Measuring Vertical Rainfall Velocity through Spaceborne Doppler Radar: Performance Analysis and System Requirements

Simone Tanelli[1], Eastwood Im[1], Stephen L. Durden[1], Luca Facheris[2]

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA
2. Dipartimento di Ingegneria Elettronica - Università di Firenze - Via di S. Marta, 3 50139 Firenze - Italy

Phone No.: 1-818-354-0492 Email: eastwood.im@jpl.nasa.gov

Abstract - In this paper we will present the results of the trade studies on the performances of a spaceborne Doppler radar in measuring vertical rainfall velocity. Particular emphases will be placed on: 1) the choice of the PRF vs. antenna size ratio, 2) the choice of the observational strategy, 3) the choice of the operating frequency; and the 4) processing strategy. The results show that accuracies of 1 m/s or better can be achieved with the currently available technology and with careful selection the system parameters.

1. INTRODUCTION

Knowledge of the global distribution of the vertical velocity of precipitation is important in estimating latent heat fluxes, and therefore in the general study of energy transportation in the atmosphere. Such knowledge can only be acquired with the use of spaceborne Doppler precipitation radars. Although the high relative speed of the radar with respect to the rainfall particles introduces significant broadening in the Doppler spectrum, recent studies have proven that the average vertical velocity can be measured to acceptable accuracy levels by appropriate selection of radar parameters and of the spectral moments estimator [1,2]. Furthermore, methods to correct for specific errors arising from NUBF effects [2,3] and pointing uncertainties have recently been developed [4]. In this paper the system performances are analyzed accounting for all the aforementioned sources of error and the use of the corresponding correcting techniques. Several configurations are analyzed within the category of single-antenna, cross-track scanning, narrow-beam (i.e., antenna 3dB beamwidth $\theta_{3dB} < 1°$), pulse Doppler radars mounted on a Low Earth Orbit spacecraft – this cathegory will be referred to as DPR in the remainder of this paper.

2. VERTICAL VELOCITY ESTIMATION IN IDEAL CONDITIONS

The shape of the Doppler spectrum observable from a DPR is determined by the velocity of all the raindrops within a volume of resolution relative to the radar. The high linear velocity of the spacecraft ($v_s \sim 7$ km/s) is the main contribution to such relative velocity even for very small forward/aft angles (*e.g.*, a non-moving target seen by DPR at an off-nadir angle of $\theta = 0.05°$ and a zero azimuth with respect to the line of flight has an apparent velocity of ~6 m/s). For this reason when the raindrops are homogeneously distributed within the volume of resolution, the Doppler spectrum is determined mainly by the two-way antenna pattern [2,5,6]. In general it is well approximated by a Gaussian with width w (in m/s):

$$w = \sqrt{\sigma_R^2 + (\theta_{3dB} v_s)^2 / [16\ln(2)]} \qquad (1)$$

where σ_R is the spread of rainfall velocity due to spread of terminal velocities, wind shear and turbulence (typically ranging from 1 to 5 m/s [5]). The Doppler spectrum is measured by processing radar pulses transmitted with a Pulse Repetition Frequency (*PRF*) at the operating wavelength λ, therefore the performances of any spectral moment estimator are better evaluated by considering the normalized spectral width $w_N = w/(2v_m)$ where $v_m = (PRF\ \lambda/4)$ is the maximum unambiguous Doppler velocity.

Ground based and airborne radars are typically designed in order to have $w_N < 0.1$ (narrow spectrum). Table 1 shows the w_N resulting from a set of possible spaceborne configurations. In Table 1, the maximum *PRF* is set by the requirement on the minimum unambiguous range: $PRF < (c/2H)\cos(\beta)$ where H is the troposphere thickness, β is the maximum cross-track scanning angle, and c is the speed of light. The three selected operating frequencies are the radar frequencies (currently or planned) in use on several precipitation/cloud spaceborne missions (*e.g.*, TRMM, CloudSat, GPM). Three atmospheric conditions are considered: σ_R=1 m/s little/no-turbulence, σ_R=3 m/s moderate turbulence and σ_R=5 m/s strong turbulence. The approximate antenna beamwidth is calculated as $\theta_{3dB} = 1.2\ \lambda/D$.

To estimate precipitation vertical velocity, configurations leading to $w_N \geq 0.3$ are of no use (spectrum heavily aliased and almost white). The 2 m size antenna (such as in TRMM and GPM) is therefore not suitable for Doppler measurements. At the other extreme all configurations leading to $w_N < 0.1$ (narrow spectrum) require the use of a very large antenna. On the other hand several configurations lead to $0.1 < w_N < 0.3$ (broad spectrum). The performances of Pulse Pair processor (PP) and Fourier based (DFT) spectral moment estimators are described in [1,7], the main indications drawn by analyzing the results shown in Figure 1 are:

- the range of vertical velocities that can be estimated without appreciable bias is:

$$|v| < (PRF\lambda/2)\cdot(0.5 - \alpha_0 w_N^2) \qquad (2)$$

where $\alpha_0=4$ for the PP and $\alpha_0=5$ for an iterative DFT [1,2,4].

σ_R	Ku band (13.6 GHz)							Ka band (35 GHz)							W band (94 GHz)						
	D	*2*	*3*	*4*	*5*	*6*	*10*	*D*	*2*	*3*	*4*	*5*	*6*	*10*	*D*	*2*	*3*	*4*	*5*	*6*	*10*
	θ_{3dB}	*.76*	*.51*	*.38*	*.30*	*.25*	*.15*	θ_{3dB}	*.29*	*.20*	*.15*	*.12*	*.10*	*.06*	θ_{3dB}	*.11*	*.07*	*.05*	*.04*	*.04*	*.02*
	PRF							**PRF**							**PRF**						
	5000	.50	.34	.25	.20	.17	.10	**5000**	.51	.34	.26	.21	.17	.11	**5000**	.52	.36	.28	.24	.21	.16
1	**6000**	.42	.28	.21	.17	.14	.09	**6000**	.42	.28	.21	.17	.15	.09	**6000**	.43	.30	.23	.20	.17	.13
	7000	.36	.24	.18	.14	.12	.07	**7000**	.36	.24	.18	.15	.12	.08	**7000**	.37	.26	.20	.17	.15	.11
	8000	.32	.21	.16	.13	.11	.06	**8000**	.32	.21	.16	.13	.11	.07	**8000**	.32	.22	.18	.15	.13	.10
	PRF							**PRF**							**PRF**						
	5000	.51	.34	.26	.21	.18	.11	**5000**	.52	.36	.29	.25	.22	.17	**5000**	.63	.50	.45	.43	.41	.39
3	**6000**	.42	.28	.22	.17	.15	.10	**6000**	.44	.30	.24	.20	.18	.14	**6000**	.52	.42	.38	.36	.34	.32
	7000	.36	.24	.18	.15	.13	.08	**7000**	.37	.26	.21	.18	.16	.12	**7000**	.45	.36	.32	.30	.29	.28
	8000	.32	.21	.16	.13	.11	.07	**8000**	.33	.23	.18	.15	.14	.11	**8000**	.39	.32	.28	.27	.26	.24
	PRF							**PRF**							**PRF**						
	5000	.51	.35	.27	.22	.19	.14	**5000**	.56	.41	.34	.31	.29	.25	**5000**	.80	.71	.68	.66	.65	.63
5	**6000**	.43	.29	.22	.18	.16	.11	**6000**	.46	.34	.29	.26	.24	.21	**6000**	.67	.59	.56	.55	.54	.53
	7000	.37	.25	.19	.16	.14	.10	**7000**	.40	.29	.25	.22	.21	.18	**7000**	.57	.51	.48	.47	.46	.45
	8000	.32	.22	.17	.14	.12	.08	**8000**	.35	.26	.21	.19	.18	.16	**8000**	.50	.44	.42	.41	.41	.40

Table 1. Normalized spectral widths w_N for different configurations of the radar system. D is the antenna diameter [m], θ_{3dB} [deg] is the corresponding antenna 3dB beamwidth (in radians: $\theta_{3dB} = 1.2\ \lambda/D$ where λ is the operating wavelength), PRF [Hz] is the Pulse Repetition Frequency. Also, three atmospheric configurations are considered: σ_R=1 m/s little/no-turbulence, σ_R=3 m/s moderate turbulence and σ_R=5 m/s strong turbulence (note: σ_R includes also the spread of the terminal velocities of drops with different diameter).

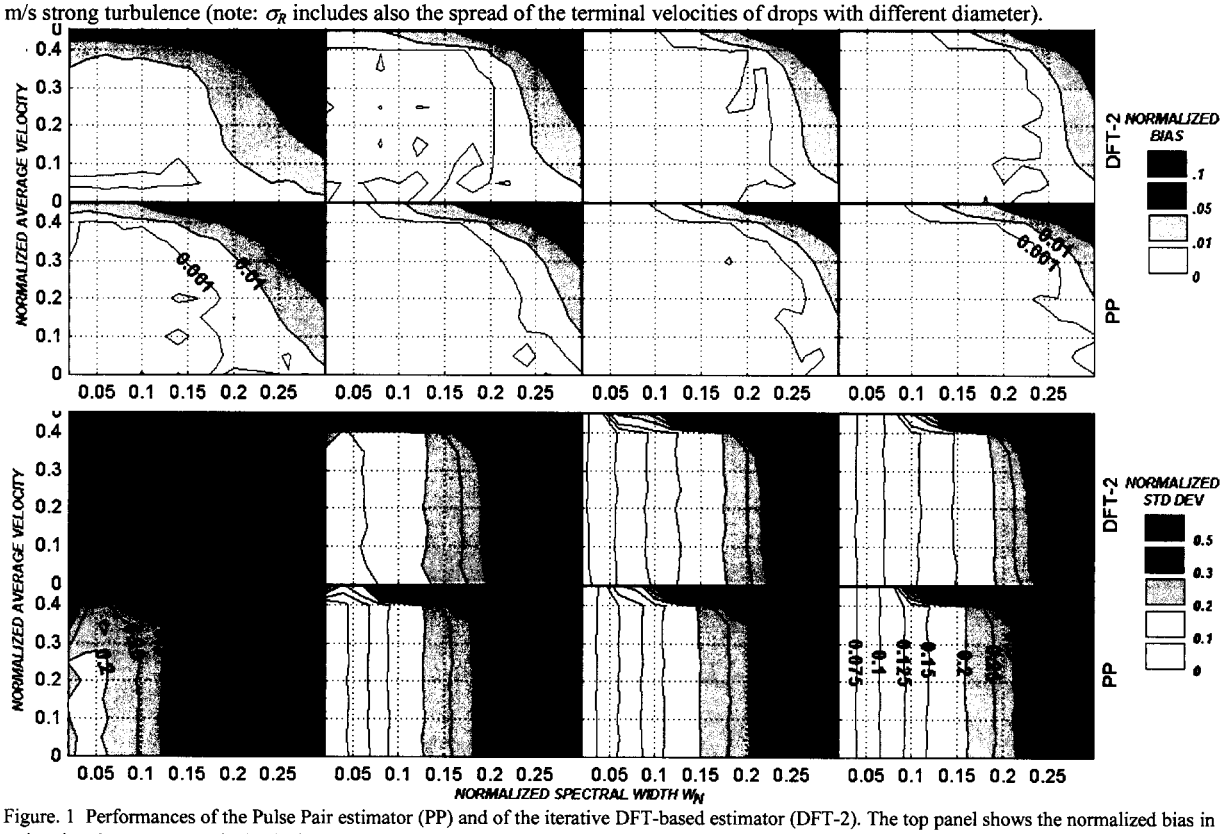

Figure. 1 Performances of the Pulse Pair estimator (PP) and of the iterative DFT-based estimator (DFT-2). The top panel shows the normalized bias in estimating the average vertical velocity, the normalizing factor is PRFλ/2. The bottom panel shows the normalized standard deviation, the normalizing factor here is $M^{0.5}$ PRFλ/2. These performances were obtained using M = 64, the generalization of this result to different M is discussed in [1].

- within the aforementioned range the variance on the PP estimates of the vertical velocity is smaller than DFT estimates for $w_N < 0.1$ but it is generally larger for $0.1 < w_N < 0.25$. For $w_N > 0.25$ the performances of both algorithms degrade rapidly and reliable estimates can be obtained only using very large M. Also, performances of both algorithms degrade rapidly for SNR < 5dB (DFT being the most affected). Overall, in the range $0.1 < w_N < 0.25$ the PP algorithms grants a somewhat wider range of applicability but DFT grants smaller variances on the estimates.

Besides the antenna size, the PRF and the SNR, two more parameters affect the performances of DPR: the operating wavelength λ and the number of processed samples per estimate M.

The choice of operating frequency is mainly determined by the kind of hydrometeors to be observed, and in particular, by their average size. In general, we note that, for a given antenna size, higher frequencies result in narrower θ_{3dB} and smaller v_m. From (1) follows that if $\sigma_R = 0$ the choice of λ does not affect w_N. However, as shown in Table 1, this is not the case for $\sigma_R > 0$. While the spectrum width for Ku and Ka band is only marginally sensitive to the atmospheric conditions, the spectrum width for a W band radar is sufficiently narrow only for the smaller values of σ_R. On the other hand, note that smaller v_m leads to smaller uncertainties in velocity estimates for the same w_N.

As shown in Figure 1, the variance in vertical velocity estimates is $\propto 1/M$. The upper limit of M, under the assumption of an homogeneous rainfall field, is determined mainly by the scanning requirements:

$$M \leq (h_s \theta_{3dB} PRF)/(v_s M_B) \qquad (3)$$

where M_B is the number of beams in one cross track scan and h_s is the satellite altuitude. However, as shown in the next section, this is not the case under more general conditions.

2. VERTICAL VELOCITY ESTIMATION IN NON-IDEAL CONDITIONS

The effects of Nonuniform Beam Filling (NUBF) and of pointing uncertainties (PU) have been analyzed in [2], [3] and [4]. It was found that the bias introduced on vertical velocity estimates by NUBF and PU can often reach values of several m/s, however, the Combined Time Frequency (CFT) correction technique capable of removing these biases was developed. Such technique relies on the joint time-Doppler frequency analysis of the measured spectra, which have to be acquired from volumes of resolution with significant overlapping in the along-track direction. The CFT (applied to either homogeneous or non-homogeneous rainfields) performs comparably to the DFT applied to homogeneous rainfields. CFT processes each spectrum from a contiguous series of M samples, and its capabilities of removing NUBF effects depend on the Fourier analysis of a sufficient number M_S of spectra insisting on the same target $M_S = h_s PRF^2 \lambda /(2v_s^2 MM_B)$. In particular, optimum CFT performances are obtained for:

$$M^2 \approx (\lambda/2) h_s PRF^2 / v_s^2 \qquad (4)$$

and $M_B = 1$ (*i.e.*, nadir looking radar) so that $M_S \sim M$. However, the synthetic along-track resolution resulting from this condition (*i.e.*, $\Delta_{x0} = IFOV/M$) is often unnecessary for most science goals. It has been found that weighted moving average over a larger horizontal resolution Δ_x improves the estimate variances. The number of equivalent samples in CFT is given by the total number of pulses transmitted per Δ_x per antenna cross-track scanning position:

$$M_C = \Delta_x PRF/(v_s M_B) \qquad (3)$$

and M_C can be used (in place of M) to derive CFT performances from Figure 1. It is therefore possible to allow $M_B > 1$ allowing some cross-track scanning capabilities (note: M_S must always be large enough to perform Fourier analysis of each sequence of spectra, say $M_S > 16$).

Note that the limits imposed by CFT are more stringent for higher operating frequencies, however, such frequencies result also in smaller beamwidths and therefore reduced NUBF effects.

In [4] a sample radar system configuration was used to show that the CFT technique can be successfully applied to sea surface Doppler spectra to correct for velocity bias due to pointing uncertainties. Oscillations below 0.5 Hz in the true pointing can be removed through CFT even when in presence of significant and non-homogeneous rain induced attenuation (which, instead, introduces significant errors in pointing estimates obtained through standard DFT processing of the sea surface).

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