto University; Yasukuni Shibata of Tokyo Metropolitan University; and Tetsuo Shina of Chiba University for contributing to the implementation plan for the future space-borne DWL in Japan and supporting the research activity of the working group. The authors thank the GPM Utilization Committee for supporting the working group. The authors wish to thank Toshikazu Itabe for many useful discussions and helpful advice.

A part of this research was supported by JSPS KAKENHI under Grant Numbers 15K06129 and 15K05293.
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Fig. 1. Numerical simulation flow from space-borne CDWL lidar simulator to OSSE.

Fig. 2. Principle and basic components of CDWL. $f$ is laser frequency. $f_{\text{shift}}$ is shifted frequency modulated by an optical device. $\Delta f$ is Doppler-shifted frequency. $\Delta f = (f_{\text{shift}} + \Delta f) - f_{\text{shift}}$. Two mixers are used to mix a single-frequency CW laser beam with an outgoing laser beam and backscattered light.

Fig. 3. Candidate orbit and coverage: (upper panel) sun-synchronous polar orbit and (lower panel) low-inclination-angle orbit.

Fig. 4. Relationship between nadir angle and horizontal line of sight (HLOS) wind speed error for various altitudes (surface, 2, 5, 8, and 10 km) for the configuration depicted in Fig. 5. The HLOS wind speed error is calculated using Eqs. (3), (7), (14), and (15), the nadir angle, and the enhanced aerosol model of the target atmospheres for use in DWL concept studies (Emmitt et al., 2001).

Fig. 5. Down-looking wind profile observation geometry of SLAS-borne CDWL using two telescopes.

Fig. 6. Candidate 2-μm laser system configurations: (a) one-oscillator configuration and (b) master oscillator and amplifier (MOPA) configuration. A single-frequency CW laser is used for the injection seeding. Q-sw is an optical component for Q-switching. PZT is a piezoelectric translator with a mirror for controlling the cavity length of the laser.
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Table 2. Comparison of SLAS-borne CDWL and space-borne direct-detection DWL. SWIR, UV, and VIS are short-wavelength infrared, ultraviolet, and visible, respectively.

Table 3. Comparison of platform parameters for SLAS-borne DWLs.

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<table>
<thead>
<tr>
<th>Target atmosphere</th>
<th>Vertical resolution (km)</th>
<th>Horizontal resolution (km)</th>
<th>Wind accuracy (m s(^{-1}))</th>
<th>Observing cycle (h)</th>
<th>Delay of availability (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower troposphere (LT)</td>
<td>Goal: 0.5  BT: 1  TH: 3</td>
<td>Goal: 15  BT: 100  TH: 500</td>
<td>Goal: 1  BT: 3  TH: 8</td>
<td>Goal: 1  BT: 6  TH: 12</td>
<td>Goal: 0.1  BT: 0.5  TH: 6</td>
</tr>
<tr>
<td>Upper troposphere (UT)</td>
<td>8</td>
<td>15</td>
<td>100</td>
<td>500</td>
<td>1</td>
</tr>
<tr>
<td>Lower stratosphere (LS)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1(b). Summary of current global wind observing systems.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Altitude (km)</th>
<th>Coverage</th>
<th>Observing cycle (hour/days)</th>
<th>Wind accuracy (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoys and ships</td>
<td>Sea surface</td>
<td>Ocean</td>
<td>24/7</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>Auto weather station</td>
<td>Surface</td>
<td>Land</td>
<td>24/7</td>
<td>0.1</td>
</tr>
<tr>
<td>Wind profiler</td>
<td>Surface - 10</td>
<td>Land</td>
<td>24/7</td>
<td>1</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Flight level</td>
<td>Mainly northern hemisphere land</td>
<td>24/7</td>
<td>1-3</td>
</tr>
<tr>
<td>Radiosonde</td>
<td>Surface – 30</td>
<td>Mainly northern hemisphere land</td>
<td>12 or 24/7</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Space-borne microwave scatterometer/radiometer</td>
<td>Sea surface</td>
<td>Ocean</td>
<td>24/7</td>
<td>2</td>
</tr>
<tr>
<td>Space-borne microwave imager (AMV)</td>
<td>Mainly cloud top</td>
<td>Land and ocean</td>
<td>3/7</td>
<td>Bias&lt;2, RMS&gt;4</td>
</tr>
</tbody>
</table>
Table 2. Comparison of SLAS-borne CDWL and space-borne direct-detection DWL. SWIR, UV, and VIS are short-wavelength infrared, ultraviolet, and visible, respectively.

<table>
<thead>
<tr>
<th></th>
<th>SLAS-borne CDWL</th>
<th>Direct-detection DWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable time zone</td>
<td>Daytime and nighttime</td>
<td>Daytime and nighttime</td>
</tr>
<tr>
<td>Target atmosphere</td>
<td>Lower troposphere</td>
<td>Troposphere, lower stratosphere</td>
</tr>
<tr>
<td>Scattering</td>
<td>Aerosol</td>
<td>Aerosol, Molecular</td>
</tr>
<tr>
<td>Wavelength band</td>
<td>SWIR</td>
<td>UV</td>
</tr>
<tr>
<td>Laser average power</td>
<td>2.5 W class</td>
<td>5 W (<strong>) class, (30 W (</strong>*) class)</td>
</tr>
<tr>
<td>Telescope size</td>
<td>Middle (0.5 m)</td>
<td>Large (1–1.5 (**) m)</td>
</tr>
<tr>
<td>Detection technique</td>
<td>Heterodyne (optical mixing)</td>
<td>Optical frequency discriminator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectrum analyzer</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Bias-free in principle, (0.0 m s⁻¹)</td>
<td>Significant bias, (0.4 m s⁻¹ (**, ****))</td>
</tr>
<tr>
<td>Precision</td>
<td>0.1–1 m s⁻¹ (*)</td>
<td>0.6–1.7 m s⁻¹ (**)</td>
</tr>
</tbody>
</table>

Table 3. Comparison of platform parameters for space-borne DWLs.

<table>
<thead>
<tr>
<th></th>
<th>SLAS-borne</th>
<th>ISS-borne JEM-CDL</th>
<th>ADM-Aeolus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital altitude (km)</td>
<td>220</td>
<td>400</td>
<td>410</td>
</tr>
<tr>
<td>Orbital inclination (°)</td>
<td>96.4 (Polar, SSO)</td>
<td>51.6 (non-SSO)</td>
<td>96.4 (SSO)</td>
</tr>
<tr>
<td>Orbital period (min)</td>
<td>89</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Instrument volume (m³)</td>
<td>1.5×1.0×1.0</td>
<td>1.8×1.0×0.8</td>
<td>4.3×1.9×2.0</td>
</tr>
<tr>
<td>Total / Instrument mass (kg)</td>
<td>600(*) / TBD</td>
<td>- / &lt;500</td>
<td>1100(**) / 470</td>
</tr>
<tr>
<td>Total / Instrument power (kW)</td>
<td>1600 / 730</td>
<td>- / 1250</td>
<td>1400 / 840</td>
</tr>
</tbody>
</table>

SLAS: super-low-altitude satellite. SSO: sun-synchronous orbit. *: target total dry mass, **: total dry mass (not including fuel)
Table 4. Summary of SLAS-borne CDWL.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Wavelength (μm)</td>
<td>2.05</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>0.125</td>
</tr>
<tr>
<td>Pulse duration (ns&lt;sub&gt;FWHM&lt;/sub&gt;)</td>
<td>200</td>
</tr>
<tr>
<td>PRF (Hz)</td>
<td>30</td>
</tr>
<tr>
<td>Telescope diameter (m)</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of laser directions</td>
<td>2</td>
</tr>
<tr>
<td>Detector quantum efficiency</td>
<td>0.8</td>
</tr>
<tr>
<td>Heterodyne efficiency</td>
<td>0.4</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>0.44</td>
</tr>
<tr>
<td>Unknown system efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Sampling frequency (MHz)</td>
<td>400</td>
</tr>
<tr>
<td>Sampling points</td>
<td>256</td>
</tr>
<tr>
<td>Azimuth angle of observation direction (°)</td>
<td>45, 135</td>
</tr>
<tr>
<td>Nadir angle of observation direction (°)</td>
<td>35</td>
</tr>
<tr>
<td>Target horizontal resolution (km)</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Target vertical resolution (km)</td>
<td></td>
</tr>
<tr>
<td>Altitude 0–3 km: &lt;0.5</td>
<td></td>
</tr>
<tr>
<td>Altitude 3–8 km: &lt;1</td>
<td></td>
</tr>
<tr>
<td>Altitude 8–20 km: &lt;2</td>
<td></td>
</tr>
</tbody>
</table>