TDC 4/17

Spaceborne Radar Measurements of Vertical Rainfall Velocity: The Non-uniform Beam Filling Considerations

Simone Tanelli,[1] Eastwood Im,[2] Stephen L. Durden,[2]
Luca Facheris,[1] Dino Giuli,[1] Ziad S. Haddad[2], Eric A. Smith[3]

1. Dipartimento di Ingegneria Elettronica - Università di Firenze - Via di S. Marta, 3 50139 Firenze - Italy
2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA
3. Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD, USA

Phone No.: 1-818-354-0492 Email: eastwood.im@jpl.nasa.gov, tanelli@achille.det.unifi.it

Abstract - **In this paper, the characteristics of the Doppler power spectrum observed by a spaceborne precipitation radar, under Non Uniform Beam Filling (NUBF) condition will be presented, and the expected performance of some standard Doppler estimators and that of a new inversion technique will be investigated and compared.**

1. INTRODUCTION

The importance of vertical motion at all scales of atmospheric circulation has brought substantial development of the Doppler radar technology in the field of precipitation monitoring. Although techniques have been developed in the last two decades for ground-based and airborne Doppler weather radars [1],[2], they do not fully address the issues pertained to spaceborne radars. These unique issues are the downward viewing geometry with a fast moving (i.e., $v_S = 7$ km/s) orbiting platform and a relatively large volume of resolution (e.g., 2km radius and 250m range res.). Also more insightful studies on spaceborne Doppler radars (e.g.,[3]) did not fully address the impact on Doppler estimates of NUBF associated with inhomogeneously distributed targets within the observing volume. The effects of this non-uniform weighting may dominate any other contribution. Under this condition, shape, average value and width of the Doppler spectrum $P(v_S,\mathbf{r_0},f)$ may not be directly correlated with the vertical velocity of the precipitating particles, in fact:

$$P(v_s,\mathbf{r}_0,f)=\int_{r_1}^{r_2}\int_0^{\pi}\int_0^{2\pi}\eta(\mathbf{r},f-f')\,W(\mathbf{r}-\mathbf{r}_0)\,r\sin\theta d\phi d\theta dr \qquad (1)$$

where r_1 and r_2 are the range limits of the resolution volume centered at $\mathbf{r_0}$ respect to the satellite; the function $W(\mathbf{r})$includes the contribution by the radar constant, the antenna gain pattern, the range weighting function, the atmospheric attenuation and the range dispersion; $\eta(\mathbf{r},f)$ is the natural Doppler velocity spectrum associated with the distribution of the falling particles, and f' is the Doppler shift. For small antenna beamwidths and nadir looking geometry f' can be approximated as:

$$f'(\theta,\phi)=qx \qquad (2)$$

$$q=(2/\lambda)\cdot(v_S/h_S) \qquad (2')$$

where λ is the radar wavelength and h_S is the satellite altitude. $\eta(\mathbf{r},f)$ is centered on the mean particle falling speed v_R, its width σ_R is determined by the different fall speed of hydrometeros of different size, turbulence and wind shear [1]. When the volume of resolution is uniformly filled (i.e., $\eta(\mathbf{r},f)=\eta(f)$) the total spectrum measured by a nadir-looking radar with a Gaussian antenna pattern can be approximated by a Gaussian function with the center determined by v_R [4]. The corresponding spectral width σ_U can be estimated as:

$$\sigma_U \cong \frac{2}{\lambda}\sqrt{\sigma_R^2+\frac{\theta_{3dB}^2 v_s^2}{4\ln 2}} \qquad (3)$$

Even for a narrow beam as the one considered in Table 1, the broadening due to the antenna motion prevails over σ_R.

On the other hand, when NUBF is encountered, the nonuniform weighting in (1) due to $\eta(\mathbf{r},f\text{-}f')$ changes the shape of the spectrum. In particular its average frequency will not match anymore with $-2v_R/\lambda$. As discussed in the next section, the magnitude of this bias depends on the shape of the along-track reflectivity profile $z_X(x)$ within the volume of resolution and on the parameter q.

2. SPECTRAL MOMENT ESTIMATION FOR WEATHER SIGNALS

The signal backscattered by moving distributed targets such as precipitating particles is described by a stochastic process with zero mean, Gaussian distribution and decorrelation time inversely proportional to the spectral width. If the spectrum is calculated from a sequence of M complex voltage samples s_k separated by T_s, each of the spectral components can be expressed as [5]:

$$\tilde{P}_k=(P_k+N_k)\cdot y(k) \qquad (4)$$

TABLE 1
SPACEBORNE DOPPLER RADAR SYSTEM PARAMETERS

v_s	7 km/s	θ_{3dB}	0.3°
h_s	432km	f_0	13.6 GHz
PRF	6000	M	128

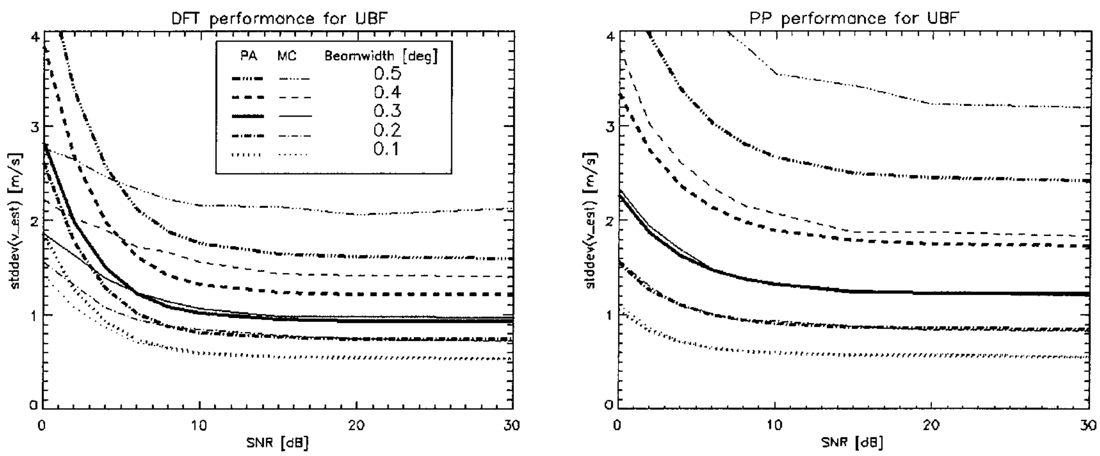

Fig. 1. Performances of standard spectral moments estimators under Uniform Beam Filling hypothesis and the radar system in Table 1. PA = Perturbation Analysis [8], MC = Simulations. σ_{UN} can be approximated here by θ_{3dB} *[degs] / 2*. As expected PA and MC differ significantly for high σ_{UN} (hypothesis for PA are not satisfied). DFT simulated estimates show higher accuracy than predicted by theory at low SNR because automatic noise estimation and removal was implemented in the DFT based estimator. PP performs better only for very small σ_{UN} (i.e., <0.05). Nevertheless additional biasing terms were observed for DFT estimators at very high σ_{UN} (e.g., >0.25), in that range both estimators are extremely unreliable.

where P_k is the value of (1) at $f = (k-M/2)/MT_s$ and y is a random variable with negative exponential distribution and unitary mean.

The estimator of the first spectral moment based on Discrete Fourier Transform is:

$$\hat{v}^{DFT} = -\frac{\lambda}{2MT_S}\left\{\hat{m} + \frac{1}{\tilde{P} - \hat{N}} \sum_{m=\hat{m}'-M/2}^{\hat{m}'+M/2} (m - \hat{m}) \cdot \left[\tilde{P}_{\mathrm{mod}_M(j)} - \hat{N}_j\right]\right\}$$

where $\hat{m}'$ is an approximation to the mean spectral line (here obtained by applying the previous expression a first time with $\hat{m}' = 0$), $\tilde{P}$ is the total power of the noisy signal and $\hat{N}$ is the estimated noise power and N_j is the noise spectral density at $f = (j-M/2)/MT_s$.

Another widely used estimator is the Pulse Pair processor (PP) which is based on the exploitation of the correlation of consecutive samples only:

$$\hat{v}^{PP} = -\frac{\lambda}{2}\frac{1}{2\pi T_S}\arg\left(\frac{1}{M-1}\sum_{k=-(M-1)/2}^{(M-1)/2-1} s_k^* s_{k+1}\right)$$

The accuracy of both estimators is strongly dependent on SNR and normalized spectral width σ_{UN} [1],[6]. The analysis of their performances is shown in Fig. 1.

NUBF effects were studied by by applying a 3D radar simulator to 3D ARMAR datasets [7]. The resolution of the ARMAR dataset is much smaller than the spatial resolution of the simulated spaceborne satellite (i.e., 200 m vs 5 km), and it provides rain intensity values together with vertical velocity estimates. Results of mean Doppler velocity estimation on such simulated spectra are shown in Fig. 3 (bottom right plots): when NUBF is present the induced bias becomes the major contribution to the error. The strong correlation of such a bias with $Z_X(x)$ can be noted by comparing the error plots with $-\nabla_x Z_X(x)$.

3. COMBINED FREQUENCY_TIME TECHNIQUE (CFT)

No frequency-only spectral moment estimator can reduce NUBF effects: in order to remove the induced bias, knowledge of sub-beam, along-track distribution of rainfall

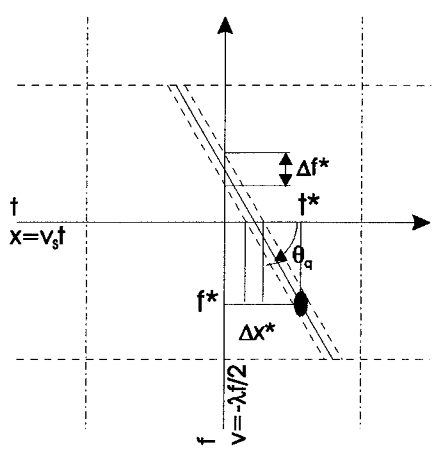

Fig.2 - Frequency-Time tracking of distributed rainfall target. The along track resolution is determined by the achievable frequency resolution and the system parameters. The expected value of the power signature of a given target varies accordingly with the two-way antenna pattern. Best fitting with the antenna pattern is performed to estimate the f^*-t^* position of the moment of maximum return form the target (i.e., alignement with the maximum gain direction)

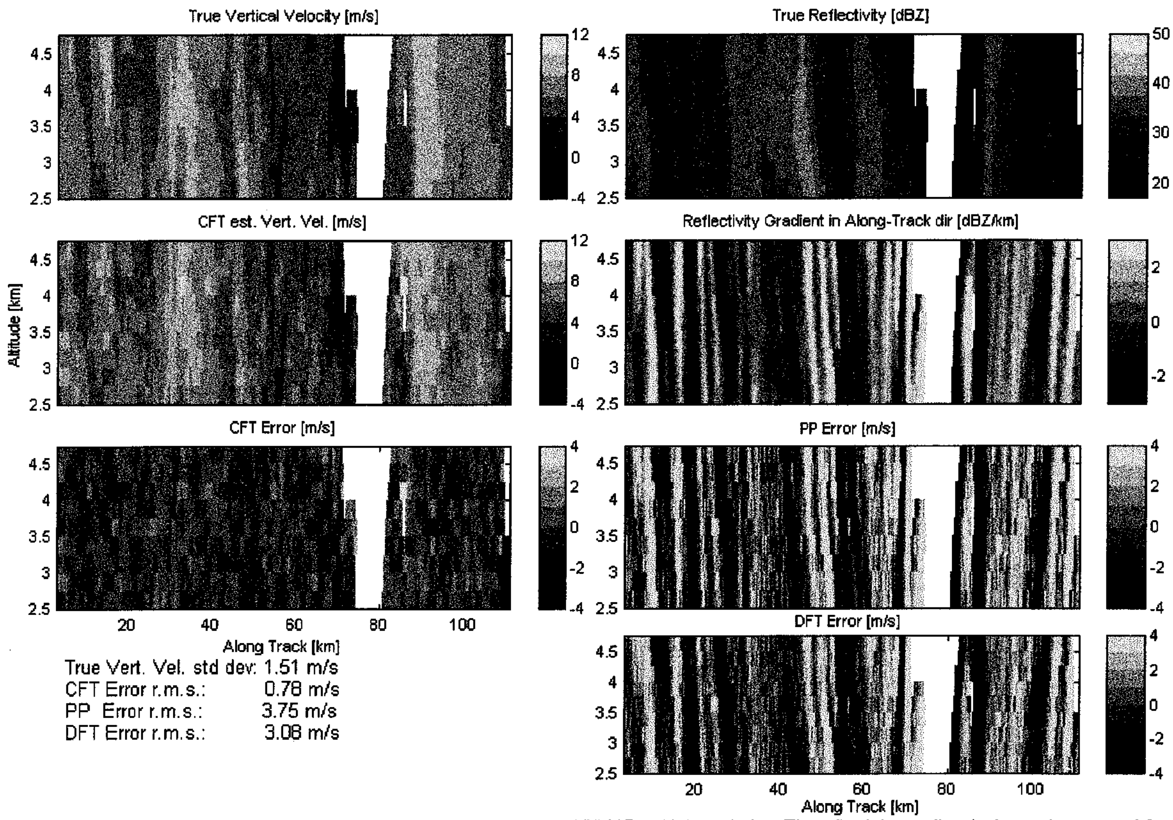

Fig. 3 Vertical section of hurricane 'Bonnie'. 'True' Values are measured by ARMAR at high resolution. The reflectivity gradient is shown sign reversed for better comparison with PP and DFT error plots. Rms of the three error plots are shown in the bottom left corner together with the true vertical velocity standard deviation. It is possible to recognize several 'true' vertical velocity features in the CFT reconstruction (which were undetectable in DFT and PP reconstructions).

(i.e., $Z_X(x)$) is necessary. The proposed technique follows a joint Frequency-Time approach close to the Doppler Beam Sharpening Approach [8] that gave birth to the Synthetic Aperture Radar methods. The concepual scheme is shown in Fig. 2. It can be assumed that the v_R of a distributed target does not change in the short time while it is illuminated by the antenna, therefore its frequency signature will move accordingly to (2) at an angle $\theta_q = atan(-qv_S)$ in the t-f plane. At every time step $t_i = iMT_S$ $P_{k(i)}$ (with $k(i) = k_0 + qv_St_i$) varies accordingly to the weighting factor W which is determined mainly by the antenna pattern. It is then possible to process the sequence of $P_{k(i)}$ with a DFT moment estimator to calculate the t_i corresponding to the peak of the antenna pattern. This allows to estimate the actual position of the target and therefore its actual v_R.

Results as the one shown in Fig. 3 demonstrate that CFT is able to correct the bias introduced by NUBF.

ACKNOWLEDGMENT

The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and by the University of Firenze through a program funded by ASI (Italian Space Agency).

REFERENCES

[1] R.J..Doviak and D.S. Zrnic, *Doppler radar and weather observations*, Academic Press, 1984.

[2] P.H. Hildebrand and R.K.Moore, "Meteorological Radar Observations from Mobile Platforms", in *Radar in Meteorology,* D.Atlas Ed. Boston, MA: American Meteor. Soc., ch. 22a, pp-286-314, 1990

[3] P. Amayenc, J.Testud and M.Marzoug, "Proposal for a spaceborne dual-beam rain Radar with Doppler capability", *J. Atm. Oce. Tech.*, 10, pp.262-276, June 1993

[4] R. Meneghini and T. Kozu, *Spaceborne Weather Radar*, Artech House Ed., 1990

[5] D.S. Zrnic, "Simulation of weatherlike Doppler Spectra and Signals", *J. App. Meteor.*, **14**, pp. 619-620

[6] T. Berger and H.L. Groginsky, Estimation of the spectral moments of pulse trains, *presented at the Int. Conf. On Inform. Theory*, Tel Aviv, Israel, 1973.

[7] S.L.Durden, E.Im, F.K.Li, W. Ricketts, A.Tanner and W.Wilson, "ARMAR: An Airborne Rain-Mapping Radar". *J. Atmos. Oceanic Technol.*, **11**, 727-737, 1994.

[8] F.T. Ulaby, R.K.Moore and A.K.Fung, *Microwave Remote Sensing*. Vol II, Addison-Wesley, 457-1064, 1982.