A Proposal of Pulse-Pair Doppler Operation on a Spaceborne Cloud-Profiling Radar in the W Band

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ABSTRACT

Pulse-pair Doppler operation is considered for the spaceborne mission. In a formalism, the condition that a measured Doppler velocity on pulse-pair operation corresponds to that on the FFT operation is derived. The coherent coupling effect of the spectral broadenings between Doppler fading and vertical wind shears is shown to strongly depend on the flight direction of a platform. This coupling effect, which has been ignored for ground-based and airborne radars, is characteristic for the space mission. Two kinds of pulse-pair operations, polarization diversity method and conventional contiguous pulse-pair method, are studied to determine the accuracy of Doppler velocity as a function of cloud reflectivity and pulse-pair interval. Advantages and disadvantages of these operations, including adverse effects of beam-pointing error, ground clutters, and sidelobes, are discussed along with a variety of parameters to design the optimum operation. In the assessment of the Doppler feasibility, new features suitable to the space mission are also proposed.

1. Introduction

Forecasts of global warming involve substantial uncertainties in climate simulations arising from difficulties in incorporating clouds to the process of radiation transfer. A step to provide more confirmed information on the global climate modeling is to collect the threedimensional distribution of clouds in the global scale. For this purpose, a mission of a spaceborne cloud-profiling radar in the first generation, called CloudSat is now under way (Li et al. 2000). However, a radar in this mission is designed to measure only the backscattering reflectivity from clouds in the nadir direction, which will provide the scalar property of clouds in the two dimensions along a satellite track. In order to increase information on clouds, the second generation of a spaceborne cloud-profiling radar is expected to be accompanied with some advanced technologies, including Doppler operation in the nadir direction, dual-frequency operation, and multibeam scanning in off-nadir directions. This paper will only deal with the Doppler operation in the nadir direction, which is expected to demonstrate the following scientific objectives.

 Validation of the falling velocity of cirrus, parameterized in the climate modeling. The typical reflectivity of cirrus observed over the altitude of 8 km is in the range of -10 to -30 dBZ. The expected falling velocity is about 0.1 m s⁻¹ in static air. The required accuracy of Doppler velocity is therefore considered to be ≈ 0.1 m s⁻¹ over an along-track integration of 10 km for cirrus of -20 dBZ or below.

- 2) Identification of drizzles from water cloud particles such as stratocumulus at a low altitude of 1–2 km. The typical reflectivity of stratocumulus is -20 dBZor below. The required accuracy for this identification is considered to be $\approx 0.5 \text{ m s}^{-1}$ over an alongtrack integration of 1 km for drizzles of -20 dBZor below.
- Characterization of the convective motion of clouds. The convective velocity is the order of 1–10 m s⁻¹. A spectral broadening of turbulence of σ_w ≈ 1–4 m s⁻¹ is expected, and vertical wind shears are estimated as κ_{zx} ≈ κ_{zy} ≈ κ_{zz} ≈ 10⁻²–10⁻⁴ s⁻¹ (Amayenc et al. 1993). The required accuracy of Doppler velocity is considered to be ≈1 m s⁻¹ over an along-track integration of 1 km for clouds of -20 dBZ or below.

Pulse-pair Doppler operation from a satellite will have some difficulties in comparison with a groundbased or an airborne cloud-profiling radar. First of all, a high velocity of the satellite causes deterioration in correlation signals due to its short coherent time arising from Doppler fading. This short coherent time, in turn, broadens the spectral width of receiving signals in its frequency space. As a consequence, when vertical wind shears exist, the spectral broadenings between the Doppler fading and the vertical wind shears couple together

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coherently rather than incoherently to enhance or reduce the resultant magnitude, depending on conditions. This effect will be considered intensively in sections 3a and 3b. Furthermore, the receiving signal of a low signalto-noise ratio (SNR) from clouds at a large distance necessitates a huge number of data integrations to increase a required accuracy in measured Doppler velocity. Hence, the accuracy evaluation along with a parameter of the spectral broadening is crucial to the feasibility study of spaceborne Doppler operations.

In general, Doppler operations are categorized as either pulse-pair or FFT operations. Because of the signal with a low SNR and a broad spectral width for the space mission, the FFT operation needs removal of noise prior to the FFT process, while the pulse-pair operation does not. Further on the latter operation, since aliasing of Doppler velocity simply depends on a pulse-pair interval, ambiguity of Doppler velocity can be resolved by staggering a pulse-pair interval depending on necessity. As a conclusion, the pulse-pair operation has been considered better than the FFT operation for a spaceborne cloud radar although the full information of Doppler spectra is lacking.

Among pulse-pair operations, two forms have been well adopted. One is an operation with polarization diversity, referred to as the HV-pair operation (Doviak and Sirmans 1973), and the other is a conventional contiguous pulse-pair operation with a single polarization, referred to as the Cng-pair operation. A pulse pattern of the HV-pair operation is schematically depicted in Fig. 1a. Here orthogonally polarized pulses are transmitted in pairs with an interval T_s smaller than a pulserepetition interval T_{pri} . The maximum receiving range without blocks of transmitting pulses can therefore be given by $c(T_{\rm pri} - T_s - \tau_p)/2$ with a pulse duration τ_p as indicated in the figure. Correlation is calculated for the paired H-V pulses to measure the Doppler velocity of an illuminated body. This pulse pattern simultaneously achieves an increase in the unambiguous range proportional to T_{pri} (i.e., $cT_{pri}/2$), and that in the dynamical range of Doppler velocity is inversely proportional to T_s (i.e., $\pi/2kT_s$). On the other side, the Cng-pair operation illustrated in Fig. 1b has a simpler pulse pattern with $T_s = T_{pri}$ and a maximum receiving range of $c(T_{pri})$ $(-\tau_p)/2$. An advantage of the Cng-pair operation is to increase the number of integrations of pulses, hence accuracy of measurement. However, due to the condition of $T_s = T_{pri}$, an increase in the unambiguous range (the maximum receiving range) leads to the decrease in the dynamical range of Doppler velocity in contrast to the HV-pair operation. In this paper, both the HV-pair and Cng-pair operations will be considered for spaceborne cloud-profiling radar to achieve the required accuracy.

The paper is organized in the following scheme. In section 2, a spaceborne cloud radar is conceptually designed with respect to the geometrical configuration. In section 3, a formulation of the incoherent Doppler correlation signal on a high-velocity platform is described.



FIG. 1. Pulse patterns of pulse-pair operations: (a) Orthopolarization diversity, referred to as HV-pair operation, H and V denote polarimetries in the H and V directions, respectively. Here T_s and T_{pri} represent a pulse-pair interval and a pulse-repetition interval, respectively. (b) Contiguous pulse-pair operation with a single polarization, referred to as Cng-pair operation, in which the T_s is identical to the T_{pri} . In both (a) and (b), the maximum receiving ranges without blocks of transmitting pulses are indicated.

In section 4, the performance of Doppler measurement from space is considered on the basis of accuracy in Doppler velocity, including adverse effects. The discussion and conclusion are found in section 5.

2. Conceptual design of a spaceborne cloudprofiling radar

A schematic configuration of a spaceborne radar observation is depicted in Fig. 2. In the figure, a satellite orbit is set at an altitude of $h_{sat} = 450$ km. The comoving frame with the satellite at a velocity of $v_{pl} = 7.6$ km s⁻¹ is chosen, in which the *z* axis is in the nadir direction and the *x* axis is parallel to the flight direction. The specifications of a transmitting system used for evaluation are summarized in Table 1 on the basis of an airborne cloud-profiling radar SPIDER (Horie et al. 2000). A pulse of radiation frequency 94.05 GHz (Wband) is transmitted from a circular antenna of 2-m diameter to clouds in the nadir direction.

In this section, we shall estimate a necessary alongtrack integration on non-Doppler operations. For this purpose, the base of clouds is supposed at an altitude of $h_{clo} = 2$ km from the earth's surface. The thickness of the clouds is assumed to be comparable to the resolution range of the radar to ignore absorption by the clouds for simplicity. Under these conditions, the total



FIG. 2. A schematic figure of a spaceborne cloud-profiling radar. The footprint diameter of 800 m corresponds to the case of the 2-m antenna. The order of the beamwidth θ_d is 0.1°. The frame comoving with the platform has the *z* axis in the nadir direction, and the *x* axis parallel to the flight direction.

received power P_r is given by the weather radar equation for water clouds (Gossard and Strauch 1983; Doviak and Zrnic 1993):

$$P_{r} = \frac{\pi^{3}}{2^{10} \ln 2} \frac{P_{t} G^{2} \theta_{d}^{2} c \tau_{p}}{\lambda^{2} L_{a}^{2} L_{t}} \frac{1}{z_{0}^{2}} |K|^{2} Z.$$
(1)

In this representation, P_t is a transmitted power, G is an one-way gain of the antenna, θ_d is an angle of beamwidth, c is the speed of light, and τ_p is a pulse duration. Here λ is the wavelength of radiated beam; z_0 is the range distance from the satellite to the clouds, that is, $z_0 = h_{\rm sat} - h_{\rm clo}$; and L_a is an one-way absorption/scattering loss by air, assumed to be 1 dB. If the clouds are sufficiently thick, absorption by the clouds can be included in the value of L_a . Here K is the dielectric factor of water for which Ulaby et al. (1981) reviewed the values of $|K|^2 = 0.69$ at 0°C, and $|K|^2 = 0.82$ at 20°C at 94 GHz. Here the smaller value of $|K|^2 = 0.69$ will be chosen to clarify a threshold of the along-track integration. The L_t is a two-way system loss assumed to be 4 dB. The reflectivity factor Z of clouds is set optimistically at -30 dBZ for the requirements of (1-3)in the introduction.

Using the values from Table 1, the received power $P_r = -129$ dBm and the signal-to-noise ratio per pulse (SNR = -15.3 dB) are evaluated. On the other hand, an effective signal-to-noise ratio SNR_{eff} for incoherent integration (Ulaby et al. 1981; Meneghini and Kozu 1990) is defined as

$$\text{SNR}_{\text{eff}} = \left[\frac{1}{N}\left(1 + \frac{1}{\text{SNR}}\right)^2 + \frac{1}{C_{\text{nse}}N}\left(\frac{1}{\text{SNR}}\right)^2\right]^{-1/2},$$
 (2)

in which *N* is a sampling number of signals, and C_{nse} is a noise sampling factor set at 8, which the SPIDER adopted. In Table 2, the SNR_{eff} is calculated for the clouds of -30 dBZ after N = 6000 integration, corresponding to the flight distance of 10 km for the ve-

TABLE 1. Specifications of a spaceborne cloud-profiling radar. Parameters are based on an airborne radar SPIDER (Horie et al. 2000).

Frequency	f	94.05 GHz
Wavelength	λ	$3.19 \times 10^{-3} \text{ m}$
Altitude	$h_{\rm sat}$	450 km
Antenna diameter	l	2 m
Antenna gain	G	64.3 dB
Beamwidth	θ_d	0.1°
System loss	Ĺ	4 dB
Transmitted power	P_{t}	2 kW
Pulse width	$ au_{n}$	3.33 µs
Noise figure	\vec{F}	5 dB
Receiving bandwidth	$B = 1.2/\tau_{p}$	0.36 MHz
Noise power	$P_n = k_B T B F$	-113 dBm

locity of 7.6 km s⁻¹ with a pulse-repetition interval of $T_{\rm pri} = 222 \ \mu \text{s}$ (4.5 kHz). The value of SNR_{eff} = 3.2 dB indicates a possibility to measure the Doppler velocity of clouds of $-30 \ \text{dBZ}$ from the satellite with the 2-m antenna and an along-track integration over 10 km.

3. Formulation of incoherent Doppler signals

a. Correlation signal

The design of a spaceborne Doppler radar requires evaluation of correlation signals for pulse-pair operation. Kobayashi (2002) has recently derived a unified formalism of the Doppler signals, including the incoherent, quasi-coherent, and coherent scatterings. It also shows that the incoherent scattering is the only term of finite contribution to the total signal around 95 GHz in accordance with the previous works of Gossard (1979) and de Wolf et al. (2000). Thus the incoherent term will be exclusively considered in this paper.

The origin of time reference for the formulation is set on the time of the first transmission of paired pulses. Details of the following derivation should be referred to Kobayashi (2002). The velocity \boldsymbol{v} of a cloud particle at position \mathbf{x} and time t is assumed to be independent of the z coordinate within the resolution range. Thus in the frame comoving with the platform (Fig. 2), the velocity \boldsymbol{v} for a fixed-range parameter $z_0 = ct$ can be approximated as a function of the transverse coordinates \mathbf{x}_{\perp} in the following form:

$$\mathbf{v} (\mathbf{x}_{\perp}, t, D; z_0) = \sum_{i=x,y,z} v_{wi}(\mathbf{x}_{\perp}, t; z_0) \hat{i} - v_{pl} \hat{x} + v_f(D) \hat{z}.$$
(3)

TABLE 2. Received power and SNR. Here P_r is the total received power per pulse. The SNR per pulse and the effective SNR are denoted by SNR and SNR_{eff}, respectively. The base of clouds of Z = -30 DBZ are assumed to be at the altitude of 2 km. The calculations are performed for the parameters of Table 1 along with the integration number N = 6000.

Z = -30 dBZ	
P_r	-129 dBm
SNR	-15.3 dB
$\text{SNR}_{\text{eff}} (N = 6000)$	3.2 dB

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Here v_{wi} is a wind velocity along the *i* (=*x*, *y*, *z*) direction, v_{pl} is a constant velocity of the platform (satellite) along the *x* direction, and $v_f(D)$ is the terminal falling velocity of a cloud particle of diameter *D* along the *z* direction. Furthermore the velocity of the cloud particle transported by a wind has been assumed independent of its particle size, and hence equal to the wind velocity $\mathbf{v}_w(\mathbf{x}_{\perp}, t; z_0)$ according to Amayenc et al. (1993) and de Wolf et al. (2000). For theoretical consideration, suppose that each component of the wind velocity \mathbf{v}_w obeys a Gaussian distribution, the ensemble averages of which are given by

$$\langle \boldsymbol{v}_{wx}(\mathbf{x}_{\perp}, t; z_0) \rangle = \overline{\boldsymbol{v}_{wx}} + \boldsymbol{\kappa}_{xy} y \langle \boldsymbol{v}_{wy}(\mathbf{x}_{\perp}, t; z_0) \rangle = \overline{\boldsymbol{v}_{wy}} + \boldsymbol{\kappa}_{yx} x \langle \boldsymbol{v}_{wz}(\mathbf{x}_{\perp}, t; z_0) \rangle = \overline{\boldsymbol{v}_{wz}} + \boldsymbol{\kappa}_{zx} x + \boldsymbol{\kappa}_{zy} y,$$
 (4)

where $\overline{v_{wi}}$ (*i* = *x*, *y*, *z*) are constants, and κ_{ij} (*i*, *j* = *x*, *y*, *z*) are wind shear constants. The corresponding variances of these velocities are set to be constant:

$$\sigma_{\rm wi}^2 \equiv {\rm const}(i = x, y, z). \tag{5}$$

Under these conditions, the correlation signal of the incoherent scattering can be calculated to the form:

$$R(\tau - t)_{\rm inc} \simeq \frac{2.61P_t G^2 \eta c \tau_p \pi \theta_d^2 \lambda^2}{(4\pi)^2 \ln 2z_0^2} \\ \times \exp[-j2k(\overline{v_{\rm fob}} + \overline{v_{wz}})T_s] \\ \times \exp(-2k^2 T_s^2 \sigma_{\rm comb}^2) \\ \times \exp(-2k^2 T_s^2 \sigma_{\rm wfob}^2) \exp(-2k^2 T_s^2 \sigma_{wz}^2),$$
(6)

in which the volumetric scattering reflectivity η is defined through the cloud density *n* and the backscattering amplitude *S*(*D*) along with the average over the diameter *D*:

$$\eta \equiv 4\pi n \langle |S(D)|^2 \rangle_D. \tag{7}$$

In Eq. (6), k is the radiation wavenumber. The $\overline{v_{\text{fob}}}$ and $\sigma_{v\text{fob}}^2$ are the average and variance of the terminal falling velocity $v_f(D)$, respectively, described later in Eqs. (9) and (10). The σ_{comb}^2 is the spectral broadening due to the coupling effect between Doppler fading and wind shears, defined in Eq. (13). Further it is mentioned that in the case of water particles, the introduction of $\eta = \pi^5 |K|^2 Z \lambda^{-4}$ with $T_s = 0$ will retrieve the usual radar equation of Eq. (1) along with the additional absorptions of L_a and L_t . However the definition of Eq. (7) is more general to be applied to arbitrary weather particles regardless of Mie or Rayleigh scatterings.

Rigorously, Eq. (6) can be derived for paired pulses with a single polarization, under which the first and second signals received in pairs are identical except for the difference in Doppler phase. Thus Eq. (6) can be applied to the Cng-pair operation without any additional condition. On the other hand, for the HV-pair operation, signals received in the H and V channels have different polarizations. Consequently, the identity of receiving signals in pairs is not generally held. However, Eq. (6) can be proven to be satisfied for the HV-pair operation in the nadir direction under the following conditions (Kobayashi 2002).

- Weather particles are symmetrical for the H and V directions, viewed from the nadir (beam) direction (e.g., for liquid particles).
- 2) Weather particles are asymmetrical for the H and V particles like ice particles; however, the orientations of these particles are random on viewing along the nadir (beam) direction. The applicabilities of these conditions to the objectives 1)–3) in the introduction will be discussed in section 5. In this section, one of the conditions 1) and 2) will be assumed so as to apply Eq. (6) to the HV-pair operation for evaluating parameters required on the accuracy calculation in the next section.

In the course of the derivation of Eq. (6), a condition has been imposed on the pulse-pair interval T_s :

$$|2kv_f(D)T_s| \ll 1. \tag{8}$$

Then, approximation up to the second-order quantities yields

$$dDN(D)|S(D)|^{2} \exp[-j2kv_{f}(D)T_{s}]$$

$$\approx \langle |S(D)|^{2} \rangle_{D} \exp(-j2k\overline{v_{\text{fob}}}T_{s}) \exp(-2k^{2}T_{s}^{2}\sigma_{v_{\text{fob}}}^{2}), \quad (9)$$

in which the weighted average $\overline{v_{\text{fob}}}$ and variance $\sigma_{v_{\text{fob}}}^2$ of $v_f(D)$ have been defined through a normalized size distribution function N(D):

$$1 \equiv \int dDN(D) \quad \langle |S(D)|^2 \rangle_D = \int dDN(D)|S(D)|^2$$
$$\overline{v}_{fob} = (\langle |S(D)|^2 \rangle_D)^{-1} \int dDN(D)|S(D)|^2 v_f(D)$$
$$\overline{v}_{fob}^2 = (\langle |S(D)|^2 \rangle_D)^{-1} \int dDN(D)|S(D)|^2 v_f^2(D)$$
$$\sigma_{v_{fob}}^2 = \overline{v}_{fob}^2 - (\overline{v}_{fob})^2. \tag{10}$$

It is seen that these definitions have simple correspondences to those of the FFT method (Atlas et al. 1973; Frisch et al. 1995; Sato et al. 1990; Wakasugi et al. 1987). In case that Eq. (8) is not satisfied, then alternately the distribution of

$$N(D)|S(D)|^2 \left/ \frac{dv_f(D)}{dD} \right. \tag{11}$$

would obey a Gaussian distribution with respect to $v_f(D)$ to obtain a form of Eq. (9). Even though a Gaussian distribution may be assumed for most situations, the conditions of Eq. (8) result in good convergence to Eq. (9) regardless of the type of the distribution of Eq. (11), and also guarantees simpler data treatment. An upper

(a)

limit of T_s for the convergence defined in Eq. (8) can be determined by setting a typical order of $\overline{v}_{fob} \approx 1 \text{ m} \text{ s}^{-1}$:

$$T_s \ll 250 \ \mu s. \tag{12}$$

Next, a characteristic spectral broadening on the space mission, that is, σ_{comb}^2 in Eq. (6), shall be described. Approximation for a small beamwidth θ_d yields the following form (Kobayashi 2002):

$$\sigma_{\rm comb}^{2} = \frac{\theta_{0}^{2}}{2.6} \Biggl\{ [(\overline{\upsilon_{x}} + \kappa_{zx}z_{0})^{2} + (\overline{\upsilon_{y}} + \kappa_{zy}z_{0})^{2}] + \frac{\theta_{0}^{2}z_{0}^{2}}{2.6}(\kappa_{xy} + \kappa_{yx})^{2} \Biggr\},$$
(13)

with half the beam width,

$$\theta_0 = \theta_d / 2 \simeq \pi / kl, \tag{14}$$

and the effective cross winds defined by

$$\overline{v_x} = \overline{v_{wx}} - v_{pl} \qquad \overline{v_y} = \overline{v_{wy}}. \tag{15}$$

The substitutions of $\overline{v_y} = 0$, $\kappa_{yx} = 0$, and $\kappa_{zx} = \kappa_{zy} =$ 0, reduce Eq. (13) to a formula of the spectral broadening due to a horizontal wind and its horizontal wind shear (Sloss and Atlas 1968), while the substitutions of $\overline{v_x} = \overline{v_y} = 0$, $\kappa_{zx} = 0$, and $\kappa_{xy} = \kappa_{yx} = 0$, reduce it to a formula for the spectral broadening due to the radial wind shear κ_{zy} (Atlas et al. 1969). Notice that Eq. (13) involves information more than the generalization of the previous works, that is the coupling of the spectral broadenings between the Doppler fading due to $\overline{v_x}$, $\overline{v_y}$, and the vertical wind shears, κ_{zx} , κ_{zy} . This coupling effect is a natural consequence under the Fraunhofer approximation. Isodops due to the effective cross wind $\overline{v_x}$ can be represented by linear lines perpendicular to the x axis as schematically shown in the overview of Fig. 3a. The magnitude of the corresponding Doppler effect represented by $\overline{v_x}\theta = \overline{v_x}x/z_0$ from Eq. (13) is proportional to the distance *x*, as indicated by the thick arrows in the side view of Fig. 3b. These figures therefore show that the Doppler fading can be regarded as an apparent vertical wind shear, adding up coherently on the real vertical wind shear of $\kappa_{zx} z_0 \theta = \kappa_{zx} x$. Further this coupling effect can be either constructive or destructive, depending on the sign of κ_{zx} , or, equivalently, on the flight direction. In other words, the coupling spectral broadening σ_{comb}^2 is determined not only by the magnitudes of the platform velocity and the vertical wind shears, but also by their mutual geometrical configurations (see also section 3b). For ground-based and airborne radars, however, the spectral broadening of Doppler fading is so small that we can generally ignore the coupling effect. As a final comment on $\sigma_{\rm comb}^2$, Eq. (13) indicates that a larger diameter of antenna should be used to increase the coherent time, which arises from reduction in the size of the footprint.





isodopes

FIG. 3. Schematic figures of the effect of Doppler fading: (a) An overview, (b) a side view. The *x* and *z* axes are in the flight direction of a platform and the nadir direction, respectively. (a) The large circle represents the footprint of a radar; the small circles and crosses represents the upward and downward directions of Doppler velocities, respectively. (b) The magnitudes of the Doppler velocities are indicated by the thick arrows. Both (a) and (b) show that the Doppler fading in the Fraunhofer approximation can be regarded as an apparent vertical wind shear.

b. Coherent time on Doppler operation

The spectral broadenings on pulse-pair Doppler operation in Eq. (6) are composed of the following:

- 1) Coupling between the Doppler fading and the vertical wind shears: σ_{comb}^2 .
- 2) Variance of the terminal falling velocity of a cloud particle weighted by $|S(D)|^2$: $\sigma_{\nu fob}^2$.
- 3) Temporal fluctuation of wind velocity and/or fluctuation due to turbulence in the beam direction: σ_{wz}^2 .

In this section, the coherent times of these three elements are estimated.

The first-listed spectral broadening σ_{comb}^2 , defined in Eq. (13), is calculated for the parameters in Table 1. In the case of very weak vertical wind shears, that is, $\kappa_{zx} \approx \kappa_{zy} \approx 0$, we obtain

$$\sigma_{\rm comb}^2 \simeq \frac{\theta_0^2}{2.6} v_{\rm pl}^2 = 14.25 \quad ({\rm m \ s^{-1}})^2, \qquad (16)$$

with the platform velocity v_{pl} and half the beamwidth θ_0 . In the case of relatively strong vertical wind shears, the shear constants can be assumed as $\kappa_{zx} \approx \kappa_{zy} \approx 5 \times 10^{-3} \text{ s}^{-1}$ according to Amayenc et al. (1993). Thus Eq. (13) gives

$$\begin{aligned} \sigma_{\text{comb}}^2 &\simeq \frac{\theta_0^2}{2.6} [(-\upsilon_{\text{pl}} + \kappa_{zx} z_0)^2 + (\kappa_{zy} z_0)^2] \\ &= \begin{cases} 8.3 & \text{for } \kappa_{zx} > 0\\ 25.1 & \text{for } \kappa_{zx} < 0 & (\text{m s}^{-1})^2. \end{cases} \end{aligned}$$
(17)

Equation (17) numerically illustrates the dependence of

TABLE 3. Spectral broadenings σ_{vi}^2 and the corresponding coherent times T_{ci} with weak wind shears and turbulence. Each element σ_{vi}^2 of the spectral broadenings is defined in the text in section 3b. The corresponding coherent time is defined as $T_{ci} = (2k^2\sigma_{vi}^2)^{-1/2}$. The total spectral broadening σ_{tot}^2 and its coherent time T_c are defined as $\sigma_{vot}^2 = \sigma_{comb}^2 + \sigma_{vfob}^2 + \sigma_{vz}^2$ and $T_c = (2k^2\sigma_{to}^2)^{-1/2}$, respectively.

	$\sigma_{vi}^2 ({ m m \ s^{-1}})^2$	T_{ci} (μ s)
$\sigma^2_{\rm comb}$	14.25	95.0
$\sigma_{v_{fob}}^2$	0.25	717
$\sigma^2_{w_7}$	1	358
Total	$\sigma_{\rm tot}^2 = 15.5$	$T_c = 91.1$

the coupling on the sign of κ_{zx} , or equivalently on a flight direction as discussed in the last section.

Here other kinds of wind shears not included in the representation of σ_{comb}^2 should be mentioned. Among them, a radial stretching wind shear represented by $\overline{v_{wz}} + \kappa_{zz}(z - z'_0)$ that has the ability to give the same order contribution as the vertical wind shears κ_{zx} , κ_{zy} do. Its spectral broadening can be estimated using the representation of Doviak and Zrnic (1993):

$$\sigma_{r-\text{str}}^2 \simeq \left(\frac{0.35\kappa_{zz}c\tau_{\text{pulse}}}{2}\right)^2 \sim 0.2 \quad (\text{m s}^{-1})^2, \quad (18)$$

which is seen to be small in comparison with σ_{comb}^2 for the spaceborne radar, and can be practically included within the uncertainty of σ_{comb}^2 .

The second-listed spectral broadening σ_{vfob}^2 due to the variance of the terminal falling velocity is next estimated. Since the data treatment of pulse-pair operation has been proven to correspond to that of FFT operation as described in Eq. (10), the value of $\sigma_{vfob}^2 \approx (0.5)^2$ (m s⁻¹)² measured on FFT operation by Gossard et al. (1997) can be adopted for the evaluation.

The third-listed spectral broadening σ_{wz}^2 from the temporal fluctuation of vertical wind and/or the fluctuation due to turbulence can be estimated as $\sigma_{wz}^2 \approx 1^2 - 4^2$ (m s⁻¹)² according to Amayenc et al. (1993) and Gossard et al. (1997).

In Table 3, the spectral broadenings σ_{vi}^2 (i.e., σ_{comb}^2 , σ_{vfob}^2 , σ_{wz}^2) and the corresponding coherent times $T_{ci} = (2k^2\sigma_{vi}^2)^{-1/2}$ are summarized for the calm weather condition with very weak vertical wind shears (i.e., $\sigma_{wz}^2 \approx 1 \text{ m}^2 \text{ s}^{-2}$, $\kappa_{zx} \approx \kappa_{zy} \approx \kappa_{zz} = 0 \text{ s}^{-1}$). The total spectral broadening σ_{tot}^2 is defined from Eq. (6) as

$$\sigma_{\rm tot}^2 = \sigma_{\rm comb}^2 + \sigma_{\nu fob}^2 + \sigma_{wz}^2, \qquad (19)$$

from which the total coherent time is defined as $T_c = (2k^2\sigma_{tot}^2)^{-1/2}$.

The feasibility of spaceborne Doppler operation should be assessed as a first step for the calm weather condition to recognize the theoretical limit. Thus the further estimations of the accuracy of Doppler velocity will be based on Table 3.

4. Performance of Doppler measurement

a. Accuracy of Doppler velocity

Prior to the calculation of the accuracy of Doppler velocity, conditions on the pulse-pair interval T_s and the pulse-repetition interval T_{pri} will be considered in addition to Eq. (12). Suppose that the beam pointing is controlled by the order of 0.1° , a portion of the platform velocity with the order of 10 m s^{-1} may be contaminated into a measured velocity as will be derived in section 4b(1). To avoid the aliasing of Doppler velocity caused by this contamination, the pulse-pair interval T_s should be restricted so as to give a large dynamical range of Doppler velocity:

$$T_s \leq 70 \ \mu s.$$
 (20)

Furthermore the requirement on the minimum unambiguous range of 15 km places the lower limit of the pulse-repetition interval T_{pri} as

$$100 \ \mu s \le T_{\rm pri}.\tag{21}$$

The conditions of Eqs. (20) and (21) can be satisfied simultaneously on the HV-pair operation, while not on the Cng-pair operation due to the condition of $T_s = T_{pri}$. This fact would tempt us to conclude that the Cng-pair operation can hardly be adopted unless the angle of mispointing beam is controlled by less than 0.1°. However, if information of the mispointing angle is given in advance by some other method such as a combination with the HV-pair-I operation as will be discussed in section 5, then the Cng-pair operation is to be performed for the space mission.

Zrnic (1977) derived an accuracy estimator of Doppler velocity for the general pulse-pair operation with a single polarization, referred to as Gen-pair operation, by a perturbation technique based on a complex Gaussian process (Reed 1962). The pulse pattern of the Genpair operation can be obtained by replacing the orthopolarized pulse pairs in Fig. 1a with the single-polarized ones. The Gen-pair operation itself plays a major role in theoretical analysis of the accuracy. In the following paragraph, the estimator of the Gen-pair operation is summarized on the basis of Doviak and Zrnic (1993).

Suppose that a signal correlation at time t is represented by

$$r(t) = Se^{-(t/T_c)^2} e^{-j2kv_D t} + N\delta(t), \qquad (22)$$

in which T_c is the total coherent time defined in the last section. Here *S* and *N* are powers of signal and noise, respectively. Then the variance of a mean Doppler velocity v_D on the Gen-pair operation is given by this formula:

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$$\operatorname{var}(v_{D}) = \frac{\lambda^{2}}{16\pi^{2}T_{s}^{2}} \times \left\{ \frac{1 - \rho^{2}(T_{s})}{2M^{2}\rho^{2}(T_{s})} \sum_{m=-(M-1)}^{M-1} \rho^{2}(mT_{\text{pri}})(M - |m|) + \frac{N^{2}}{2MS^{2}\rho^{2}(T_{s})} + \frac{N}{MS\rho^{2}(T_{s})} \times \left[1 + \left(1 - \frac{1}{M}\right)\rho(2T_{s})\delta(T - T_{s}) \right] \right\},$$
(23)

in which a normalized correlation function has been defined as

$$\rho(t) = e^{-(t/T_c)^2},$$
(24)

and *M* is the total number of pulse pairs represented through an along-track integration *L* and a platform velocity v_{pl} :

$$M = L/v_{\rm pl}T_{\rm pri}.$$
 (25)

It is noted that Eq. (23) is always applicable to the Cngpair operation because the Gen-pair operation includes the Cng-pair operation as a special case of $T_s = T_{pri}$.

Here we shall consider the application of Eq. (23) to the HV-pair operation. Notice that an explicit correlation signal of Eq. (6) has the same form as Eq. (22) except for the independent white noise term. It indicates that the application of Eq. (23) to the HV-pair operation is identical to that of Eq. (6), which is defined by the conditions of 1) and 2) as discussed in section 3a. Thus in the rest of the paper, these conditions will again be assumed to apply Eqs. (6) and (23), not only to the Cngpair operation but also to the HV-pair one, for the feasibility study.

The accuracies of Doppler velocity are calculated from Eq. (23) as $[var(v_D)]^{1/2}$ on the parameters in Tables 1 and 3. The results are plotted as a function of the pulse-pair interval T_s in Fig. 4 for the HV-pair operation with the pulse-repetition interval $T_{pri} = 222 \ \mu s$, and in Fig. 5 for the Cng-pair operation with $T_s = T_{pri}$. The along-track integrations L are set at 1 and 10 km for Figs. 4a, 5a and 4b, 5b, respectively. Hence the accuracies of Figs. 4b, 5b are smaller than those of Figs. 4a, 5a by a factor of $\approx (10)^{1/2}$, because the accuracy, as a first approximation, is inversely proportional to the square root of the total number of integrations. The curves in each figure are given for clouds of -30 to +20 dBZ corresponding to the SNR of -15 to +35 dB from top to bottom. Notice that the accuracy of v_D is determined by two competitive effects: one of which is the decrease in resolution of Doppler phase at a small T_s and, the other is the deterioration in correlation at a large T_s . The former effect is more important for lower SNRs, and the latter effect is for higher SNRs. For this reason, the minimum point of each curve shifts from high to low values of T_s as the



Pulse pair interval T_s (µsec)

FIG. 4. Accuracy of Doppler velocity vs pulse-pair interval T_s on the HV-pair operation for the 2-m antenna. Here $T_s = 10$ and 60 μ s correspond to the operations HV-pair-I and HV-pair-II indicated in the figure, respectively. The calculation is performed for the parameters of Table 1 with $T_{\rm pri} = 222 \ \mu$ s. Along-track integrations are set at (a) 1 and (b) 10 km.

SNR increases. It is a little bit frowned upon to apply the perturbation method of Eq. (23) to the high noise signals of SNR = -5 dB (clouds of -20 dBZ) and SNR = -15 dB (clouds of -30 dBZ). This point will be revisited later in section 5.

On the basis of these calculations, appropriate values of T_s are to be selected for the spaceborne mission. First we shall start with the HV-pair operation plotted in Fig. 4. It is noted that the adopted pulse-repetition interval $T_{\rm pri} = 222 \ \mu s$ satisfies the condition of Eq. (21). In view of a large dynamical range of Doppler velocity and good coherence, a short pulse-pair interval $T_s = 10 \ \mu s$ is preferably chosen, referred to as the HV-pair-I operation. This operation well satisfies the convergence condition of Eq. (12), and the other condition of Eq. (20) on T_s . The pulse-pair interval $T_s = 60 \ \mu s$ can also be chosen for another appropriate operation, referred to as the HV-pair-II operation, due to the following reasons. Figure 4 shows that for the clouds of -10 dBZ with the relatively low SNR = 5 dB, the optimal point of the accuracy is given for about $T_s = 60 \ \mu s$. Moreover



Pulse pair interval $T_s (= T_{pri})$ (µsec)

FIG. 5. Accuracy of Doppler velocity vs pulse-pair interval T_s on the Cng-pair operation for the 2-m antenna diameter. The calculation is performed for the parameters of Table 1 with $T_{pri} = T_s$. Along-track integrations are set at (a) 1 and (b) 10 km. The range of $T_s = 100-125 \ \mu s$ indicated by the arrows is appropriate with respect to the accuracy and the unambiguous range.

this value still satisfies the conditions of Eqs. (12) and (20). The characteristics of the HV-pair-I and -II operations with the 2-m antenna are summarized in the first and second portions of Table 4.

Second, the Cng-pair operation in Fig. 5 shall be considered. The appropriate range of T_s can be chosen as $T_s = 100-125 \ \mu s$ satisfying the convergence condition of Eq. (12). The upper limit of $T_s = 125 \ \mu s$ has been determined from Fig. 5a by the fact that beyond $T_s =$ $125 \ \mu s$ the accuracies deviate more from $\approx 1 \ m \ s^{-1}$ for clouds of $-20 \ dBZ$. The lower limit of $T_s = 100 \ \mu s$ comes from the condition of Eq. (21) along with $T_s =$ $T_{\rm pri}$. The characteristics of the Cng-pair operation with the 2-m antenna are also found in the first and second portions of Table 4. Since this operation is accompanied by trade-off between the unambiguous range and the accuracy, an optimal value of T_s should be chosen from the range of $100-125 \ \mu s$, depending on a detailed mission requirement.

The accuracy of Doppler velocity should further be calculated to a larger antenna to improve both the spectral broadening and the antenna gain. The feasible antenna diameter is limited by the fairing size of a launcher. Suppose that a Japanese H-IIA Launcher is used, it allows us to design a circular antenna of 4-m diameter. The results of calculated accuracy with the 4-m antenna are shown in Fig. 6a for the HV-pair operation (HVpair-I and -II), and in Fig. 6b for the Cng-pair operation. Both the figures are plotted only for the alongtrack integration of L = 1 km. The appropriate range of T_s on the Cng-pair operation can be extended to T_s = 100–150 μ s. The upper limit of $T_s = 150 \ \mu$ s has been roughly determined by the convergence condition of Eq. (12) rather than by the accuracy. The substantial improvement in velocity accuracy is seen, reaching less than 0.25 m s⁻¹ for clouds of -20 dBZ on both the HV-pair-II and Cng-pair operations with the alongtrack integration of L = 1 km. These accuracies can be reduced to less than 0.1 m s⁻¹ for L = 10 km (Table 4). The characteristics of the operations with the 4-m antenna are shown in the first and third portions of Table 4.

Advantages and disadvantages of the three operations in view of the objectives 1)–3) listed in the introduction will be discussed in section 5.

b. Consideration of miscellaneous effects

1) BEAM-POINTING ERROR

A geometrical consideration shows that the following replacements on the x and z componential terms of Eq. (3) must be performed for a beam mispointing (off nadir) angle θ_t of the order of 0.1° toward the flight direction:

$$\boldsymbol{v}_{wx} - \boldsymbol{v}_{pl} \rightarrow (\boldsymbol{v}_{wx} - \boldsymbol{v}_{pl}) - (\boldsymbol{v}_{wz} + \boldsymbol{v}_f)\boldsymbol{\theta}_t$$
$$\boldsymbol{v}_{wz} + \boldsymbol{v}_f \rightarrow (\boldsymbol{v}_{wx} - \boldsymbol{v}_{pl})\boldsymbol{\theta}_t + (\boldsymbol{v}_{wz} + \boldsymbol{v}_f). \quad (26)$$

Strictly, there also exists an azimuthal mispointing angle $\varphi_t \ll 1$. However, the contributions from φ_t are of second-order small quantity, not appearing in Eq. (26). The effects of substitution of Eqs. (26) into (6) can be neglected except for the phase term of

$$\exp[-j2k(\overline{v_{\text{fob}}} + \overline{v_{wz}})] \tag{27}$$

being converted to

$$\exp\{-j2k[\overline{v_{\text{fob}}} + \overline{v_{wz}} + \theta_t(v_{wx} - v_{\text{pl}})]\}$$
$$\simeq \exp[-j2k(\overline{v_{\text{fob}}} + \overline{v_{wz}} - \theta_t v_{\text{pl}})]. \tag{28}$$

The measured Doppler velocity v_{mes} from clouds can therefore be written in the form of

$$\boldsymbol{v}_{\text{mes}} = \overline{\boldsymbol{v}_{\text{fob}}} + \overline{\boldsymbol{v}_{wz}} - \theta_t \boldsymbol{v}_{\text{pl}}.$$
 (29)

The last offset term in Eq. (29) has the order of 10 m s⁻¹, which is much larger than the other terms of $\overline{v_{fob}}$

TABLE 4. Characteristics of three pulse-pair Doppler operations. The specifications of the operations are tabulated in the first portion.	For
the Cng-pair operation, the quantities for the 2-m antenna are written first, and those for the 4-m antenna are found in the parens.	The
altitudes disturbed by the ground clutter are also tabulated in the first protion. The accuracy of Doppler velocity over the along-tr	ack
integrations of 1 and 10 km are summarized for the two antenna diameters of 2 and 4 m in the second and third portions, respectively.	

	1) HV-pair-I	2) HV-pair-II	3) Cng-pair
Pulse-pair interval T_s (µs)	10	60	100-125 (100-150)
Pulse-repetition interval $T_{\rm pri}$ (µs)	222	222	100–125 (100–150)
Dynamic range of Doppler velocity $(m s)^{-1}$	75	12.5	7.9–6.4 (7.9–5.3)
Unambiguous range (km)	33	33	15-18.8 (15-22.5)
Altitude of the ground scatter (km)	1.5	9	15-18.8 (15-22.5)
Maximum receiving range (km)	31.3	23.8	14.5–18.3 (14.5–22)
Velocity precision (m s ⁻¹) for the antenna of ϕ 2 m Clouds of -10 dBZ			
Integration distance of 1 km	0.68	0.22	0.23-0.40
Integration distance of 10 km	0.21	0.070	0.07-0.13
Clouds of -20 dBZ			
Integration distance of 1 km	3.19	0.82	0.73-1.30
Integration distance of 10 km	1.01	0.26	0.22-0.41
Velocity precision (m s ⁻¹) for the antenna of ϕ 4 m Clouds of -10 dBZ			
Integration distance of 1 km	0.32	0.092	0.08-0.11
Integration distance of 10 km	0.10	0.029	0.02-0.03
Clouds of -20 dBZ			
Integration distance of 1 km	1.16	0.23	0.13-0.18
Integration distance of 10 km	0.37	0.073	0.04-0.06
Clouds of -30 dBZ			
Integration distance of 1 km	7.00	1.33	0.67-0.90
Integration distance of 10 km	2.21	0.42	0.21-0.28

 $\sim \overline{v_{wz}} \sim 1 \text{ m s}^{-1}$ for the usual weather condition. This undesirable offset must be subtracted, for instance, by calculating the angle θ_i through echoes from sea surface, which will be discussed in section 5. To ease this procedure, the dynamical range of Doppler velocity should be chosen over 10 m s⁻¹, corresponding to the pulsepair interval less than $T_s = 70 \ \mu s$ as was earlier defined in Eq. (20).

2) VERTICAL VELOCITY OF THE SATELLITE

Depending on an orbit, it is necessary to consider the effect of the vertical velocity of a platform caused by change in a satellite altitude due to the earth's oblateness, or equivalently the effect of a nonzero flight angle to the geoid surface. The order of this velocity is 20 m s⁻¹ at maximum. If the position and velocity of the satellite is known, it is possible to correct this effect.

3) GROUND CLUTTER ON PULSE-PAIR DOPPLER OPERATION

The ground clutter is one of the largest obstacles on pulse-pair Doppler operation. A previous experiment of the SPIDER (Horie et al. 2000) showed that a measured power of the clutters from sea surfaces corresponds to the power reflected from clouds of +50 dBZ in copolarization, while in cross polarization, the power reflected is $+20 \, \text{dBZ}$ including leakage through the microwave circuit. The effect of ground clutter can be read from a bounce diagram of Fig. 7. Let ground surface be the range distance of ct_{g} . The τ_{p} and T_{s} denote a pulse duration and a pulse-pair interval, respectively. Then the leading edge of the first pulse reflected at the point G_1 on the ground will pollute the cloud signal of the second pulse scattered along the line A₁B₁ in the timedistance space. In the same manner, the trailing edge reflected at the point G₂ on the ground will pollute the second signal along the line A₂B₂. As a result, the second-pulse signals circumscribed by the rhombohedral $A_1A_2B_2B_1$ are disturbed by the ground clutter of the first pulse. These disturbed signals therefore extend in the second pulse at the altitude of $cT_s/2$ with the range width of $c\tau_p/2$. As far as only the average of Doppler velocity is concerned, this disturbance on the averaged velocity can be theoretically removed after some ensemble or temporal averages, because the ground clutters are uncorrelated to the cloud signals. However, when considering the accuracy, the disturbance will remain as apparent noises, tremendously deteriorating the quality of measurement. Hence pulse patterns should be designed to reduce the effect of the ground clutter on the targeted range. The altitudes disturbed by the ground clutter for the three operations are also summarized in the first portion of Table 4.



Pulse pair interval T_s (µsec)

FIG. 6. Accuracy of Doppler velocity vs pulse-pair interval T_s for the 4-m antenna. The parameters are the same as in Table 1 except for those related to the antenna diameter. An along-track integration is 1 km. (a) For the HV-pair operation: HV-pair-I and HV-pair-II operations are indicated by the broken lines. (b) For the Cng-pair operation: The range of $T_s = 100-150 \ \mu s$ indicated by the arrows is appropriate with respect to the unambiguous range and the convergence condition of Eq. (12).

4) SIDELOBE EFFECT

Related to the ground clutter, the sidelobe effect is briefly considered. In Table 5, the angle θ_{side} and the power amplitude P_{side} of the *n*th sidelobe for the circular antenna of 2-m diameter are tabulated in reference to the main lobe. The delay Δt in receiving time of the sidelobe to the main lobe is also tabulated for a platform at the altitude $h_{\text{sat}} = 450$ km. If a ground clutter of the main lobe is measured with -40 dBm, that of the ninth sidelobe will appear as -120 dBm from Table 5, which is the same level as the signal from clouds of -30 dBZas shown in Table 2. Thus, even the ninth sidelobe may disturb the cloud signal. This sidelobe effect can also be illustrated in the bounce diagram of Fig. 7. The ground clutter effects up to the ninth sidelobes practically extend the section G_1G_2 of the main lobe to the section G_1G_s by about 0.3 μ s. It yields another 0.45-



FIG. 7. Bounce diagram of ground clutters. Here $ct_g/2$ represents a range of the ground. Here τ_p and T_s denote a pulse duration and a pulse-pair interval, respectively. The ground clutter of the first pulse seeps into the cloud signals of the second pulse circumscribed by the rhombohedral region $A_1B_1B_2A_2$. The broken line originated from point G_s represents the effects of the ground clutters due to the 9th sidelobes.

km region of degraded data indicated by the broken line in Fig. 7.

5. Discussion and conclusions

Doppler operation in the nadir direction from a spaceborne cloud-profiling radar has been considered. The calculation of the effective signal-to-noise ratio SNR_{eff} for clouds of -30 dBZ on the non-Doppler operations with the 2-m antenna reaches to SNR_{eff} = 3 dB after *N* = 6000 integrations as shown in Table 2. It suggests that an along-track integration must be on the order of 10 km to acquire the precise Doppler data for clouds of -30 dBZ.

The more rigorous evaluations for the Doppler operations were performed on the three different operations with the 2- and 4-m antennas as summarized in Table 4. The adverse issues common between the three operations are the mispointing beam and the ground clutter.

The first issue depends on the beam-controlling ability. Unfortunately the present technology provides at most the beam-pointing accuracy of 0.1°. The consideration in section 4b(1) shows that the effect of the mispointing angle $(v_{\rm pl}\theta_t)$ must be removed from a measured Doppler velocity $v_{\rm mes}$ in Eq. (29) to determine a

TABLE 5. Sidelobes of the circular antenna of 2-m diameter: The angle θ_{side} and the power P_{side} of the *n*th sidelobe are tabulated in reference to the main lobe. The delay time Δt in receiving time to the main lobe is also calculated for the altitude of 450 km.

	$ heta_{ m side}$	$P_{\rm side}$	Δt (ns)
1st	0.149°	-35 dB	10
2nd	0.245°	-47 dB	27
3rd	0.338°	-55 dB	52
9th	0.888°	-81 dB	361



FIG. 8. A schematic diagram of combined Cng-pair operation intended to the space mission. The main pulse of the polarization H is transmitted with a pulse-pair interval of $T_{\rm sc} = T_{\rm pri}$. Pulse pairs of orthopolarization with a shorter $T_{\rm sp}$ are inserted intermittently among the main pulses with a repetition interval of $T_{\rm int} \gg T_{\rm pri}$. This orthopolarized pulse pair will be used to correct the beam-mispointing effect.

cloud velocity $(\overline{v_{fob}} + \overline{v_{wz}})$ in the beam direction. A key to the angle θ_t is to use the Doppler signal from a sea surface echo. If the velocity of a satellite v_{pl} and its flight angle $\theta_{sat} \ll 1$ to the geoid surface are known in advance, then the mispointing angle θ_t ($\ll 1$) can be obtained from a measured Doppler velocity v_{sea} of the sea surface echo through the relation of

$$\boldsymbol{v}_{\rm pl}\boldsymbol{\theta}_t = -\boldsymbol{v}_{\rm sea} + \boldsymbol{v}_{\rm pl}\boldsymbol{\theta}_{\rm sat}.$$
 (30)

Because of $|v_{\rm pl}\theta_t| \approx 10$ m s⁻¹, the short pulse-pair interval $T_s \leq 70 \ \mu s$ defined in Eq. (20) is advantageous to increase the dynamical range of velocity. From this viewpoint, the HV-pair-I operation is best, the HV-pair-II operation is critical, and the Cng-pair operation is not suitable. However, as briefly mentioned in section 4a, when the Cng-pair operation is combined to the HV-pair-I operation, the former operation turns feasible along with the correction of the mispointing beam by polarized pulse pairs. A schematic diagram of this combined operation is drawn in Fig. 8, in which the main pulses of the H polarization are transmitted with a pulse-pair interval of $T_{\rm sc} = T_{\rm pri}$. Pulse pairs of orthopolarization with a shorter interval $T_{\rm sp}$ are inserted intermittently among the main pulses with a repetition interval T_{int} ($\gg T_{pri}$). The optimal pulse pattern should be the subject of the future, accompanied with the determination of a satellite orbit. Strictly speaking, degradation in the accuracy of Doppler velocity is induced by the reduction in the total integration number *M* due to the insertion of polarized pulse pairs. In actual, this degradation can be ignored for $T_{int} \gg T_{pri}$ because the accuracy is inversely proportional to \sqrt{M} rather than M. As far as we adopt this combined Cng-pair operation despite of its complicated implementation, the three kinds of operations (HV-pair-I, HV-pair-II, Cng-pair) can be compared in terms of the accuracy and the ground clutter effect in light of the scientific objectives 1)-3) in the introduction.

The accuracy requirement of objective 1) (introduction) is satisfied by the HV-pair-II and Cng-pair operations with the 4-m antenna as shown in Table 4. However the HV-pair-II has the ground clutter effect around the altitude of 9 km, in which cirrus may exist. Hence only the Cng-pair operation with the 4-m antenna will achieve objective 1) (introduction) with respect to the accuracy and ground clutter effect. Notice that none of the operations with the 2-m antenna achieve objective 1) (introduction).

The accuracy requirement of objective 2) (introduction) is satisfied for all the operations when the 4-m antenna is used. However, the HV-pair-I operation has the ground clutter around the altitude 1.5 km near the targeted drizzles and water clouds. As a consequence, the HV-pair-II and Cng-pair operations with the 4-m antenna will achieve objective 2) (introduction) with respect to the accuracy and the ground clutter effect. For the 2-m antenna, the HV-pair-II and Cng-pair operations barely satisfy the requirement.

Objective 3) (introduction) can be achieved by the HV-pair-II and Cng-pair operations with the 4-m antenna, though the former operation cannot be applied to the altitude of 9 km due to the ground clutter effect. Considering the operations with the 2-m antenna, the HV-pair-II satisfies the requirement of 3) again except around the altitude of 9 km. The Cng-pair operation with the 2-m antenna critically satisfies this requirement with severe trade-offs between the maximum receiving range (the unambiguous range) and the accuracy. If a range requirement is near 20 km, then this operation will fail.

Total conclusions can be summarized as follows. For all the objectives 1)-3) in the introduction, the Cng-pair operation with the 4-m antenna can be considered as the best in terms of the accuracy and the ground clutter effect. This choice is also advantageous in the different viewpoint that the Cng-pair operation can be applied to ice particles observed at high altitudes for objectives 1)-3 (introduction), regardless of the condition of 2) in section 3a. On the other hands the HV-pair-II operation is generally appropriate for a low altitude of 1-2km. First of all, the HV-pair-II operation has no ground clutter effect at this altitude. Second, clouds at this altitude are expected to be composed of liquid particles, which certainly guarantees condition 1) in section 3a. Third, the maximum receiving range of the HV-pair-II operation is larger than that of the Cng-pair operation. Fourth, its relatively wide dynamical range of Doppler velocity can guarantee simpler implementation in comparison with the Cng-pair operation, which is to be combined to the HV-pair operation. For these reasons, as far as only objective 2) (in the introduction) is concerned, the HV-pair-II operation with the 4-m antenna is best. In the same manner, when objective 3) (in the introduction) is performed only at a low altitude of 1-2 km, the HV-pair-II operation can be regarded as the best for both the 2- and 4-m antennas.

In this paper, the antenna diameters of 2 and 4 m have been chosen to clarify the limit of accuracy in Doppler velocity to accomplish objectives 1)–3) (in the introduction). In a general space mission, an antenna size will be determined by the balance between mission requirements and the fairing size of an assigned launcher.



FIG. 9. A schematic diagram of a variable $T_{\rm pri}$ operation. A satellite altitude is set at $h_{\rm sat} = 450$ km. The first pulse reflected on the ground surface is received at the position of 96 μ s near the trailing edge of received signals between the 24th and 25th pulses. As the $h_{\rm sat}$ increases with geolatitude, the receiving window will move toward the 25th pulse for a fixed $T_{\rm pri}$. In contrast, on varying the $T_{\rm pri}$ as a function of geolatitude (i.e., satellite altitude), the receiving window will remain in a restricted region between the pulses.

Hence the best operation will change depending on the chosen antenna size.

In general, the perturbation method is subject to be jeopardized for the low SNRs as mentioned in section 4a. E. Im, (2001, personal communication) has recently showed from simulations that the perturbation method can be effective for the signals of up to SNR = 0 dB for the $T_s \approx 60 \ \mu s$ with spaceborne parameters. This kind of simulation should be applied to the lower SNRs in the future because negative SNRs play an important role in the space mission.

For any of the three operations, a variable $T_{\rm pri}$ had better be adopted as schematically drawn in Fig. 9. In the figure, suppose that a Cng-pair operation is performed on the equator with a satellite altitude of $h_{\rm sat} = 450$ km and the pulse parameters of $T_s = T_{\rm pri} = 121 \ \mu s$, then the ground clutters are received at the position of 96 μs near the trailing edge of the received signals between the 24th and 25th pulses. Here the received position has been derived from the equation of

$$t_{\rm gnd} = 2 \ h_{\rm sat}/c \approx 121 \times 24 + 96 \ (\mu s).$$
 (31)

As the satellite moves to a higher geolatitude, the increase in the satellite altitude h_{sat} shifts the receiving position toward the 25th pulse, eventually thrusting a portion of the received signals into the 25th pulse. Since the receiving circuit on the radar is blocked during transmission, cloud information at the altitude corresponding to the 25th transmission pulse and its guard times will be lost. To avoid this issue, we should vary the value of $T_{\rm pri}$ as a function of geolatitude to allow the reflected signal to always be received at some restricted region between the 24th and 25th pulses. Ideally, a value of $T_{\rm pri}$ is to be chosen so that the surface signal is received as close to the 25th pulse as technically possible. Here the variable $T_{\rm pri}$ operation has been described for a Cngpair operation rather illustratively to show its concept. On an actual space mission, however, the value of $T_{\rm pri}$ should be varied discretely rather than continuously at

predetermined geolatitudes due to technological problems. As a further note regarding the Cng-pair operation that is to be combined to the HV-pair-I operation, the pulse-repetition interval of the HV pairs, that is, T_{int} in Fig. 8, must be varied with synchronization to the T_{pri} . The other pulse-pair interval T_{sp} of an HV pair is not necessarily varied. Consequently, the possibility of the variable T_{pri} operation should be intensively studied in the future, accompanied by the determination of a satellite orbit.

Finally, an issue appearing on the left-hand side of Eq. (28) is discussed. In the preceding sections, the contribution from the horizontal wind represented by $\theta_{\nu}v_{\mu\nu}$ has been ignored. This is because the value of $\theta_t v_{wx}$ is negligible for the horizontal wind v_{wx} on the order of 10 m s⁻¹. However in the case of $v_{wx} \approx 100$ m s⁻¹, the contribution of $\theta_t v_{wx} \approx 0.1$ m s⁻¹ must be taken into account as a systematic bias/error. Unfortunately there is no way to distinguish this $\theta_t v_{wx}$ from the targeted velocity of $\overline{v_{fob}} + \overline{v_{wz}}$ as long as the pulse-pair operation is performed by a single and fixed beam. A solution to this difficulty is to adopt dual-beam operation proposed by Amayenc et al. (1993) or to artificially incline the beam angle for measuring the horizontal velocity v_{wx} . Despite this defect, pulse-pair Doppler operation by a single beam in the nadir direction is valuable to provide both scientific and technical verifications and advancements for future research including the dual-beam operation.

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