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Crossbeam Wind Measurements Using Spaced-Antenna and Doppler Beam Swinging Based on Monopulse Configurations with the National Weather Radar Testbed

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1. Introduction

- The Spaced-Antenna Interferometry (SAI) technique has been used to measure crossbeam wind components as well as radial velocity.
- FCA, INT, SZL and CCR have been used to estimate crossbeam wind. They are all based on the SAI technique.
- The Doppler Beam Swinging (DBS) is another common technique used to measure crossbeam wind. Crossbeam wind components are derived from measurements of the Doppler velocities along two beam sequentially pointed in the wind component plane.
- The National Weather Radar Testbed (NWRT) is a phase array radar, which has two receiving channels: sum and difference. These two channels can be used to estimate crossbeam wind directly using the SAI technique. In addition, the sum channel can be used to estimate crossbeam wind using the DBS technique.

Fig .1 The NWRT antenna is being installed at Norman, Oklahoma

2. SAI For Monopulse Configuration

- Auto-correlations for the sum and difference signals are written as:

$$C_{dd}(\tau)=C_{11}(\tau)+C_{22}(\tau)-C_{12}(\tau)-C_{21}(\tau)$$

$$C_{11}(\tau)=\exp(-2jkv_{x'}(0)\tau-2k^2\sigma_{tx'}^2\tau^2-2k^2\sigma_{e\phi}^2\tau^2v_{y'}^2(0)-2k^2\sigma_{e\theta}^2\tau^2v_{z'}^2(0))$$

$$C_{22}(\tau)=\exp(-2jkv_{x'}(0)\tau-2k^2\sigma_{tx'}^2\tau^2-2k^2\sigma_{e\phi}^2\tau^2v_{y'}^2(0)-2k^2\sigma_{e\theta}^2\tau^2v_{z'}^2(0))$$

$$C_{12}(\tau)=\exp(-2jkv_{x'}(0)\tau-2k^2\sigma_{tx'}^2\tau^2-2k^2\sigma_{e\phi}^2(v_{y'}(0)\tau-\Delta y'_{12}/2)^2-2k^2\sigma_{e\theta}^2(v_{z'}(0)\tau-\Delta z'_{12}/2)^2)$$

$$C_{21}(\tau)=\exp(-2jkv_{x'}(0)\tau-2k^2\sigma_{tx'}^2\tau^2-2k^2\sigma_{e\phi}^2(v_{y'}(0)\tau+\Delta y'_{12}/2)^2-2k^2\sigma_{e\theta}^2(v_{z'}(0)\tau+\Delta z'_{12}/2)^2)$$

$$C_{ss}(\tau)=\exp[-2jkv_{x'}(0)\tau-2k^2\sigma_{tx'}^2\tau^2-2k^2\sigma_{e\phi s}^2\tau^2v_{y'}^2(0)-2k^2\sigma_{e\theta s}^2\tau^2v_{z'}^2(0)]$$

- After we obtain the time-domain auto correlation functions, we can use Fourier Transform to retrieve their power spectrum density, they are written as:

$$S_{ss}(v)=\frac{1}{\pi}\sqrt{\frac{\pi}{2\sigma_{tx'}^2+2\sigma_{e\phi s}^2v_{y'}^2(0)}}\exp\left(-\frac{(v-v_{x'}(0))^2}{2\sigma_{tx'}^2+2\sigma_{e\phi s}^2v_{y'}^2(0)}\right)$$

$$S_{dd}(v)=\frac{2}{\pi}\sqrt{\frac{\pi}{2\sigma_{tx'}^2+2\sigma_{e\phi}^2v_{y'}^2(0)}}\exp\left(-\frac{(v-v_{x'}(0))^2}{2\sigma_{tx'}^2+2\sigma_{e\phi}^2v_{y'}^2(0)}\right)\left(1-\exp\left(-\frac{k^2\sigma_{e\phi}^2\Delta y_{12}'^{\,2}\sigma_{tx'}^2}{2\sigma_{tx'}^2+2\sigma_{e\phi}^2v_{y'}^2(0)}\right)\cos(\alpha)\right)$$

$$\alpha=\frac{k\sigma_{e\phi}^2v_{y'}(0)\Delta y'_{12}}{\sigma_{tx'}^2+\sigma_{e\phi}^2v_{y'}^2(0)}(v-v_{x'}(0))$$

- If v is equal to $v_{x'}(0)$, we can rewrite the two equations :

$$S_{ss}(v_{x'}(0))=\frac{1}{\pi}\sqrt{\frac{\pi}{2\sigma_{tx'}^2+2\sigma_{e\phi s}^2v_{y'}^2(0)}}$$

$$S_{dd}(v_{x'}(0))=\frac{2}{\pi}\sqrt{\frac{\pi}{2\sigma_{tx'}^2+2\sigma_{e\phi}^2v_{y'}^2(0)}}\left(1-\exp\left(-\frac{k^2\sigma_{e\phi}^2\Delta y_{12}'^{\,2}\sigma_{tx'}^2}{2\sigma_{tx'}^2+2\sigma_{e\phi}^2v_{y'}^2(0)}\right)\right)$$

- By combining the two equations above, we can solve crossbeam wind.

3. DBS Based on the NWRT

$$v_h=v_1\tan\theta_z+\frac{v_2-\frac{v_1}{\cos\theta_z}}{\sin\theta_z}$$

v_h : Crossbeam wind velocity

v_1 : Doppler velocity measured from boresight beam

v_2 : Doppler velocity measured from azimuth tilted beam

θ_z : Beam separation angle

- If the beam separation angle is small, which is always true when we need to compare SA and DBS performance for wind measurements,crossbeam wind velocity is equal to:

$$v_h=\frac{v_2-v_1}{\theta_z}$$

- Variance of horizontal wind is related to the variances of two radial velocities, the covariance of two radial velocities and θ_z .

$$\mathrm{var}[\hat{v}_h]=\frac{1}{\theta_z^2}\mathrm{var}[\hat{v}_1]+\frac{1}{\theta_z^2}\mathrm{var}[\hat{v}_2]-\frac{2}{\theta_z^2}\mathrm{cov}[\hat{v}_1,\hat{v}_2]$$

4. Results

- We ran Monte Carlo simulations to compare the performance of wind estimators using DBS and SAI with the NWRT/PAR. In order to let SAI and DBS have matched resolution volume, according to Doviak et al.[2004], we have:

$$\theta_z=\frac{\theta_6^{(2)}(SA)-\theta_6^{(2)}(DBS)}{\sqrt{2}}$$

- The 6 dB two-way beamwidth for SA is equal to 1.85 degree, the 6 dB two-way beamwidth for DBS is equal to 1.62, thus the beam separation should be equal to 0.16 degree.

- In the DBS method, we use two different receiving strategies: 1. Receiving a group of signals from first beam position and then receiving the other group of signals from the second beam position; 2. Receiving signals alternately from two beam positions. We will see the standard deviation of the crossbeam wind estimation is much smaller if we apply the second strategy, this is because the estimation errors are highly correlated and tend to cancel each other.

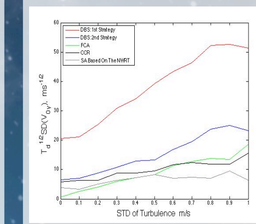

Fig .2 Normalized standard deviation of estimated crossbeam wind versus standard deviation of turbulence

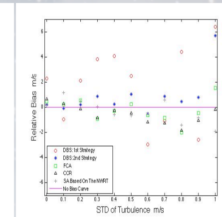

Fig .3 Relative bias of estimated crossbeam wind versus standard deviation of turbulence

5. Conclusions

- It is shown that if wind across the beam is uniform, the NWRT is capable of measuring crossbeam wind velocity as well as radial wind velocity.
- Using auto-correlations of the sum and difference signals to measure crossbeam wind can produce satisfactory crossbeam wind measurements.
- In future work, cross-correlation of the sum and difference signals will be investigated. Wind shear will be included

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