Simulation and Feasibility Study of Spaceborne Doppler Scatterometer for Ocean Surface Currents and Winds

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Outlines

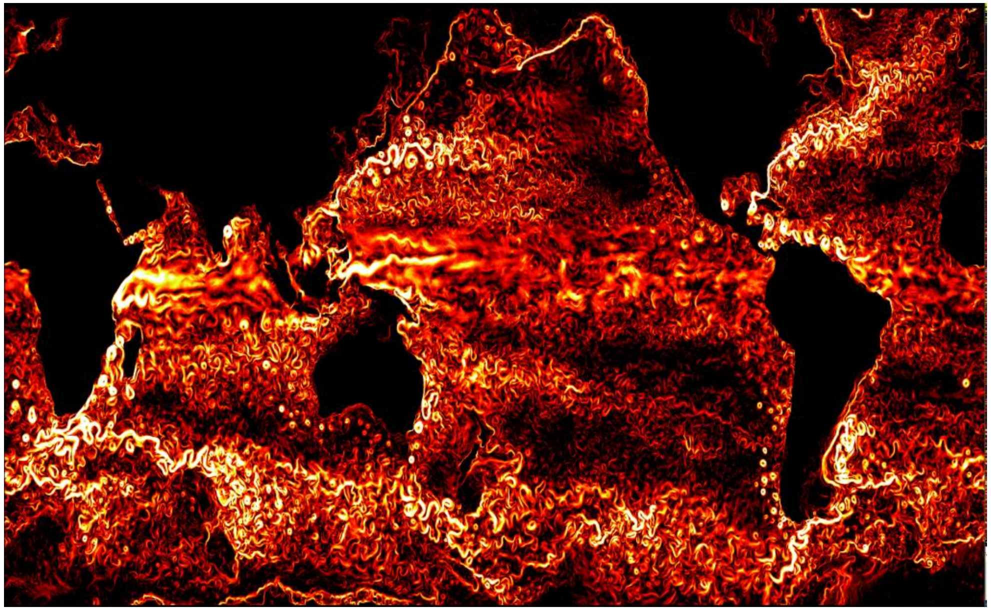
- Requirements and Objectives
- Measurement Principle
- System Concept and Parameters
- Accuracy Models and Simulations
- Summary

Requirement and Objectives

Ocean surface current is a very important parameter of ocean dynamic environment. It has been connected to global climate change, marine environment forecasting, marine navigation, engineering security and so on.

- quick global coverage
  real aperture
  wide swath
- speed vector measurement
  multiple azimuth observations

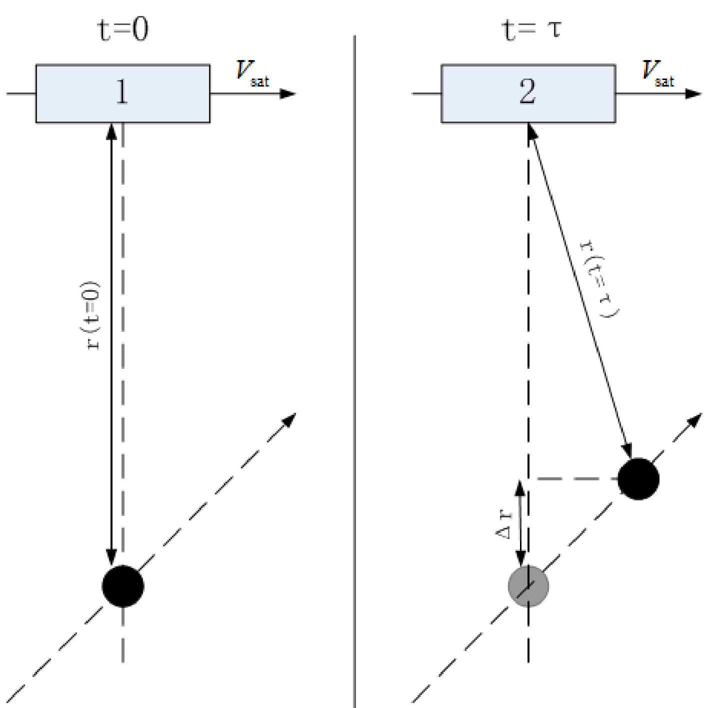
- Objective
  Pre-study for CFOSAT follow-on

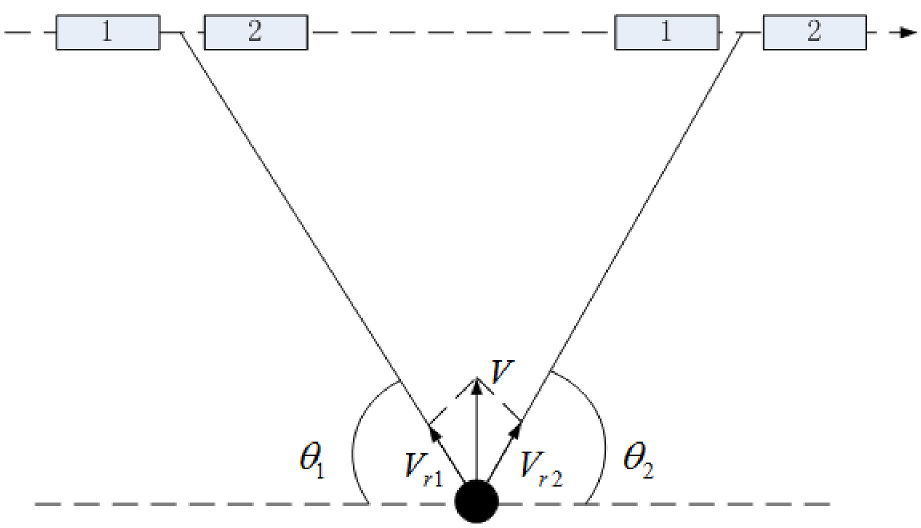


Inherit from wind scatterometer

Measurement principle

-Pulse Doppler Measurement



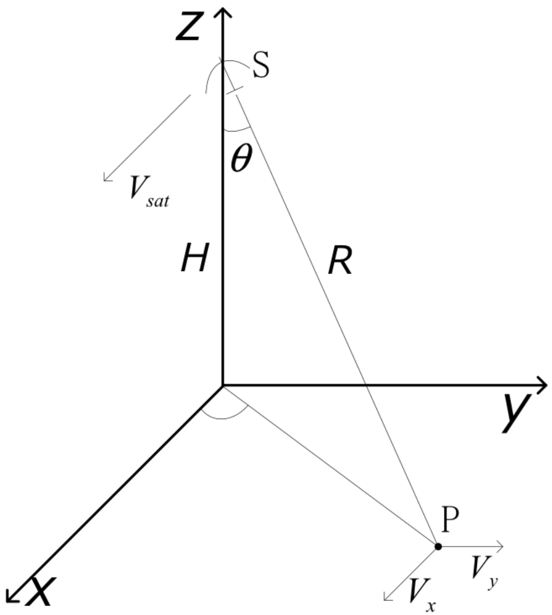


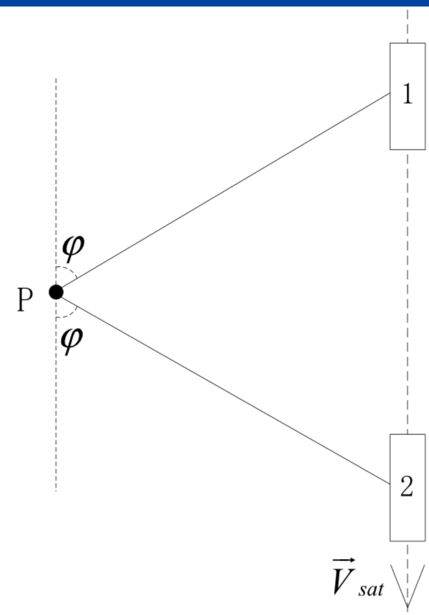
Interferometric phase: $\Delta\phi = 2k\Delta r$

Radial velocity of target: $V_r = \Delta r/\tau = \dfrac{\Delta\phi}{2k\tau}$

Speed vector: $\vec{V} = \vec{V}_{r1} + \vec{V}_{r2}$

Azimuth angle: $\theta_1 = \theta_2$





$$\vec{R}_{\text{incident}} = \overrightarrow{\text{SP}} = (H\tan\theta\cos\varphi, H\tan\theta\sin\varphi, -H)$$

$$\vec{n}_{\text{incident}} = \vec{R}_{\text{incident}} \Big/ \left|\vec{R}_{\text{incident}}\right| = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, -\cos\varphi)$$

$$\begin{aligned} V_R &= \vec{V}_{\text{sat}} \bullet \vec{n}_{\text{incident}} + \vec{V}_{\text{current}} \bullet (-\vec{n}_{\text{incident}}) \\ &= V_{\text{sat}}\sin\theta\cos\varphi - V_x\sin\theta\cos\varphi - V_y\sin\theta\sin\varphi \\ &= \sin\theta\left[\left(V_{\text{sat}} - V_x\right)\cos\varphi - V_y\sin\varphi\right] \end{aligned}$$

$$f_d = \frac{2V_R}{\lambda} = \frac{2\sin\theta\left[\left(V_{\text{sat}} - V_x\right)\cos\varphi - V_y\sin\varphi\right]}{\lambda}$$

Phase difference of pulse pair :

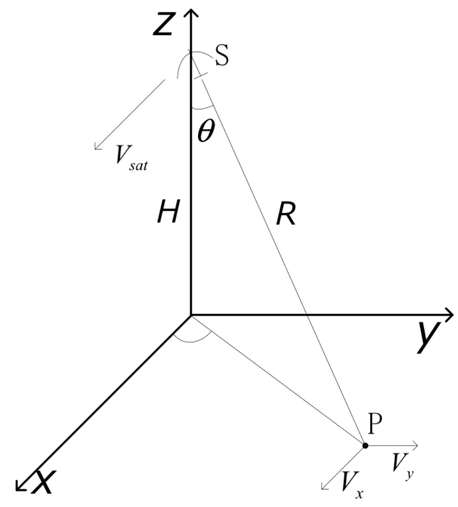
$$\phi = 2\pi f_d t = \frac{4\pi \sin\theta\left[\left(V_{sat} - V_x\right)\cos\varphi - V_y \sin\varphi\right]}{\lambda} t$$

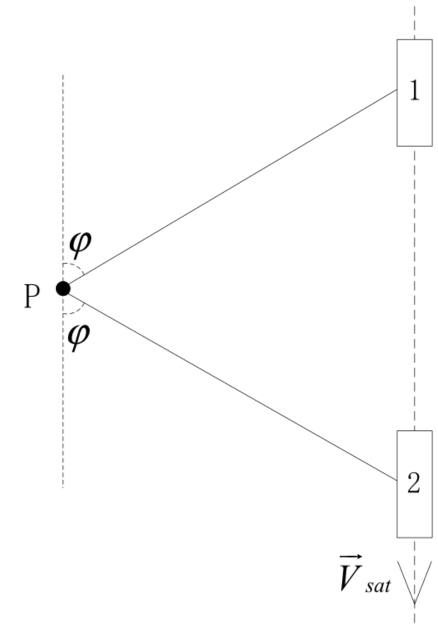
$$V_x = V_{sat} - \frac{\lambda}{4\pi \sin\theta \sin(\varphi_1 - \varphi_2) t}\left(\phi_2 \sin\varphi_1 - \phi_1 \sin\varphi_2\right)$$

$$V_y = \frac{\lambda}{4\pi \sin\theta \sin(\varphi_1 - \varphi_2) t}\left(\phi_2 \cos\varphi_1 - \phi_1 \cos\varphi_2\right)$$

$$V_x = V_{sat} + \frac{\lambda}{8\pi \sin\theta \cos\varphi_1 t}\left(\phi_2 - \phi_1\right)$$

$$V_y = -\frac{\lambda}{8\pi \sin\theta \sin\varphi_1 t}\left(\phi_2 + \phi_1\right)$$





System Concepts and Parameters

- System concepts
  Scanning radar for wide swath
  Pencil beam antenna for SNR and Doppler precision

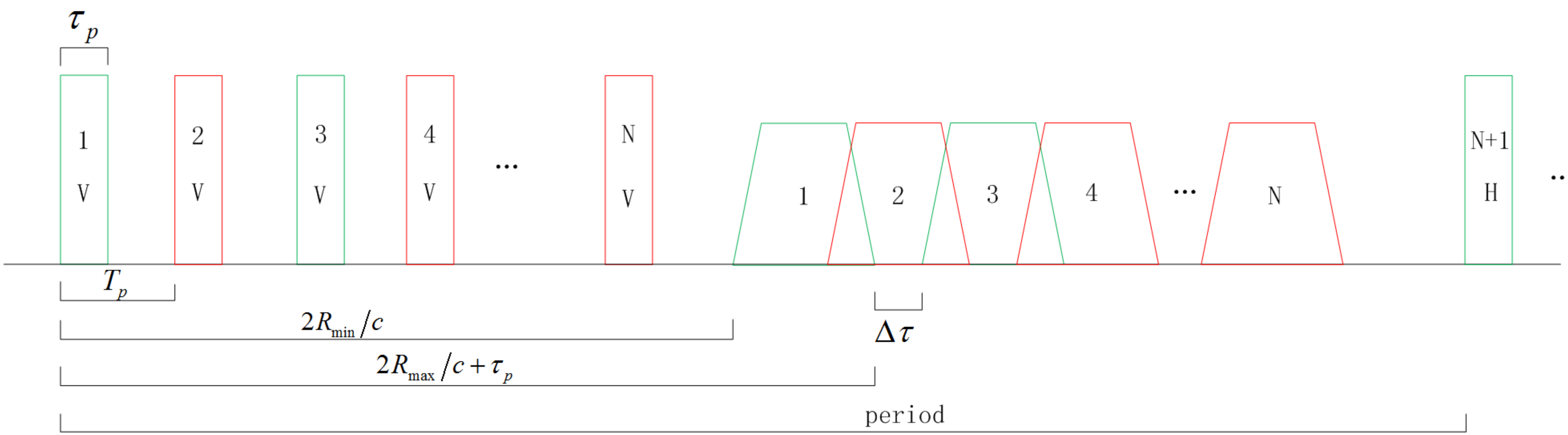
- Doppler shift Measurement and Estimation
  Pulse-train for Doppler estimation

System parameters for simulation

Orbit parameters	
Satellite altitude	519 km
Antenna parameter	
Beam width in azimuth (aperture)	1.0° (1.5m)
Beam width in range (aperture)	1.0° (1.5m)
Antenna scanning rate	22.6 rpm
Incidence angle	42.5°
Signal parameters	
Polarization	VV
Frequency	13.256 GHz
Bandwidth	5 MHz
Transmit power	200 W
PRF	11 kHz
Pulse length	89us

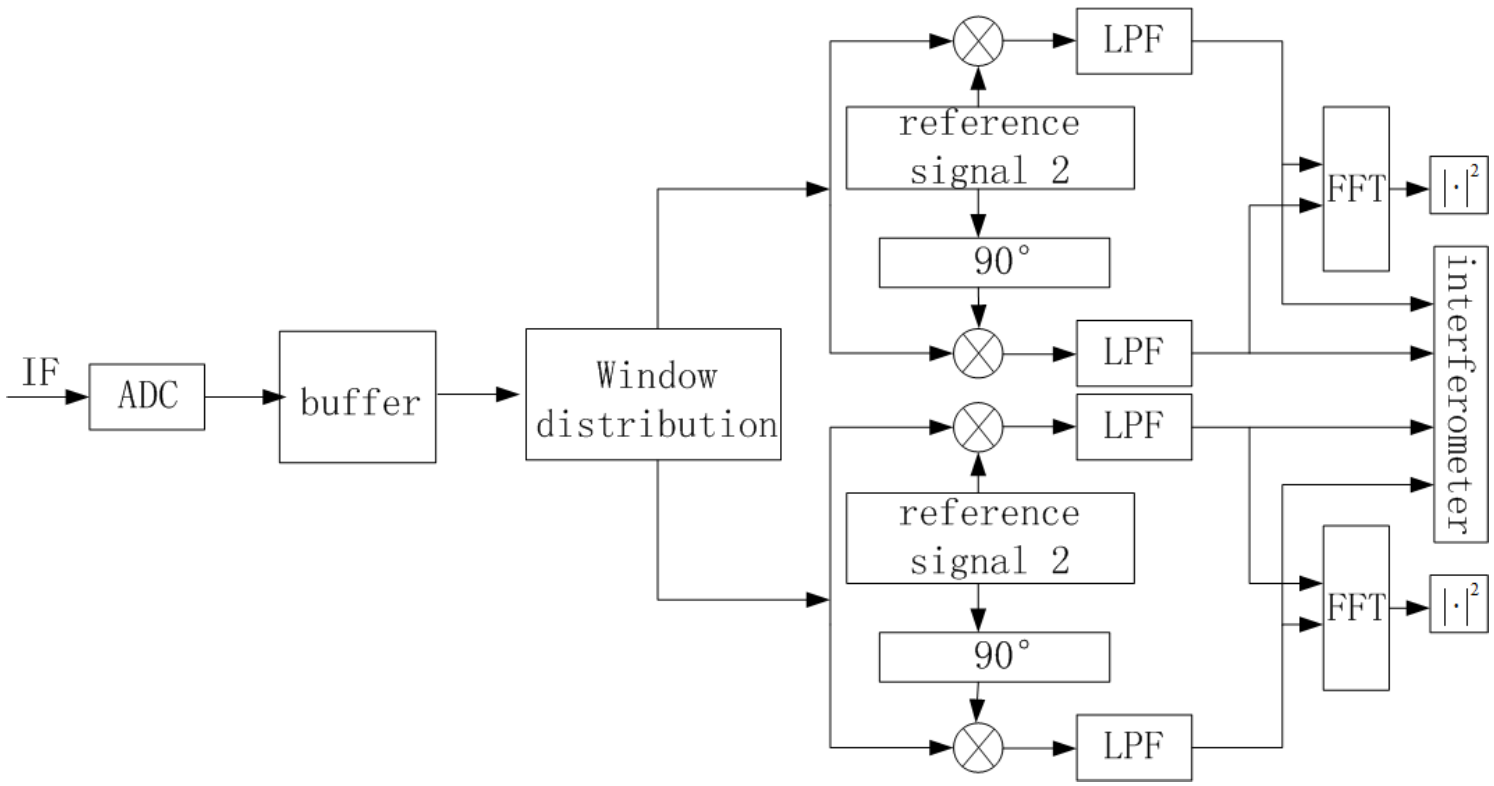
- PRF and Bandwidth are optimized.

Pulse sequences



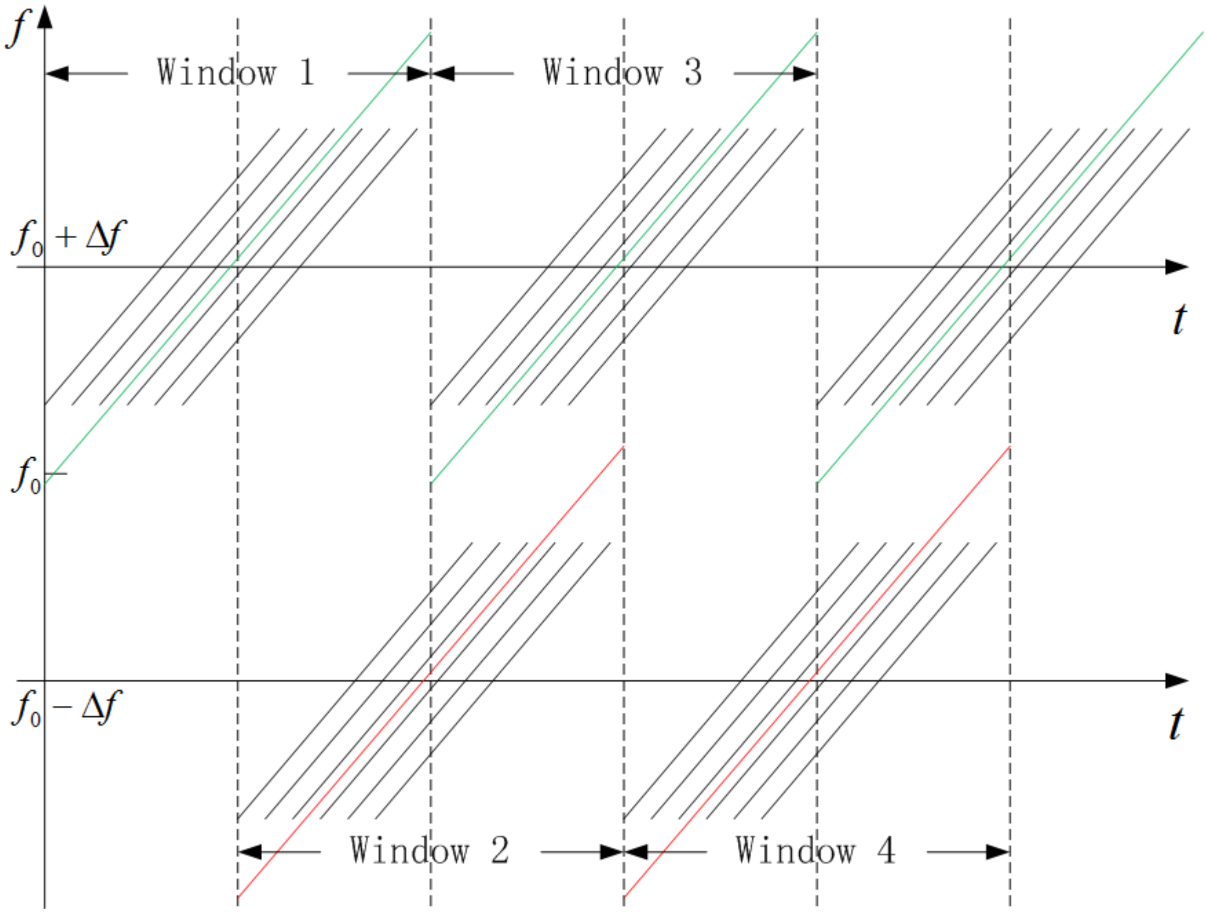
- The green and the red rectangle represent two different kind of chirp pulse with different carrier frequencies for adjacent pulses to suppress intra-pulse contamination
- The odd and even echo pairs are used for interferometric phase estimation.
- All the echoes are used for echo energy estimation.
- V and H polarization are transmitted alternatively (burst-to-burst).

Signal processing

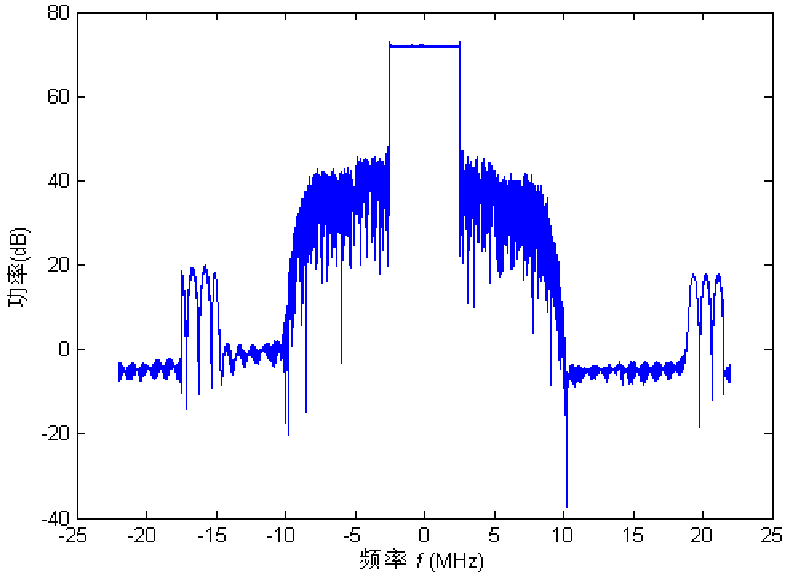


- The echoes are separated into two channels.
- Each one is the same as traditional scatterometer.
- The pulse compress are done by the full-deramp.

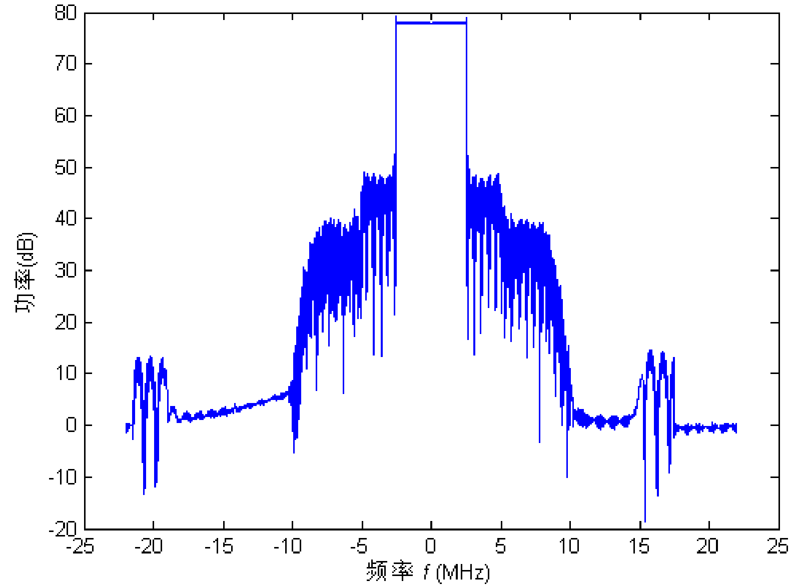
Pulse compress



- The two channels use different reference signals.
- Each reference signal has the same carrier frequency as the transmitted pulse.
- The echoes’ overlap can be separated by the low pass filter.

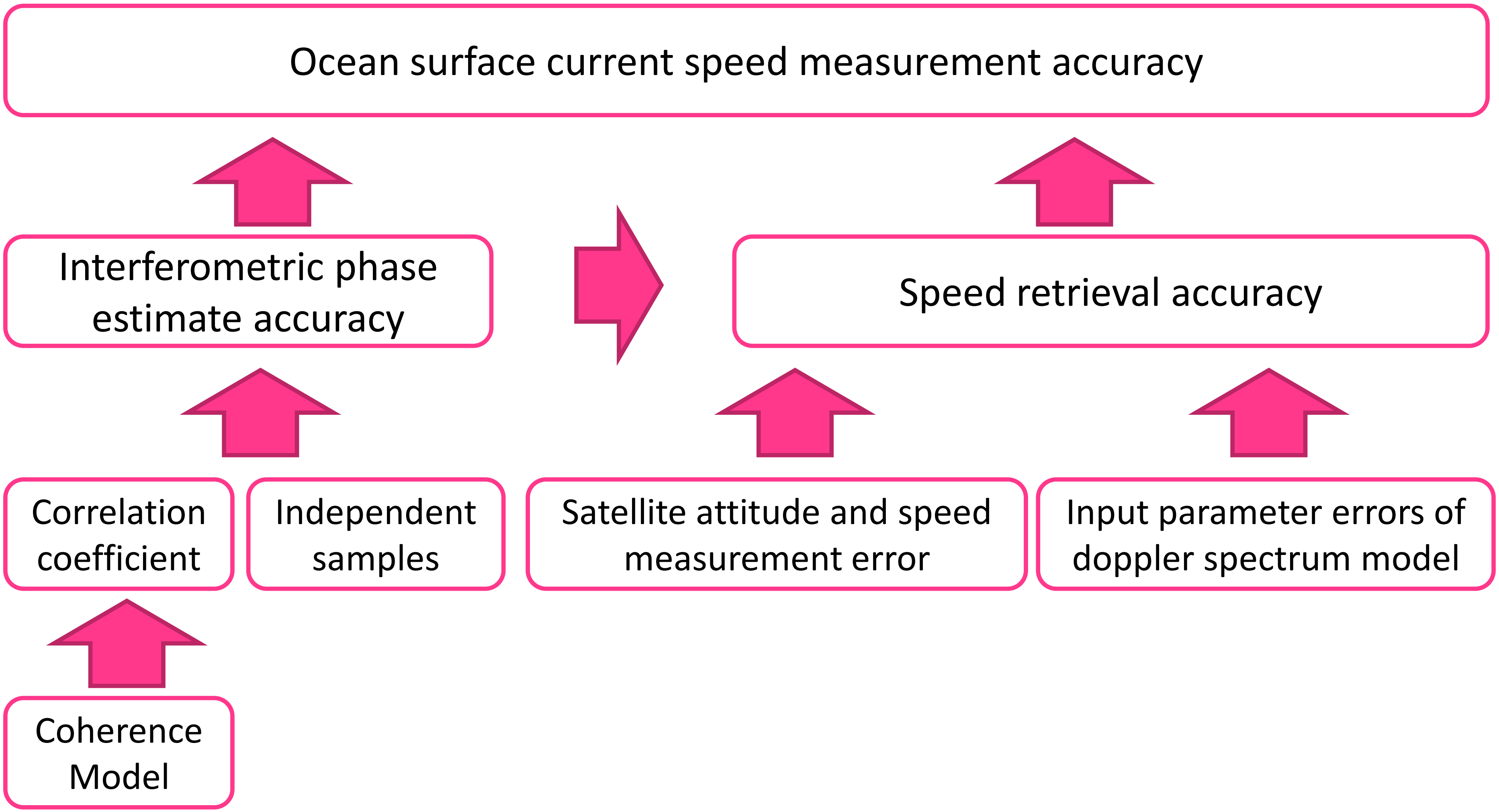


Odd pulse compression result (1,3,5,…)



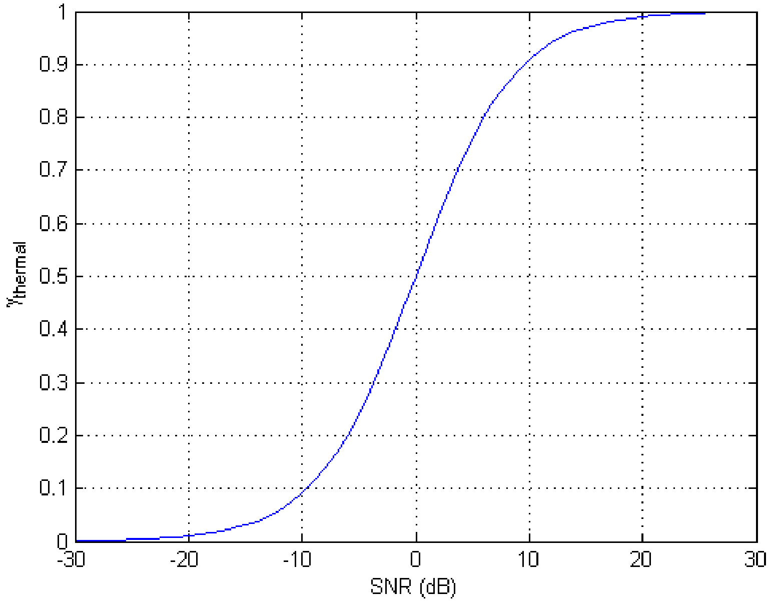
Even pulse compression result (2,4,6,…)

Accuracy Models and Simulations



Coherence model

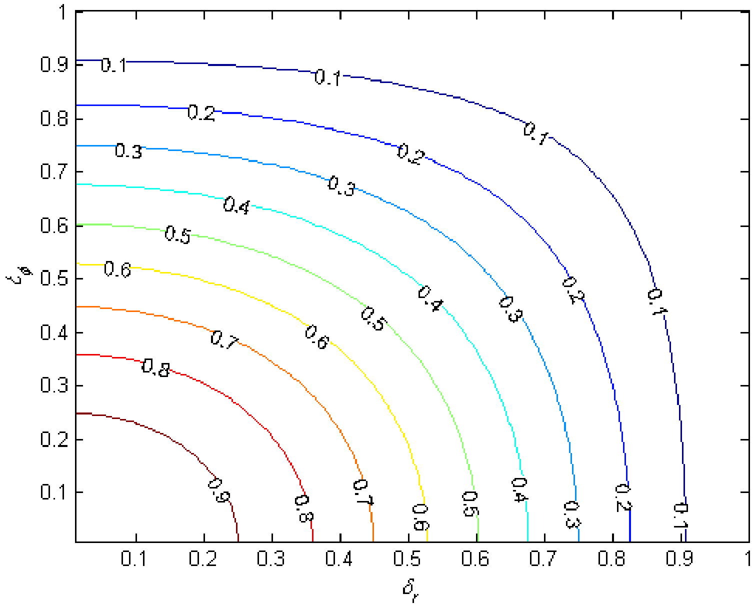
Thermal decorrelation



•Due to additive noise in the signal
• Determined by SNR

•In the low wind speed condition, thermal decorrelation will be the dominant decorrelation factor.

Mismatch decorrelation

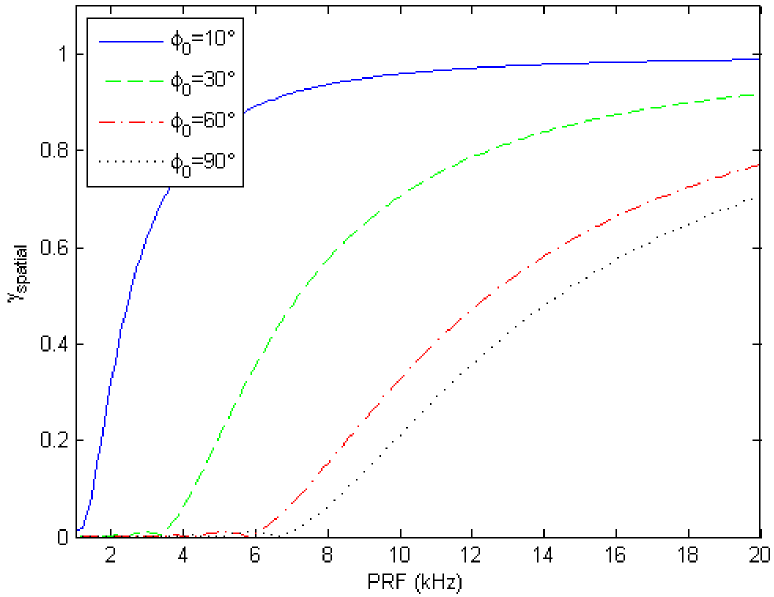


•Due to different observation regions
•Related to the satellite speed and antenna scan rate

•The mismatch decorrelation has little impact on the coherence.

Coherence model

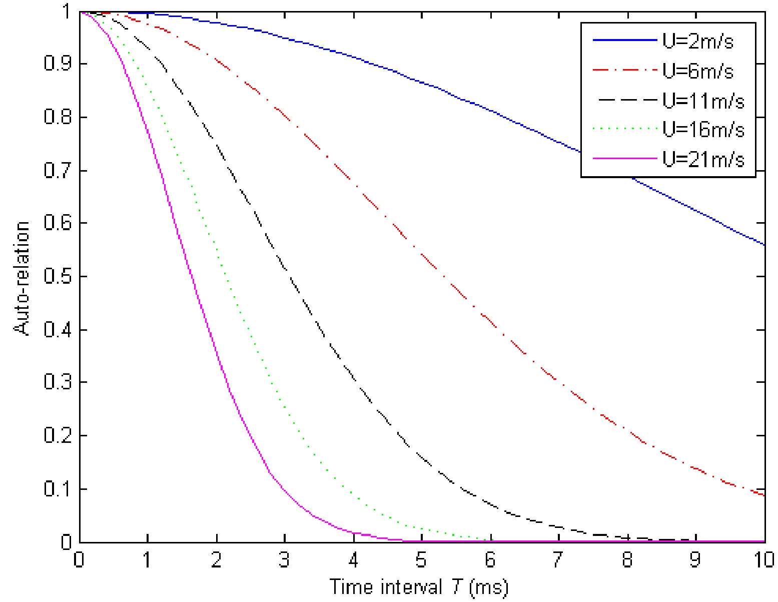
Spatial decorrelation



•Due to different observation geometry
•Positions difference is the product of the satellite speed and the time interval

•It is the dominant decorrelation factor in cross-track direction($\phi_0 = 90^\circ$).

Temporal decorrelation

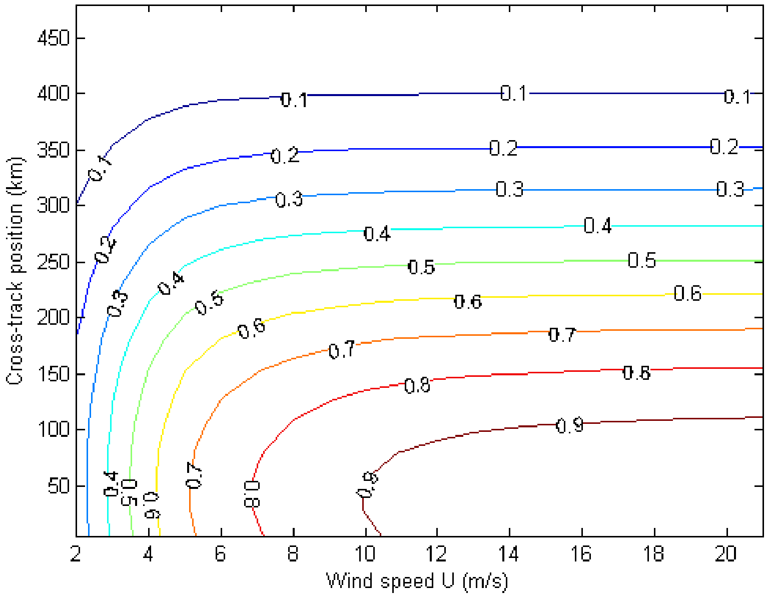


•Due to the change of the scattering characteristics of the ocean surface during the observation interval

•The temporal decorrelation is ignorable, when the PRF is higher than 1kHz.

Ocean surface current speed accuracy

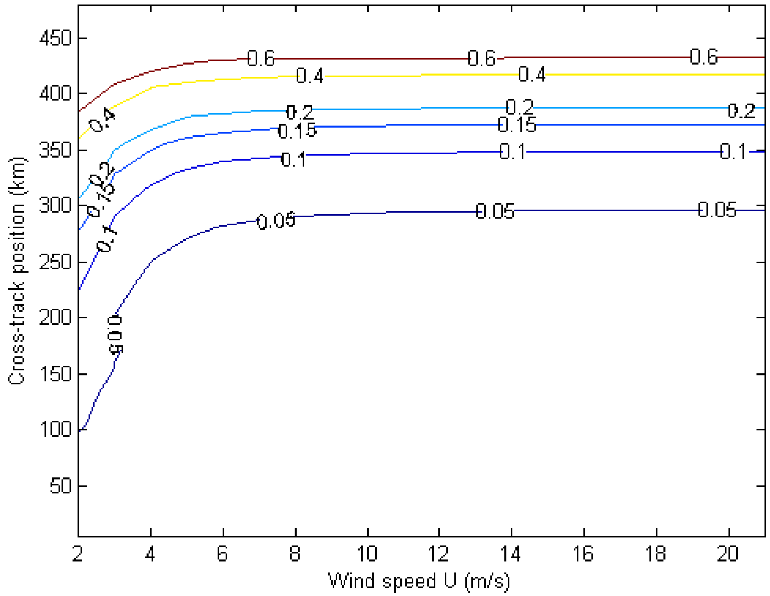
Correlation coefficient



•Correlation coefficient increases with the wind speed. (SNR improves)

•Correlation coefficient decreases with the cross-track distance.

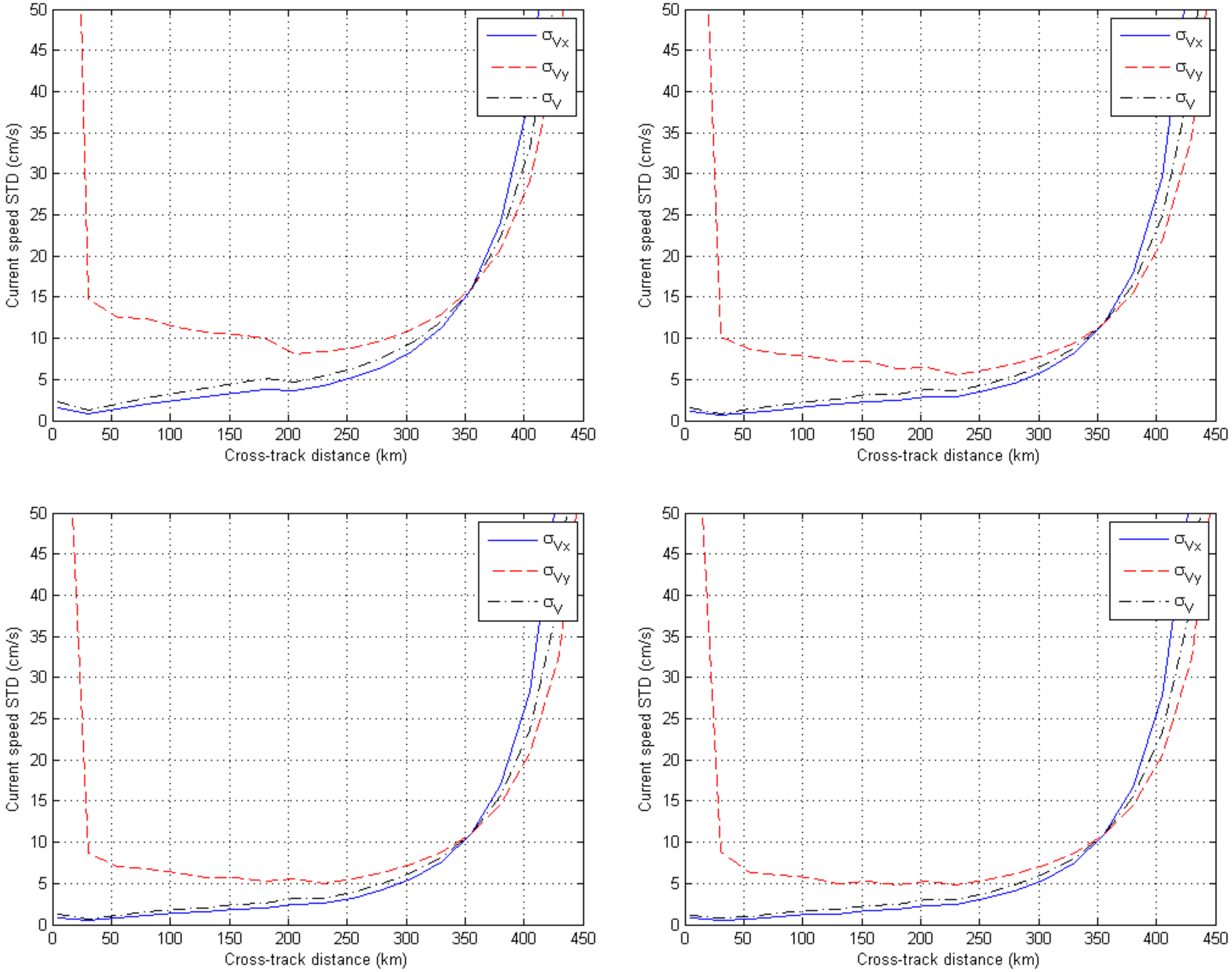
Current speed STD along radial direction



Unit: m/s   Temporal resolution: 2 days
Spatial resolution: 50km x 50km

•Current speed STD increase with the cross-track distance.

Ocean surface current speed accuracy



Wind speed: 4m/s, 7m/s, 11m/s, 20m/s

σ_{Vx} : current speed STD in along-track direction

σ_{Vy}: current speed STD in cross-track direction

σ_V : current speed STD in radial direction

- Current speed STD decrease with wind speed
- Wind speed should be larger than 4m/s

Ocean surface current speed accuracy

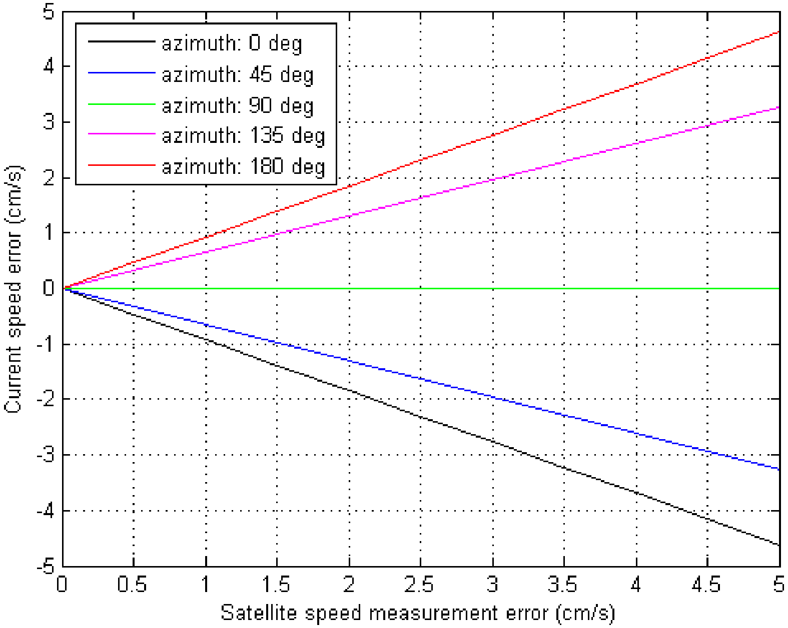
The effective swaths with different wind speed and current speed accuracy

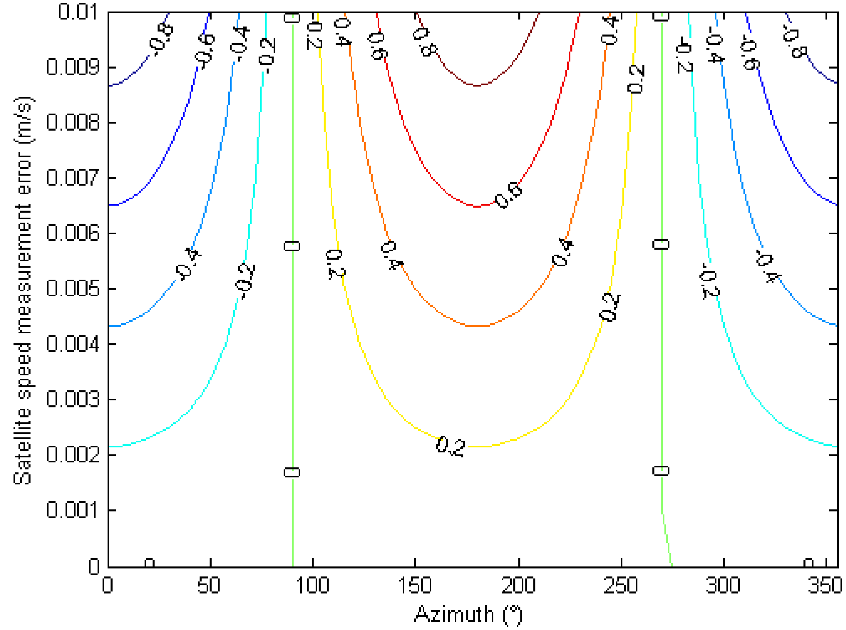
Current speed STD\Wind speed	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s	12 m/s	20 m/s
0.1m/s	0	214	471	570	604	618	622	624	626	627	630
0.15m/s	354	633	662	673	679	683	685	687	688	689	690
0.2m/s	631	677	701	710	714	717	719	720	721	722	723

Scatterometer swath: 1000 km

Effective swath: the current speed components STD for both along-track and cross-track direction are smaller than 0.1m/s.

The effect of satellite speed determination error

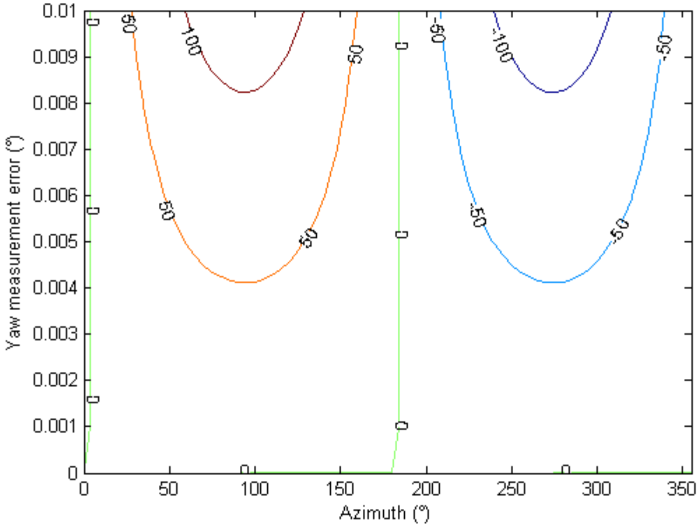


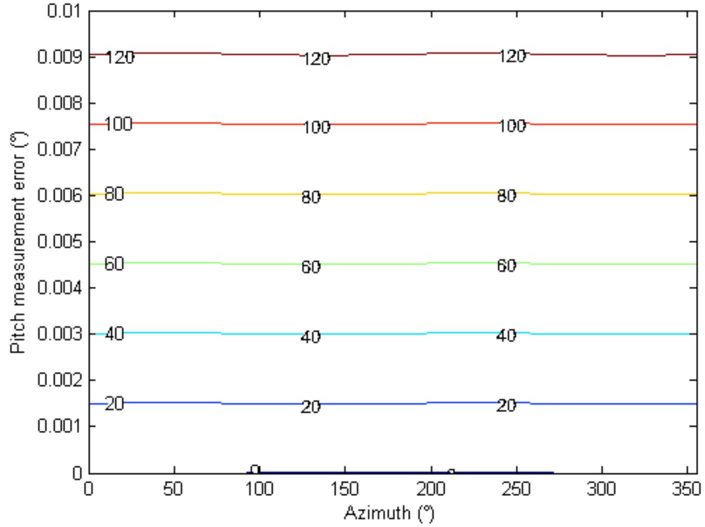


Unit: cm/s

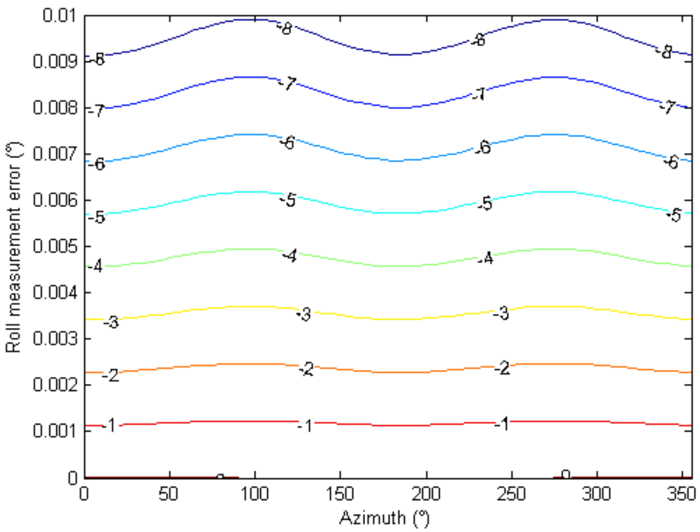
- The effect of satellite speed error on current speed retrieval accuracy is linear.
- The effect of satellite speed error for that of along-track direction is larger than that of cross-track direction.
- The effect of satellite speed error can be insignificant with high-precision satellite speed measurement.

The effect of attitude determination error



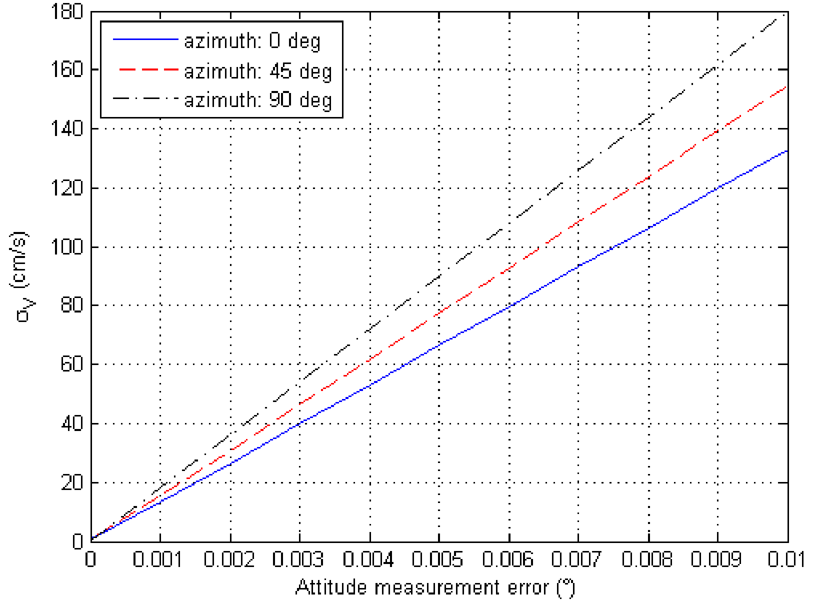


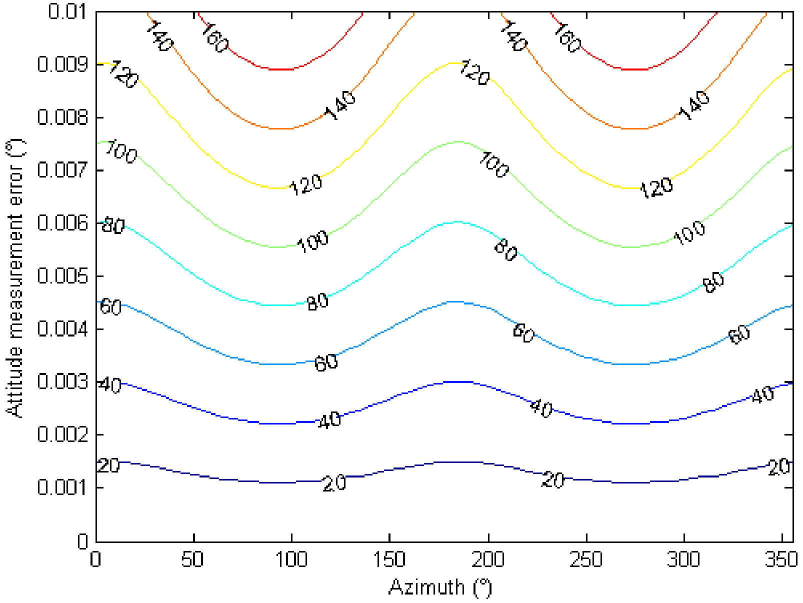
Unit: cm/s



- The effect of yaw measurement error is large in cross-track direction.
- The effect of pitch measurement error is large in all directions.
- The effect of roll measurement error is small.

The effect of attitude measurement error in total





Unit: cm/s

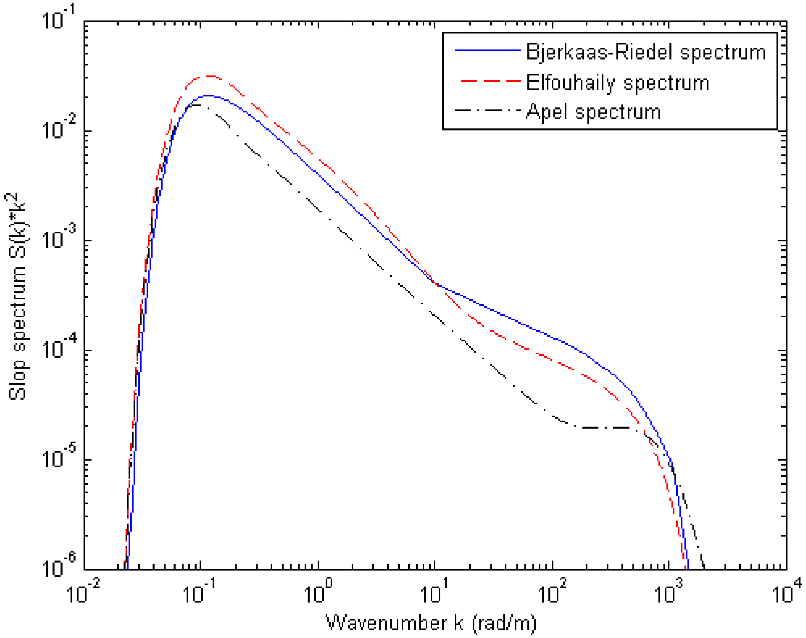
$$\Delta V_{\text{total}} = \sqrt{\Delta V_{\text{yaw}}^2 + \Delta V_{\text{pitch}}^2 + \Delta V_{\text{roll}}^2 + \Delta V_{V_{\text{sat}}}^2}$$

- Current speed error is largest along the cross-track direction.
- Current speed error is smaller than 18cm/s when the attitude determination error is smaller than 0.001° .

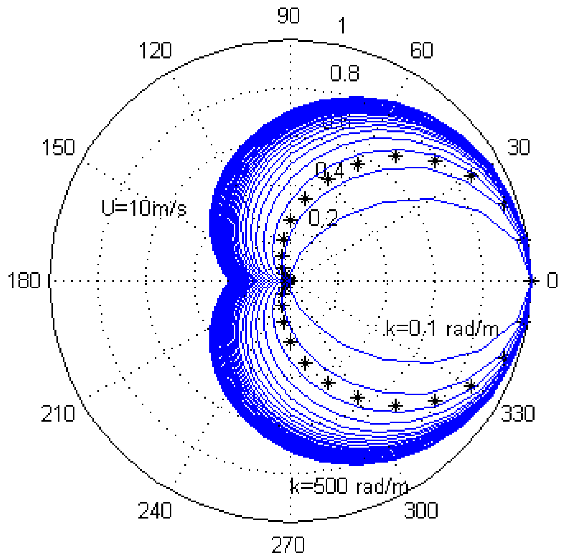
Sensitivity of parameters of Doppler spectrum model

Ocean wave spectrum used as known for retrieval;
Directional distribution function, wind speed , wind direction.

Comparison of different ocean wave spectrum



Comparison of different directional distribution function



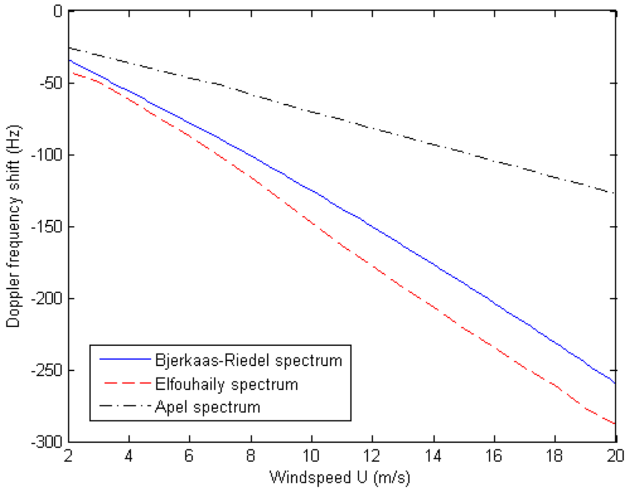
Blue lines: Gaussian function

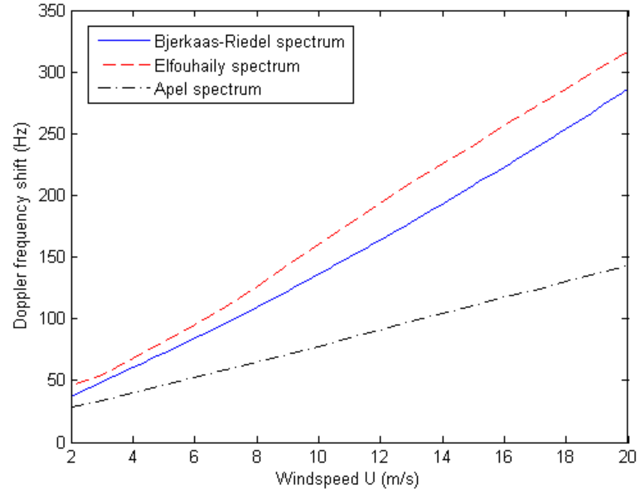
Black stars: Cosine function

The effect of ocean wave spectrum model

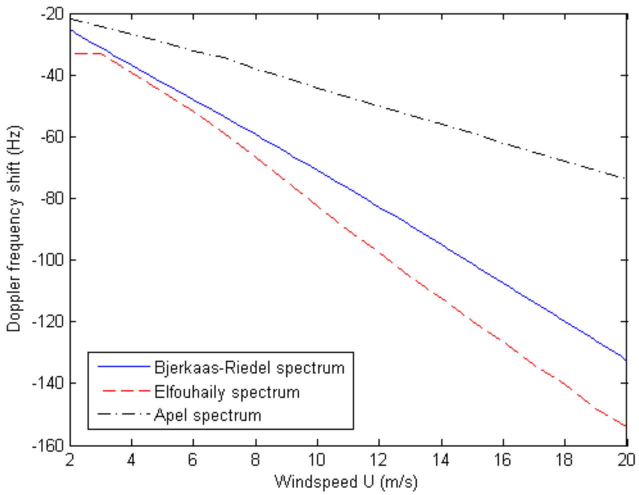
Downwind direction / **Upwind direction**

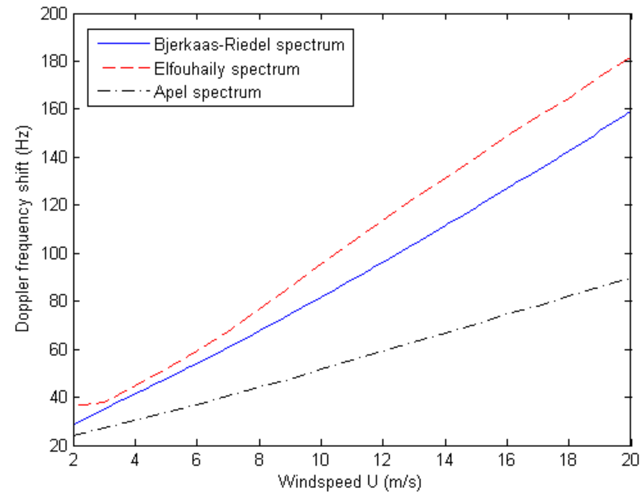
HH





VV

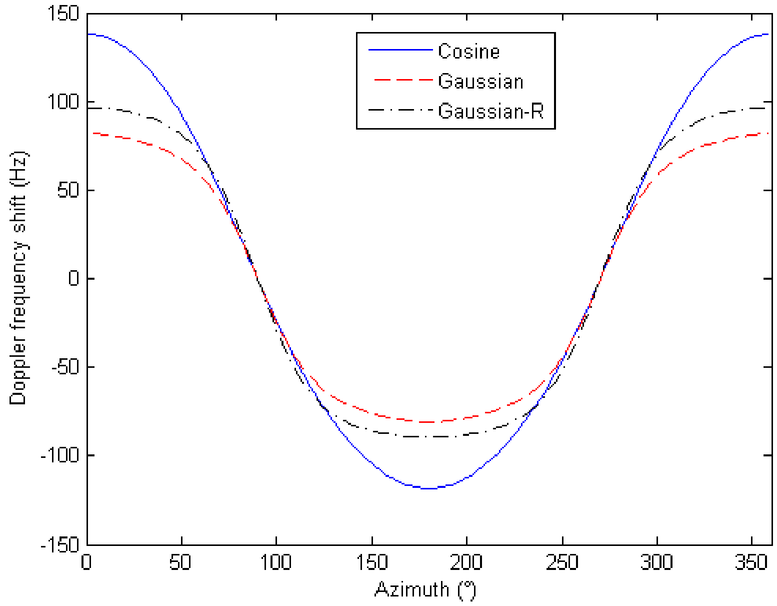




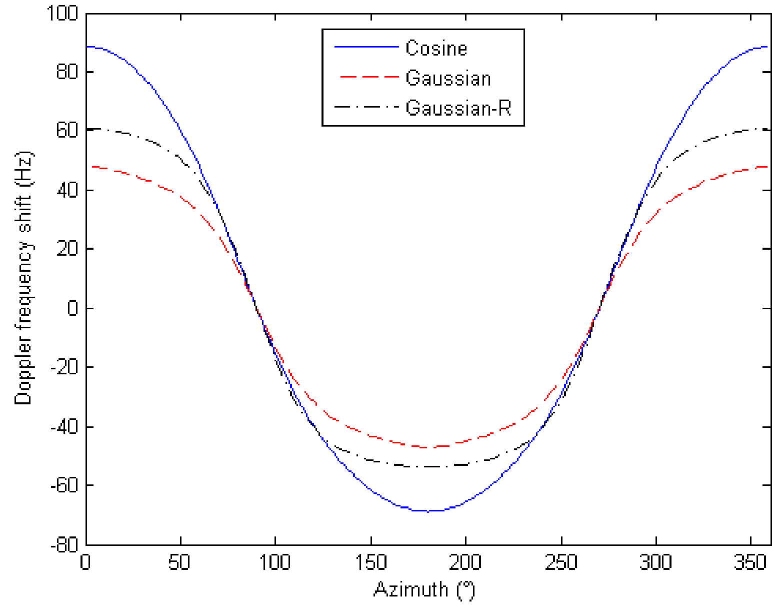
- Doppler frequency shift is sensitive to ocean wave spectrum models.
- High wind condition is more serious than that of low wind condition.
- VV polarization is better than that of HH polarization.

The effect of directional distribution function

HH polarization



VV polarization



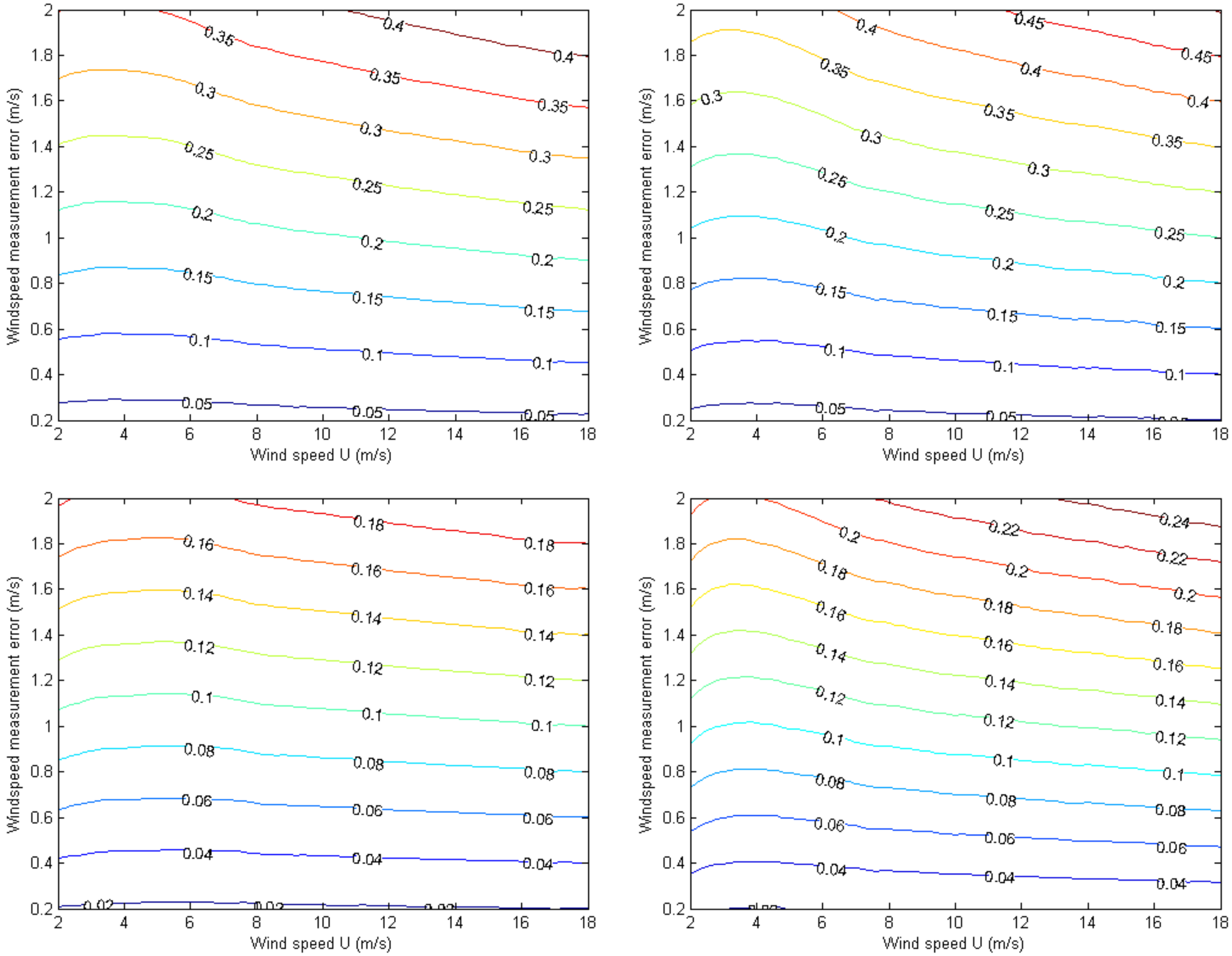
- Doppler frequency shift is sensitive to the directional distribution function in upwind and downwind directions.
- VV polarization is better than that of HH polarization.

The effect of wind speed determination error

Downwind direction | **Upwind direction**

HH

VV

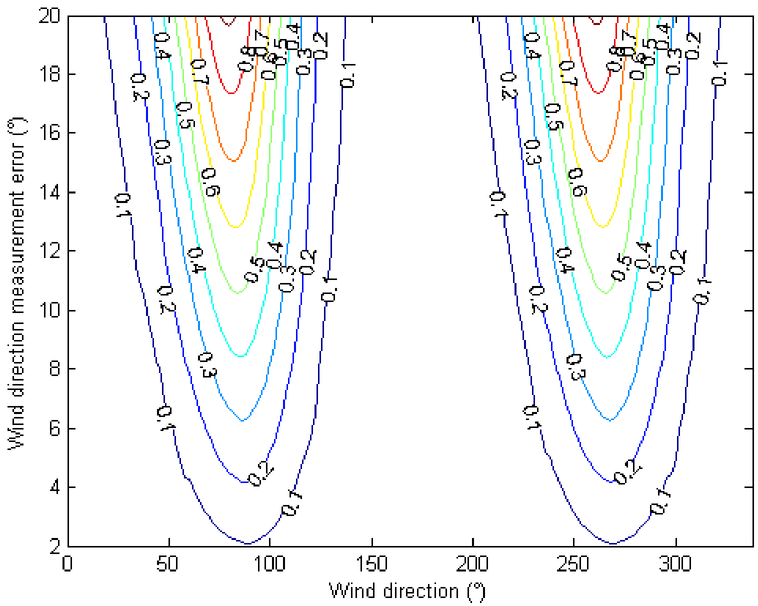


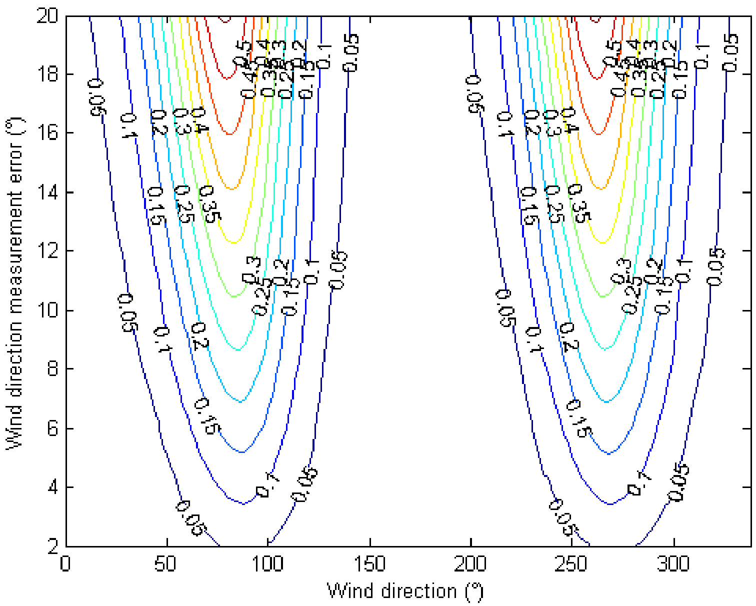
- Current speed retrieval error is sensitive to the wind speed determination error.

- VV polarization is better than that of HH polarization.

The effect of wind direction determination error

HH polarization **VV polarization**





- Current speed retrieval error is sensitive to the wind direction determination error in upwind and downwind directions.
- VV polarization is better than that of HH polarization.

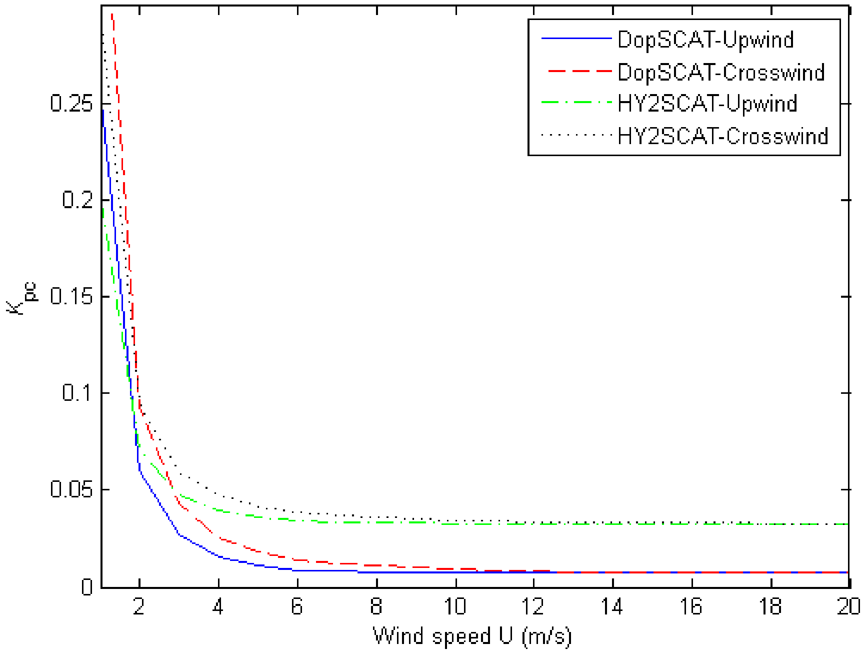
Effective swath width for current speed retrieval error smaller than the specified threshold value

(unit: km)

流速精度(m/s) \风速(m/s)	2	3	4	5	6	7	8	9	10	11	12	20
0.10	0	0	214	471	570	604	618	622	624	626	627	630
0.15	0	354	633	662	673	679	683	685	687	688	689	690
0.20	0	631	677	701	710	714	717	719	720	721	722	723
0.25	388	668	707	723	732	738	741	744	745	746	747	749
0.30	595	693	724	744	755	761	763	765	766	767	768	770
0.35	639	711	742	762	769	773	775	778	779	780	781	783
0.40	662	725	759	773	780	785	788	790	792	793	794	797
0.45	676	738	768	783	791	796	800	803	805	806	808	810
0.50	691	752	777	793	803	808	812	815	818	819	821	824

Communication error K_{pc}:

-Radiometric Accuracy of sigma 0



- Communication error K_{pc} is smaller than that of HY-2 scatterometer, when the wind speed is larger than 3m/s (orbit, power, antenna).
- The wind vector accuracy of doppler scatterometer can be improved significantly in high wind condition compared to traditional scatterometer.

Summary

- The effective swath with 0.1m/s speed accuracy for ocean surface current speed retrieval is about 60% of scatterometer's swath, when the wind speed is 7m/s.
- Current speed retrieval error is sensitivity to the Doppler spectrum model used for retrieval.
- VV polarization is better than that of HH polarization.
- The current speed retrieval error can be further reduced by long-time average.
- Communication error (K_{pc}) is smaller than of HY-2 scatterometer, when the wind speed is larger than 3m/s, and better wind performance can be expected.
- Further study for Ku/Ka dual-frequency system with higher resolution and SNR is undergoing.

Thanks！

Questions and Comments?