SIMULATION AND PERFORMANCE ANALYSIS OF THE AIRBORNE DOPPLERSCATT CONCEPT FOR SIMULTANEOUS MEASUREMENTS OF OCEAN SURFACE CURRENTS AND WINDS

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Jet Propulsion Laboratory (JPL)
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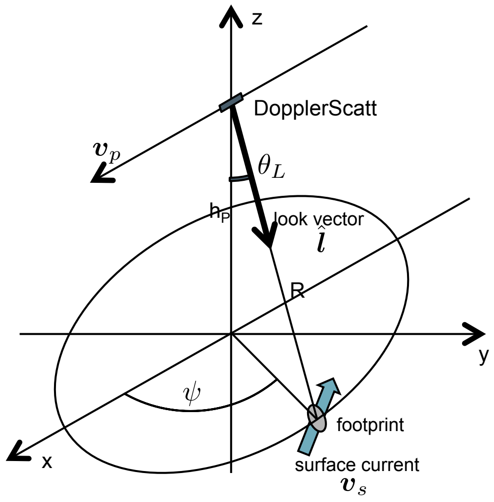
Earth Science & Technology Forum
Pasadena, CA - 6/23/15

Radar and Platform Configuration



Fixed parameters

- Nominal velocity: 180 m/s
- Nominal altitude: 8.2 km
- Frequency: 35.75 GHz
- Beamwidth: 2.9 deg
- Elevation angle: 55.9 deg
- SSPA Power 90 W
- Antenna Gain 35 dB
- Polarization VV

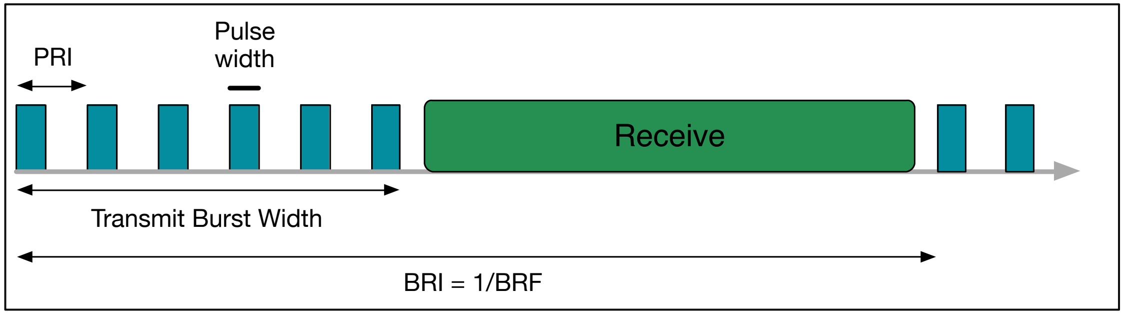
Derived characteristics

- Nominal azimuth footprint: 741 m
- Nominal elevation footprint: 1328 m
- Nominal range distance: 14.1 km – 15.2 km
- Nominal incidence angles: 54.55 deg – 57.47 deg

Requirements	
Velocity Bias	1.0 cm/s
Velocity Precision	10 cm/s
Wind Speed Accuracy	2 m/s (3-20 m/s) 10 % (20-30 m/s)
Wind Direction Accuracy	20 deg

Timing sceme:

- Rotation rate 9 rpm
- Burst Timing:
  - Number of pulses 6
  - Bandwidth 5 MHz
  - PRF 67.8 kHz
  - BRF 5.2 kHz



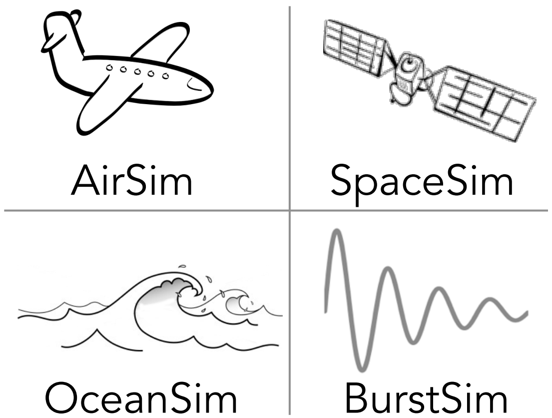
Simulator Requirements

- to understand measurement physics
- to emulate signal processing steps to fully understand all error sources and verify simplified models used by system engineering
- to evaluate global performance of retrieval accuracies
- to scale to space and to aid in space-borne design studies

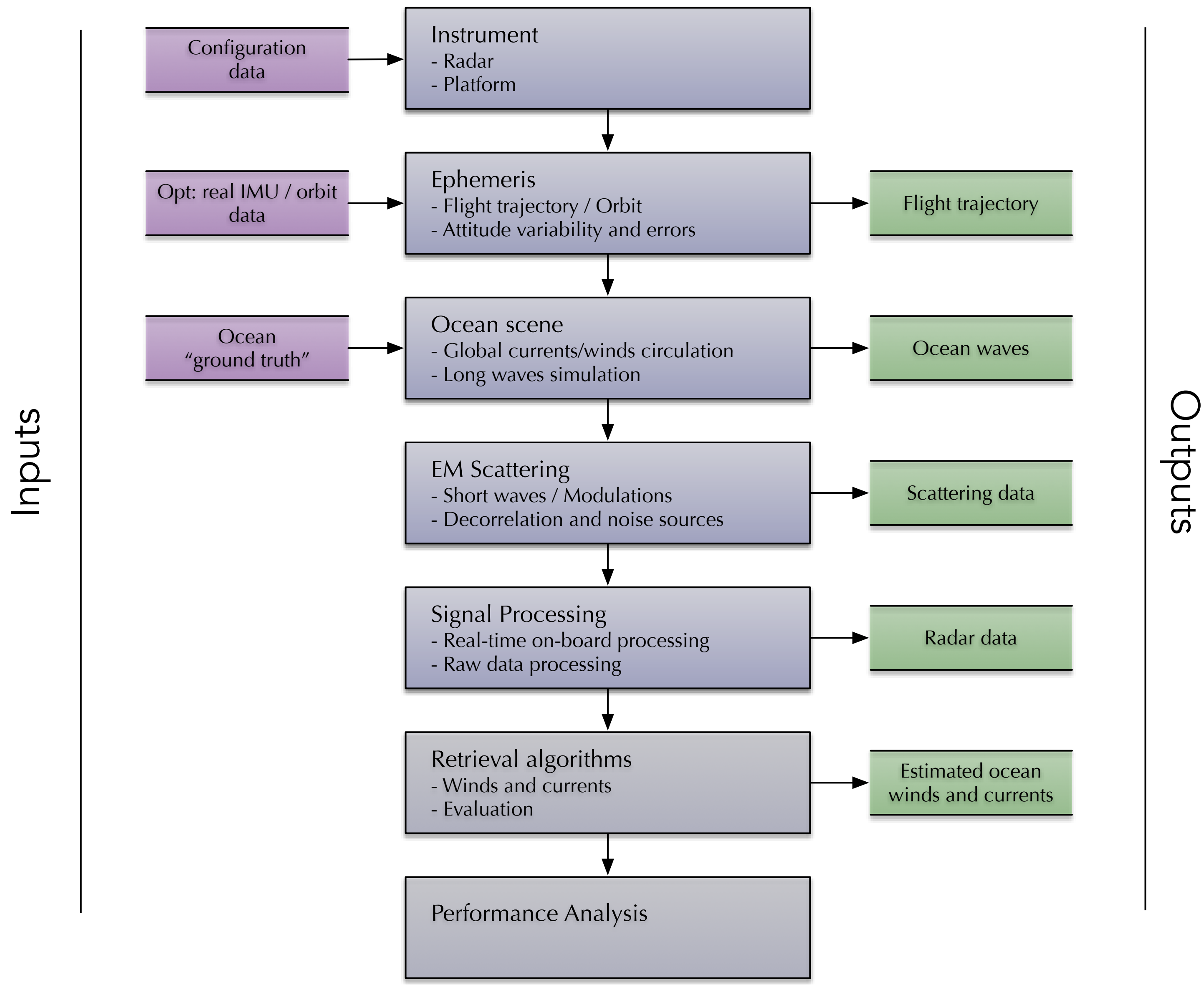
- Tasks:
  - Realistic air- and space-borne attitude and flight trajectory simulations
  - Ocean waves and their scattering simulation at high spatial and temporal scales
  - Signal processing simulation, including most hardware, signal, and geophysical error sources
  - Global end-to-end simulation of flight, radar operation, data acquisition, processing, and retrievals

- Implementation:
  - python3, modular, parallelized, git version control

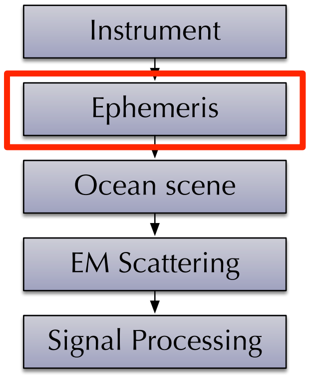
DopplerScatt Simulator



DSCAT Simulation Work Flow



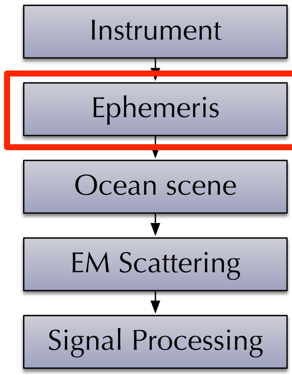
Ephemeris Module

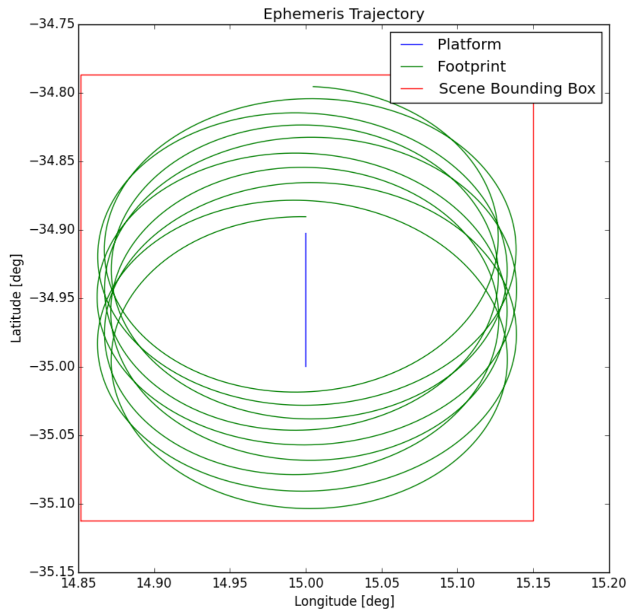


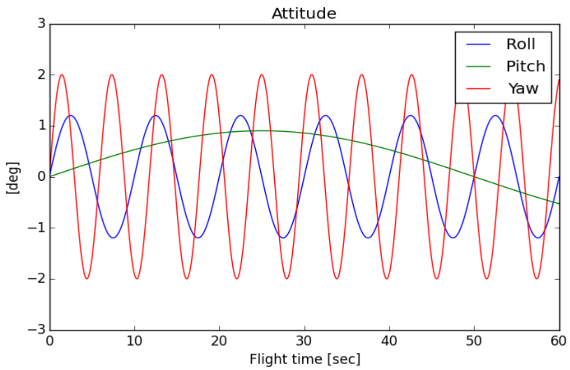
- Goal: simulation of realistic trajectories including errors and uncertainties
- Data acquisition over an extended trajectory
  - minutes to hours
  - simulating radar observables on a large scale
- Can work with real flight/IMU data or can simulate trajectories based on specifications
- Including plane and spinning mechanism errors and uncertainties
  - positioning, attitude, velocity, rotation rate, antenna pointing

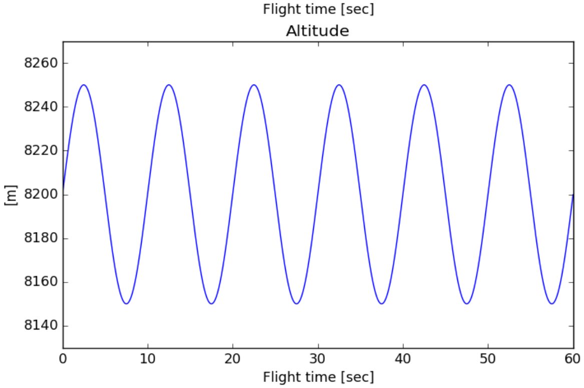
Example: Airborne Flight Trajectory

- 10 minutes flight time
- adding variability in plane attitude and altitude
- starting position (west of Cape Town)
  - Latitude: -35 deg
  - Longitude: -15 deg
  - Heading: North



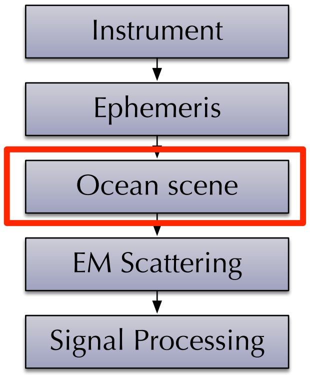


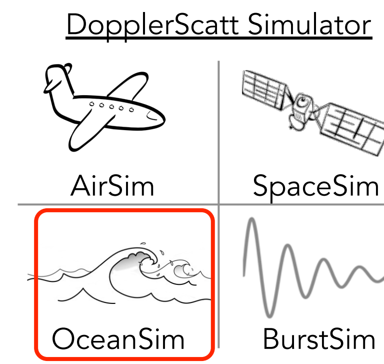




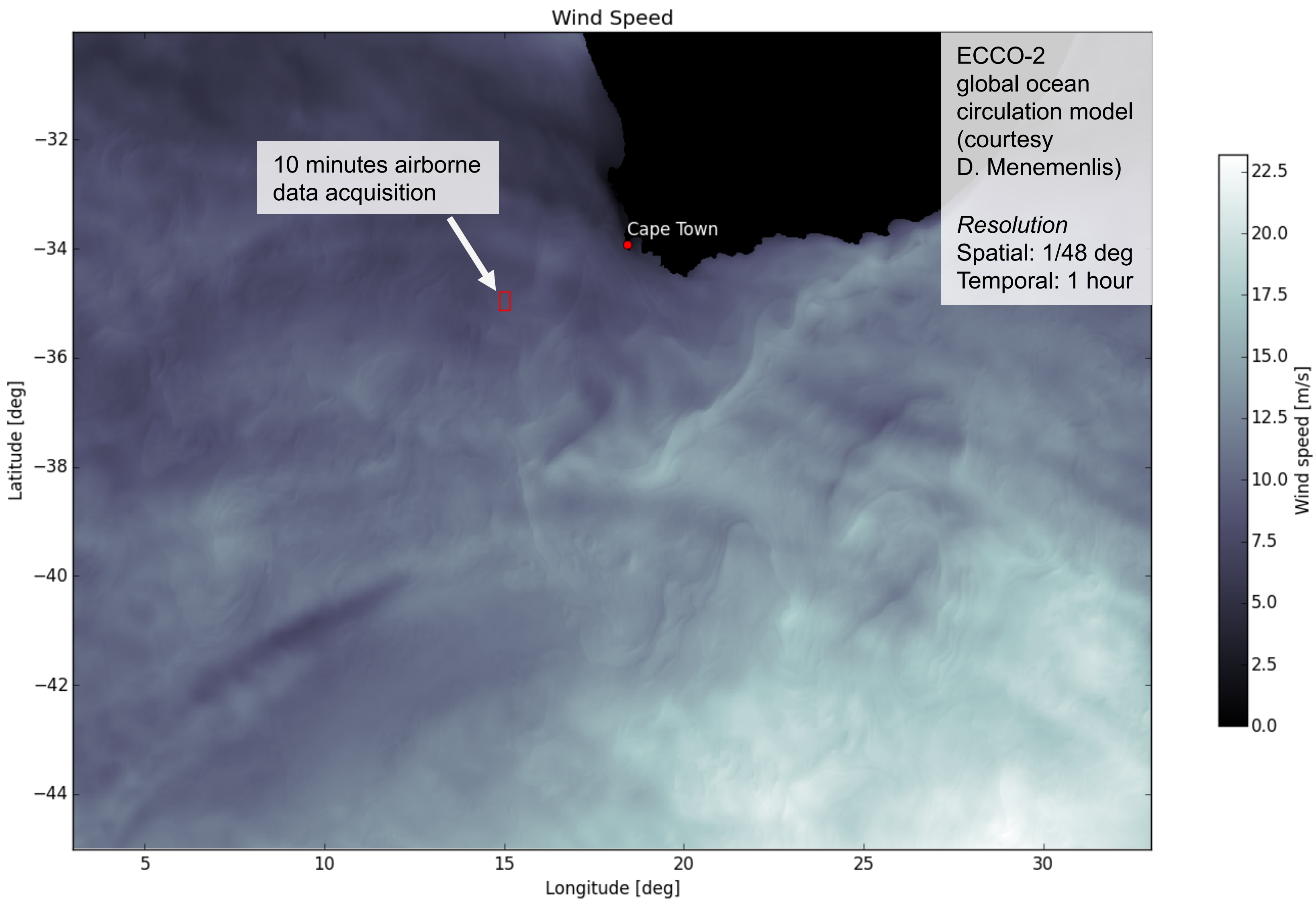
Ocean Scene Module

- Goal: accurate simulation of ocean waves and currents with high spatial and temporal resolution
- “Ground truth” from external global ocean circulation models and simulations:
  - ECCO-2 or WRF
  - Only low spatial and temporal resolution (km and hours scale)
- Include ocean state properties
  - Temperature, pressure, salinity, permittivity, density, viscosity
  - Wave fetch, swell
  - Dispersion relationships for gravity, gravity-capillar waves, for deep and shallow depths.
- Local ocean simulation based on ocean waves spectrum
  - different empirical and analytical spectra implemented
- Simulating long-wave ocean surface map at high resolution for further scattering computations





Ocean scene: underlying ground truth



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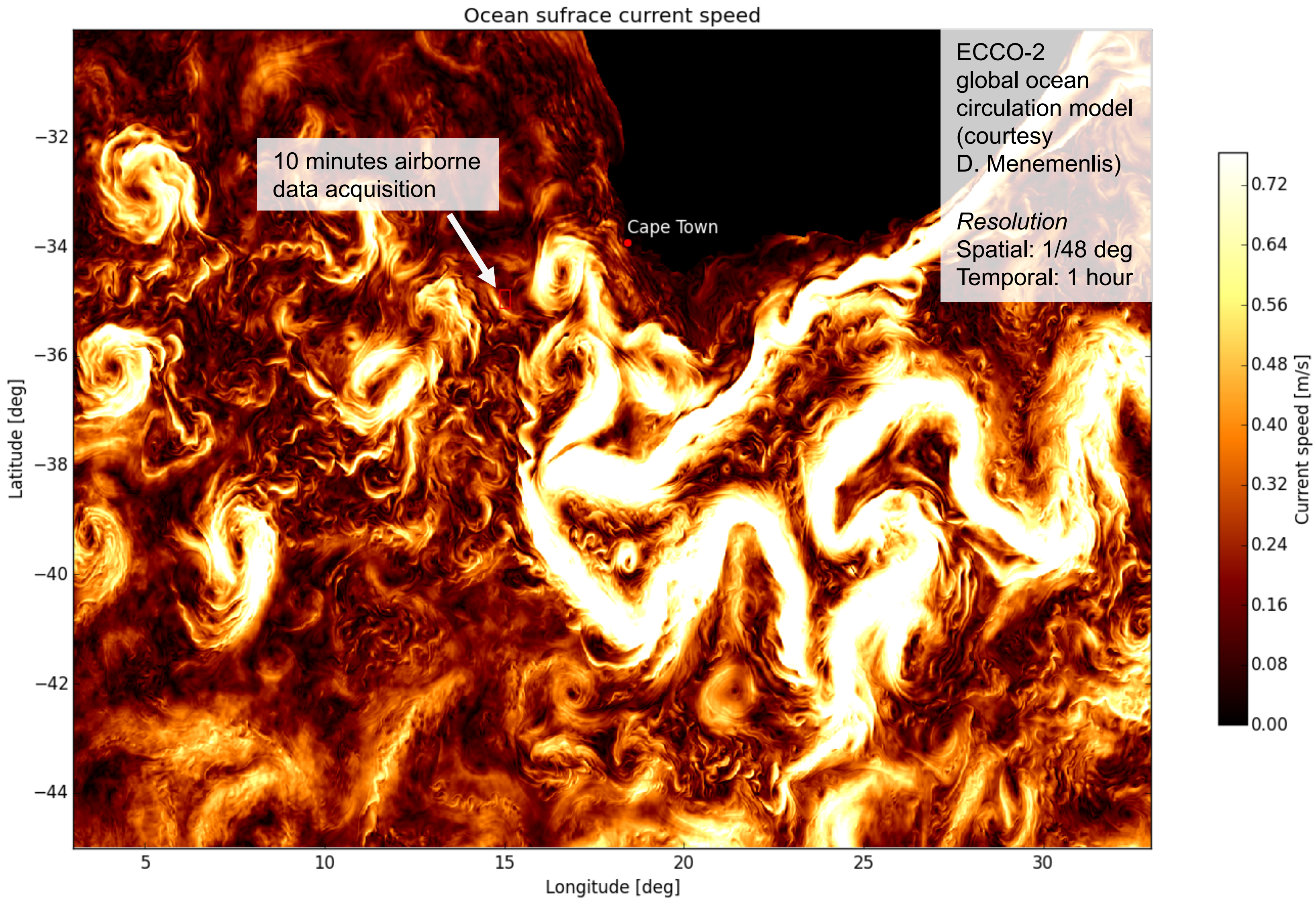
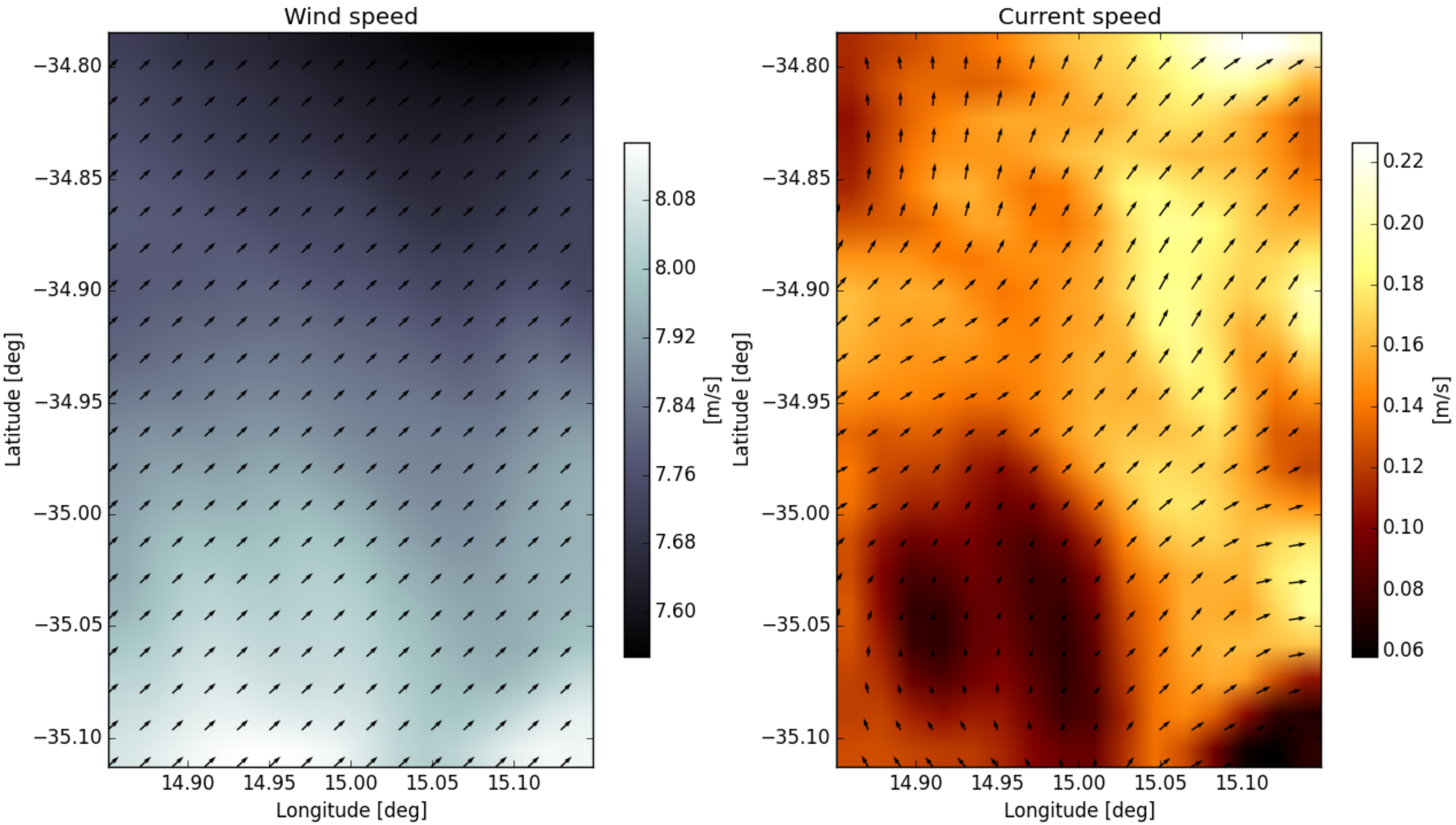


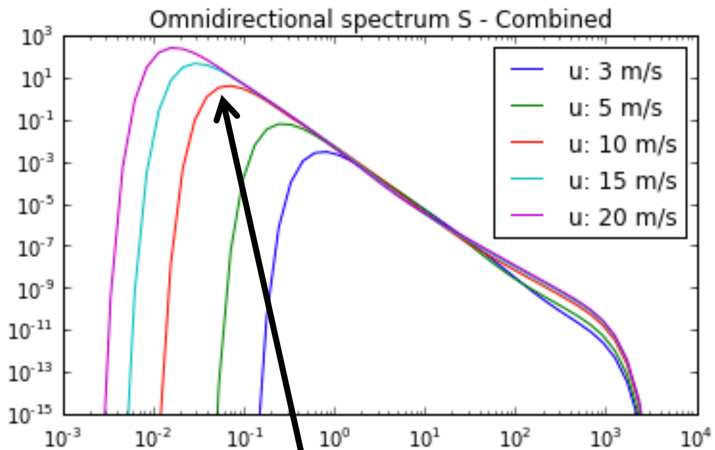
Example: winds and currents

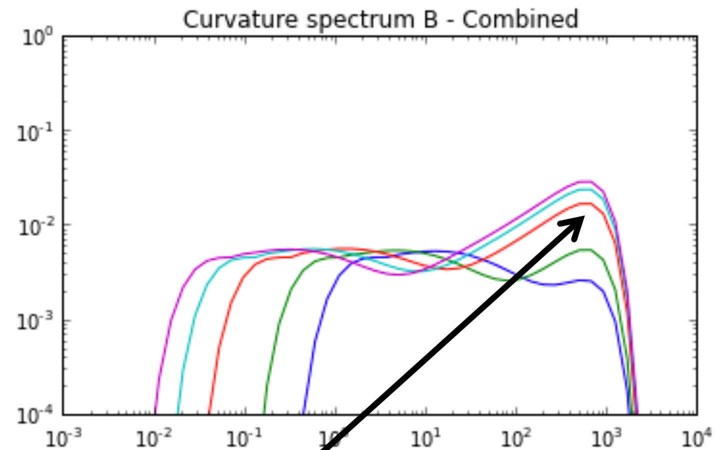


Ocean waves spectrum

Ocean Waves Spectrum for low- and high-frequency waves:

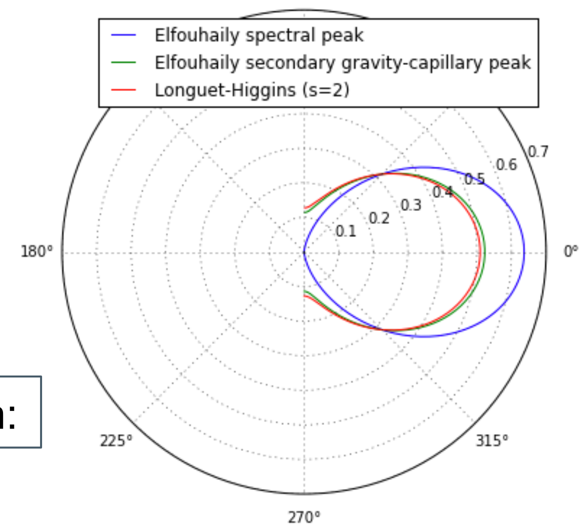
Omnidirectional spectrum:





Spectral gravity peak (wind dependent)

Secondary gravity-capillary peak



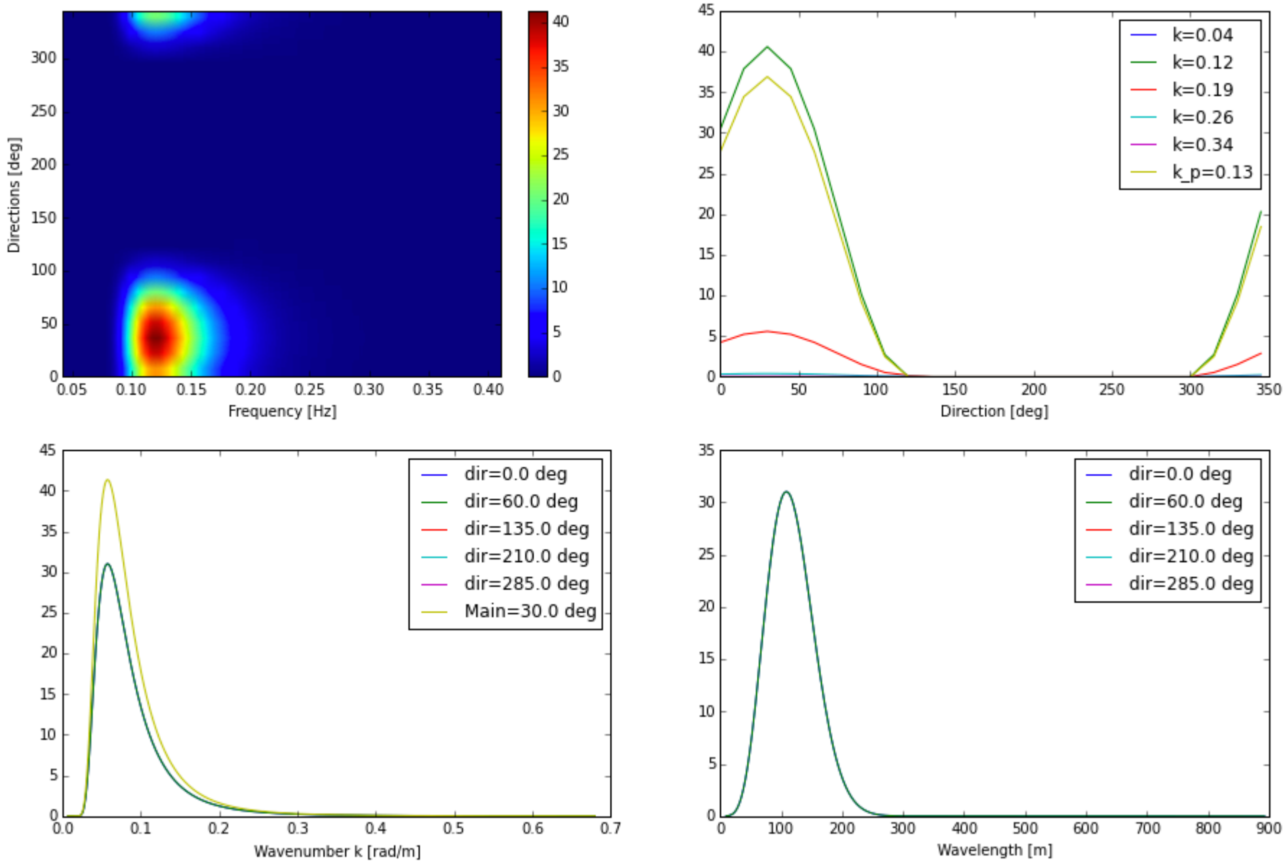
Spreading function:

T. Elfouhaily; B. Chapron; K. Katsaros; D. Vandemark, "A unified directional spectrum for long and short wind-driven waves", Journal of Geophysical Research: Oceans (1978–2012). 1997.

Example: ocean waves spectrum

<u>Example Spectrum:</u>

- wind speed of 10 m/s
- mean wind direction: 30 degrees
- deep, with large fetch



Example: simulated ocean waves

<u>Example Simulation:</u>
- wind speed of 10 m/s
- mean wind direction: 30 degrees
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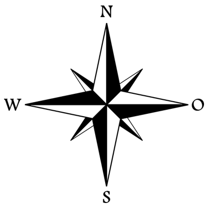
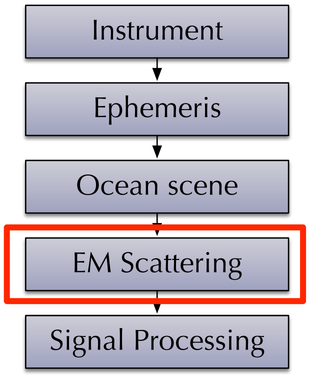


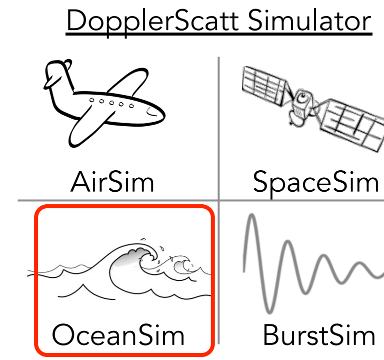
Duration: 30 sec
Real time scale.

Resolution
Spatial: 5 m
Temporal: 1 sec

EM Scattering Module

- Goals:
  - Accurate simulation of electromagnetic microwave scattering from ocean surfaces
- Development of a new geophysical model function (GMF) for operational retrieval of ocean surface currents and winds
  - Ka-band
  - Vertical and horizontal polarizations (optionally circular and linear)
  - Incidence angles range: 49-63 degrees
- Backscatter simulation using two-scale model:
  - Bragg resonance scattering (small perturbation model) in capillary waves range
  - Modulation by long waves
- Modulation Transfer Functions (MTF) of short waves by long waves:
  - geometrical: tilt, range bunching
  - hydro-dynamic modulations: non-linear wave breaking
- Speckle and decorrelation noise sources



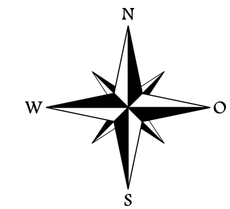


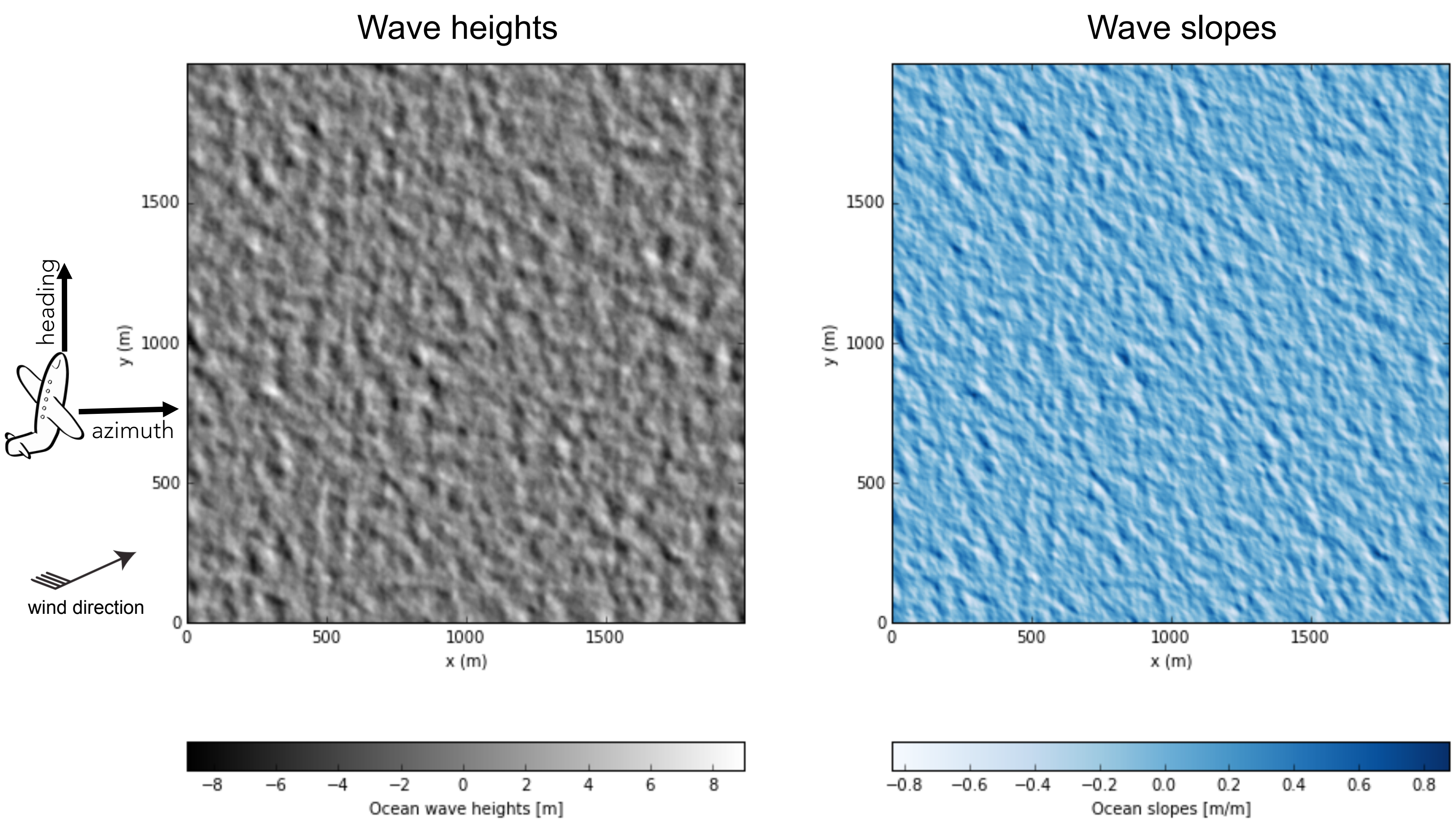
Example: ocean scattering simulations

<u>Example ocean scattering simulation:</u>

- wind speed of 10 m/s
- mean wind direction: 30 degrees
- deep, with large fetch

- radar azimuth / look direction: 0 deg (East)
- radar flight direction: 90 deg (North)
- radar (flat) incidence angle: 56 deg





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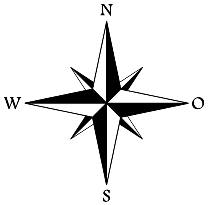

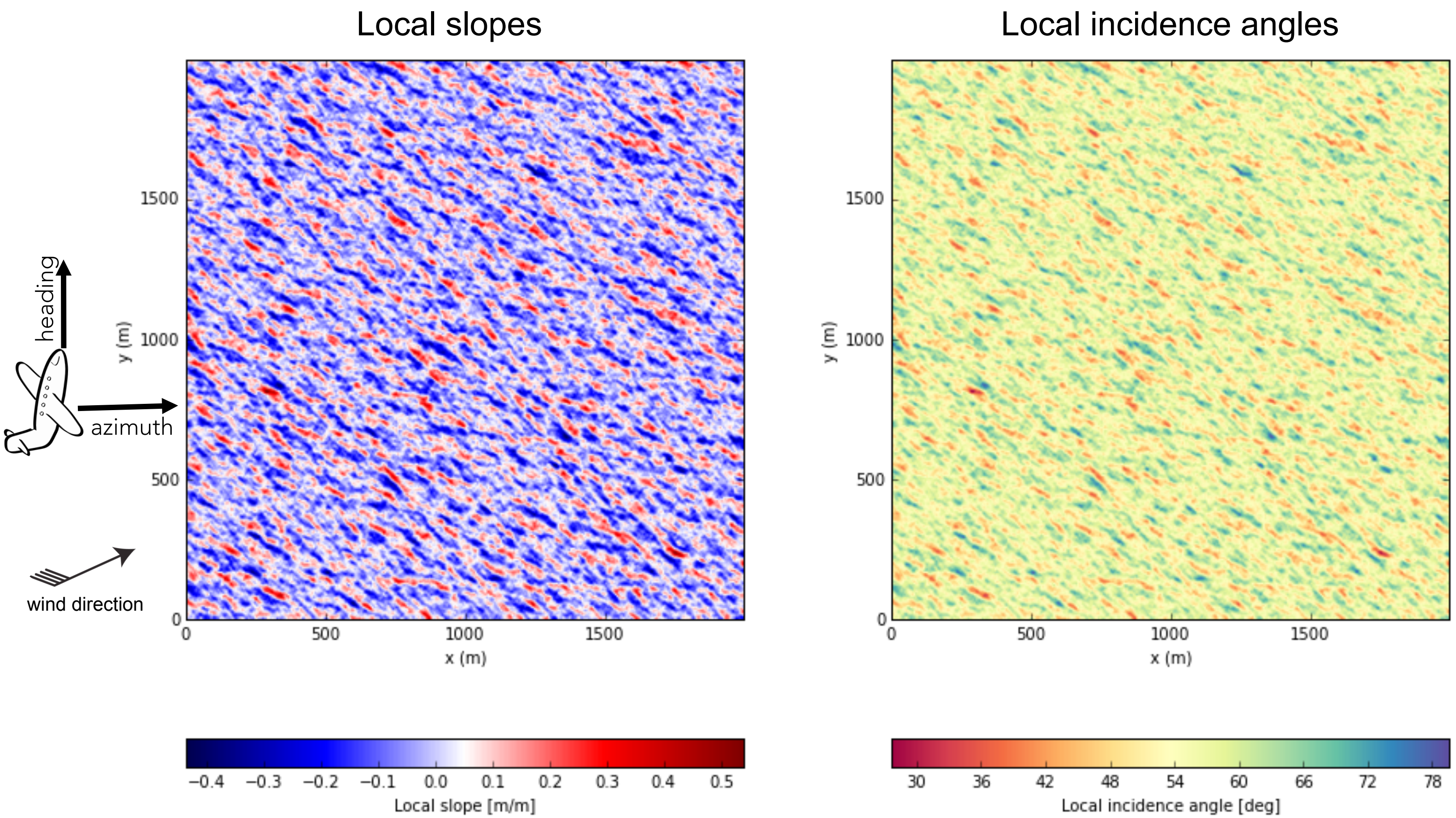

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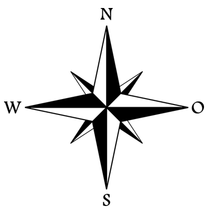
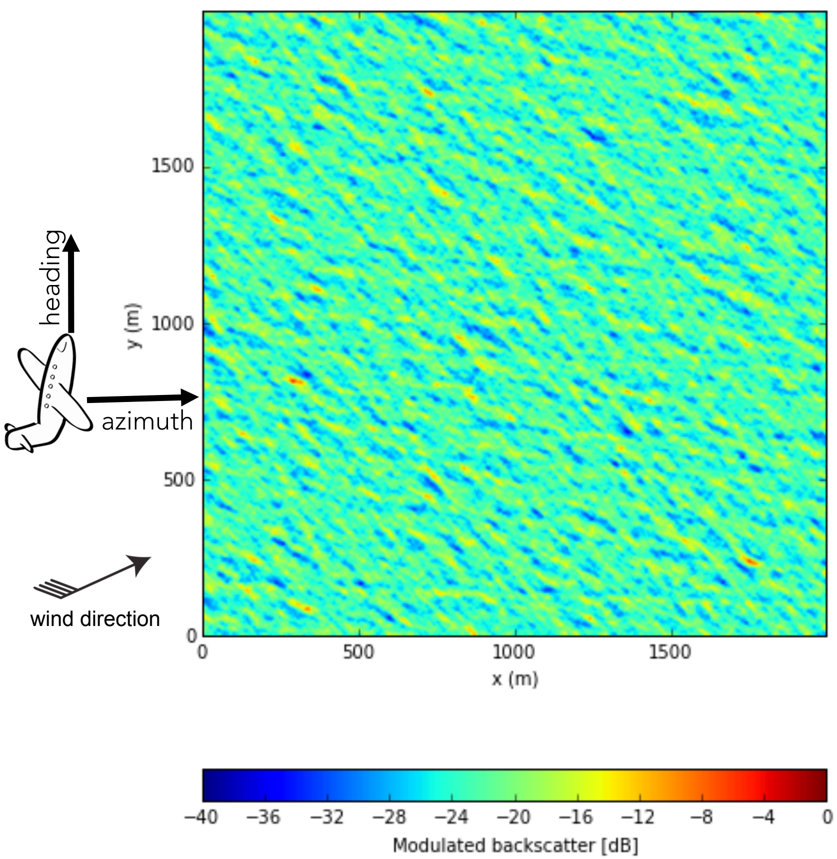
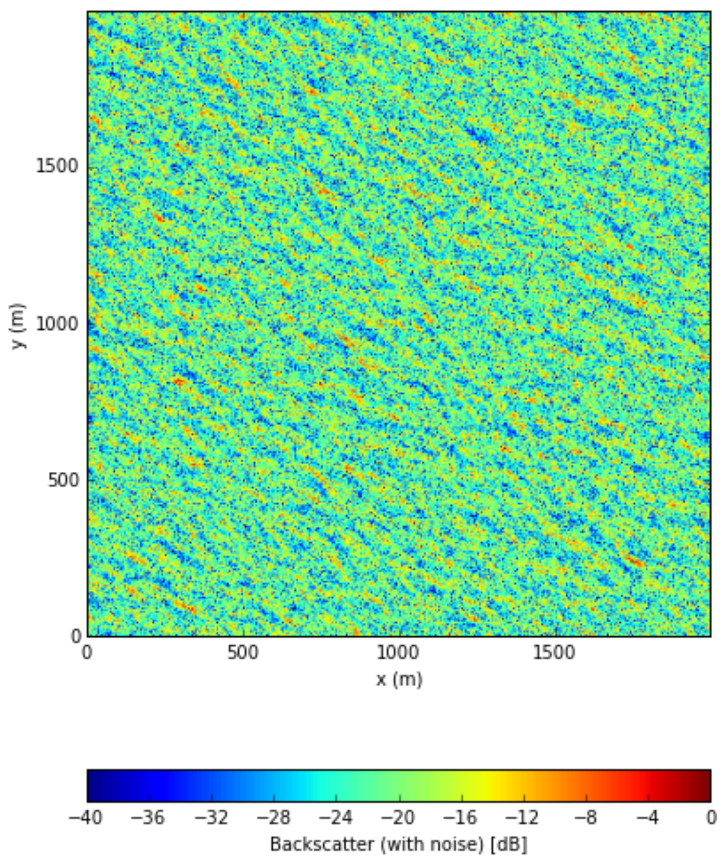


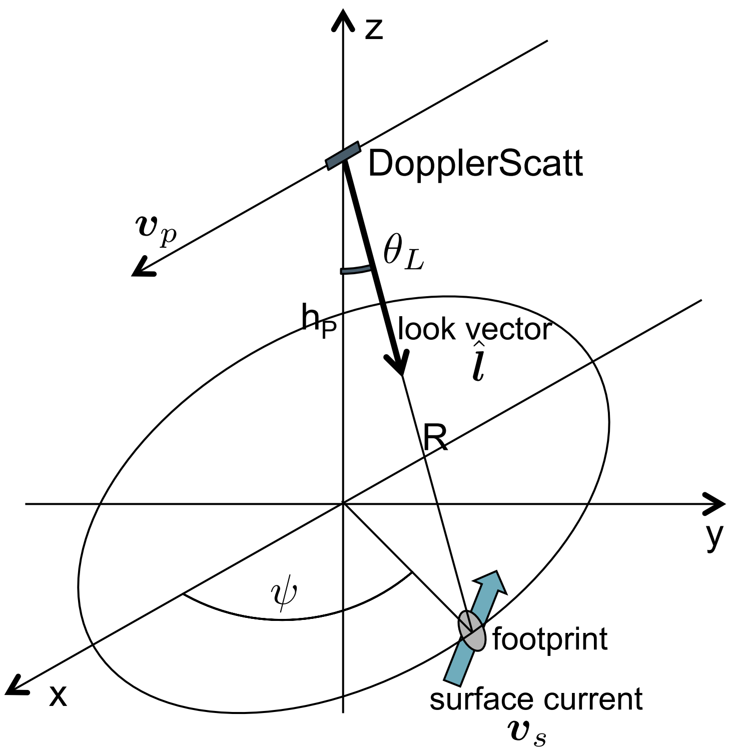
Backscatter (after modulation)



Backscatter (with Speckle noise)



System Error Analysis: Surface Velocity Model



Pulse-pair phase model

$$\langle E_1 E_1^* \rangle = A; \qquad \langle E_1 E_2^* \rangle = A\gamma e^{i\phi}$$

$$\phi = \phi_1 - \phi_2 = \arg(s_1 s_2^*) = 2k(R_2 - R_1) = \frac{4\pi}{\lambda}\tau v_r$$

where radial velocity is a combination of platform velocity, surface currents velocity and wind velocity components.

Surface velocity model

$$v_{rs} = \boldsymbol{v}_s \cdot \hat{\boldsymbol{l}} = v_s \sin\theta \cos\psi_s$$

$$= -\frac{\lambda}{4\pi\tau}\phi + v_{rp} - v_{rR} - v_{rG} - v_{rA}$$

Decorrelation sources model

$$\gamma = \gamma_{temp}\gamma_{therm}\gamma_{doppler}\gamma_{range}\gamma_{quant}$$

Sensitivity of estimated velocity

$$\delta v_{rs} = -\frac{\lambda}{4\pi\tau}\delta\phi - \frac{\phi}{4\pi\tau}\delta\lambda + \frac{\lambda\phi}{4\pi\tau^2}\delta\tau + \delta v_{rp} - \delta v_{rR} - \delta v_{rG} - \delta v_{rA}$$

System Error Analysis: Sensitivity of Velocity Estimate

$$\delta v_{rs} = -\frac{\lambda}{4\pi\tau}\delta\phi - \frac{\phi}{4\pi\tau}\delta\lambda + \frac{\lambda\phi}{4\pi\tau^2}\delta\tau + \delta v_{rp} - \delta v_{rR} - \delta v_{rG} - \delta v_{rA}$$

- Phase
  - All random decorrelation sources
  - Systematic errors from hardware implementation
- Frequency
  - Drifts in the stable local oscillator (STALO)
- Timing
  - Digital timing jitter
  - LO timing jitter
- Platform velocity
  - Next slide
- Random variations bias
  - Cross-section modulations by surface waves and current divergence
- Spatial gradient bias
  - Spatial current and wind speed gradient
- Asymmetry bias
  - System illumination asymmetries

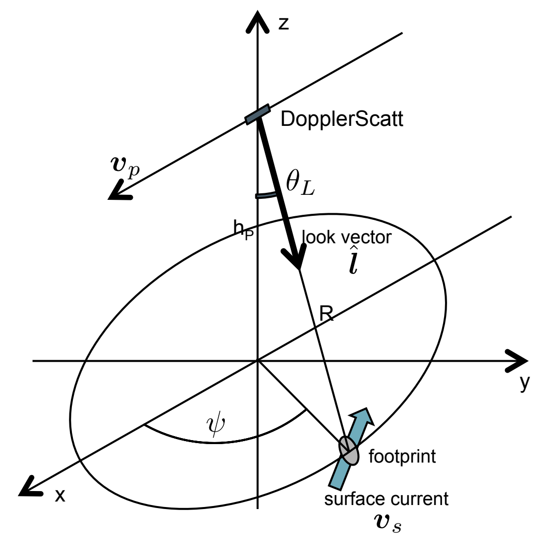
System Error Analysis: Sensitivity of Platform Velocity and Attitude

- Platform velocity
  - Assuming platform motion is aligned along the x-axis:

$$v_{rp} = \boldsymbol{v}_p \cdot \hat{\boldsymbol{l}}, \quad \text{where} \quad \hat{\boldsymbol{l}} = \begin{bmatrix} \sin\theta\cos\psi \\ \sin\theta\sin\psi \\ -\cos\psi \end{bmatrix}, \ \boldsymbol{v}_p = \begin{bmatrix} v_p \\ 0 \\ 0 \end{bmatrix}$$

$$= v_p \sin\theta\cos\psi$$

$$\delta v_{rp} = \sin\theta\cos\psi\delta v_p + v_p\cos\theta\sin\psi\delta\theta - v_p\sin\theta\sin\psi\delta\psi$$



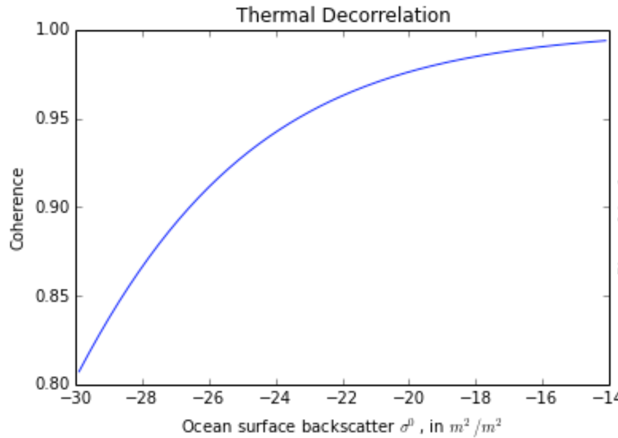
- Velocity error
  - IMU
- Incidence angle
  - Range error (due to timing errors and the knowledge of the water surface elevation)
- Azimuth angle
  - IMU
  - Spin encoder measurements

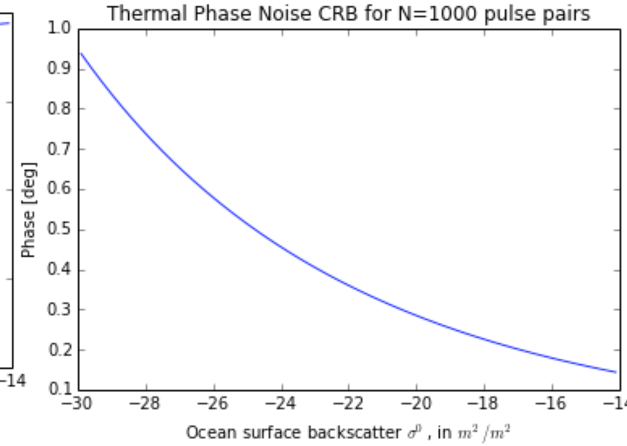
Chirped System Preliminary Performance: Decorrelation Sources

- Thermal decorrelation:

$$\gamma_{therm} = \frac{SNR}{SNR+1}$$

$$SNR = \frac{P_t G_t G_r \lambda^2 A \sigma^0}{(4\pi)^3 R^4 k T f_s L}$$



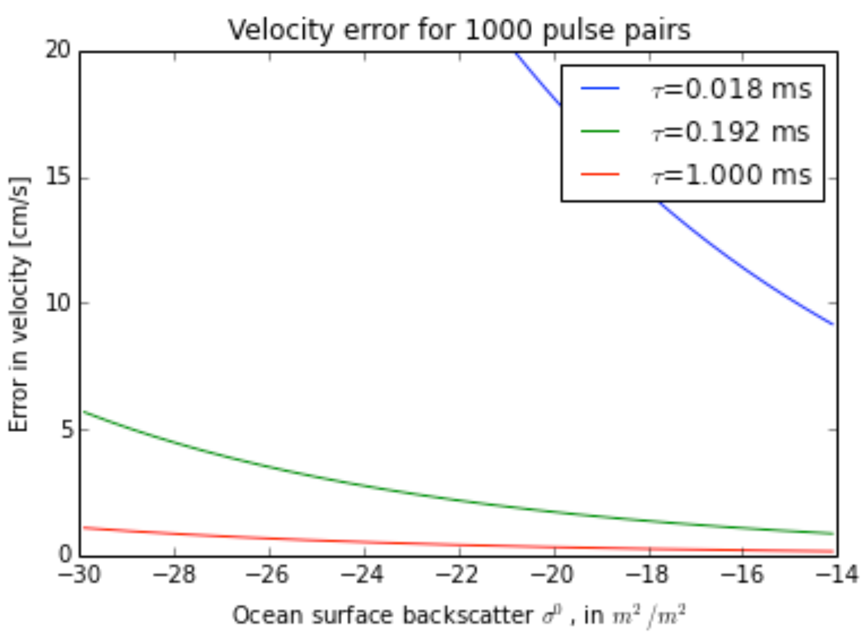


- Cramer-Rao Lower Bound for phase SDEV for N independent pulse pairs (N>4):

$$\sigma_\phi = \frac{1}{\sqrt{2N}} \frac{\sqrt{1-\gamma^2}}{\gamma}$$

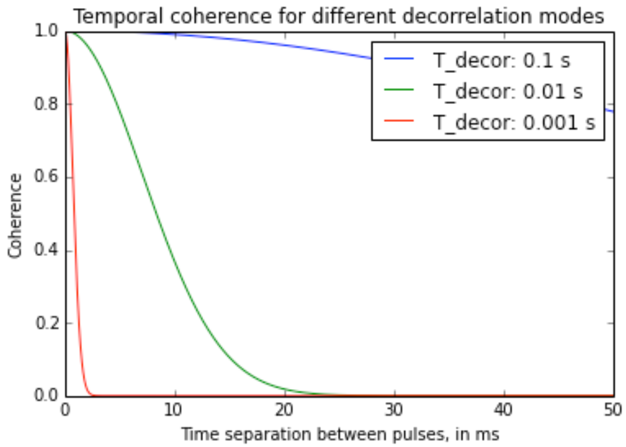
- Radial velocity error:

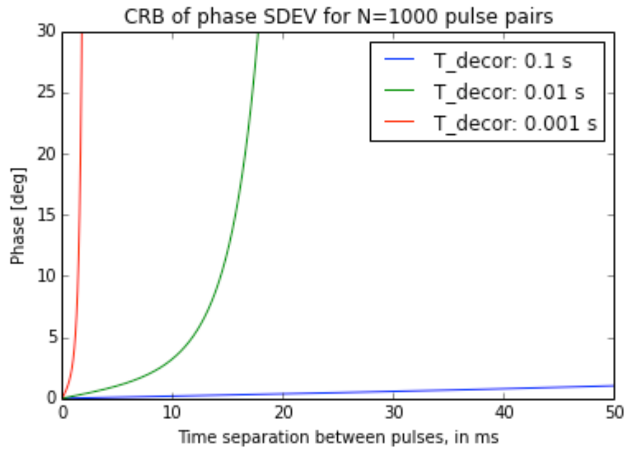
$$\delta v_{rs} = \frac{\lambda}{4\pi\tau}\delta\phi$$

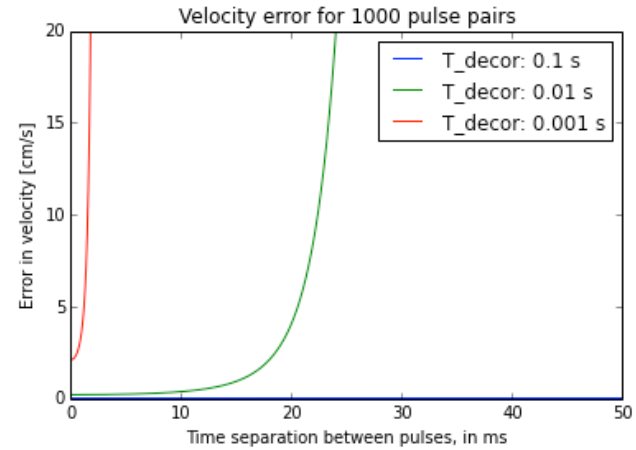


Performance: Decorrelation Sources

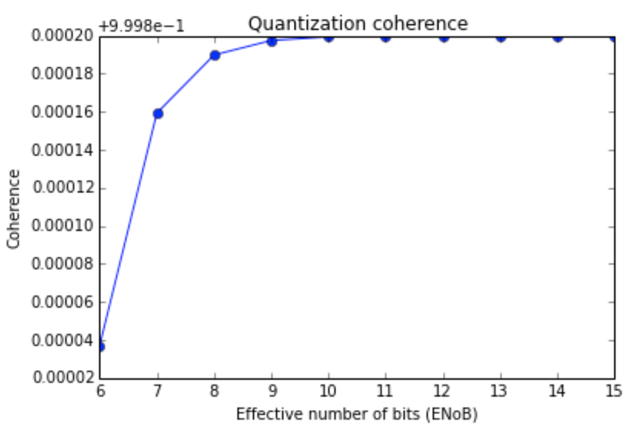
- Temporal coherence depends on time scale, wind/wave/current characteristics and interactions.
- An exponential decay model is used here, however we will have to estimate it empirically from the data

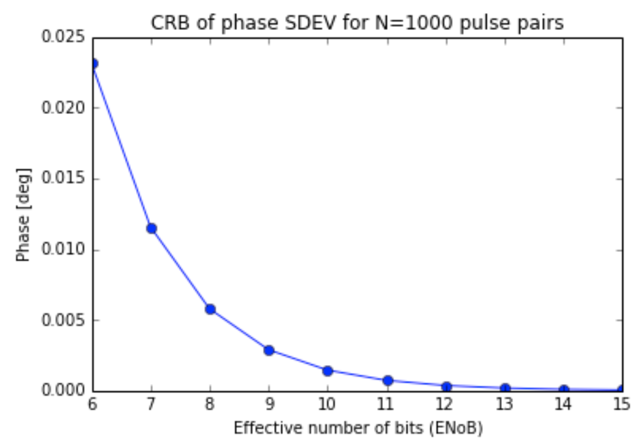


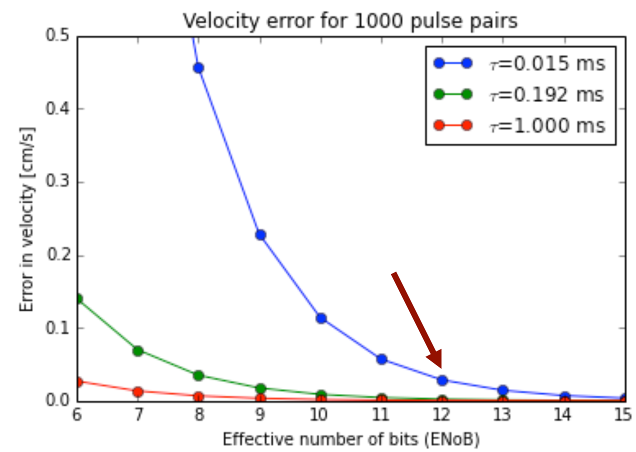




- Quantization errors

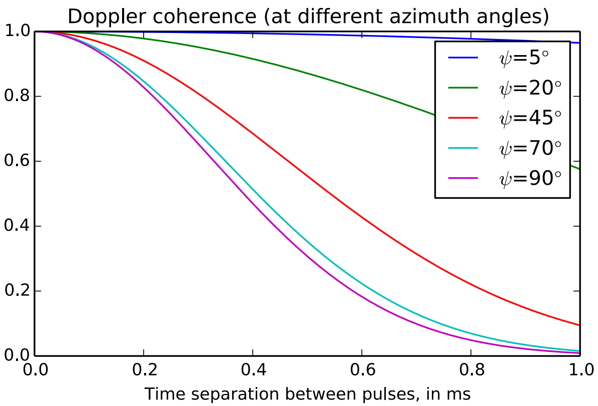


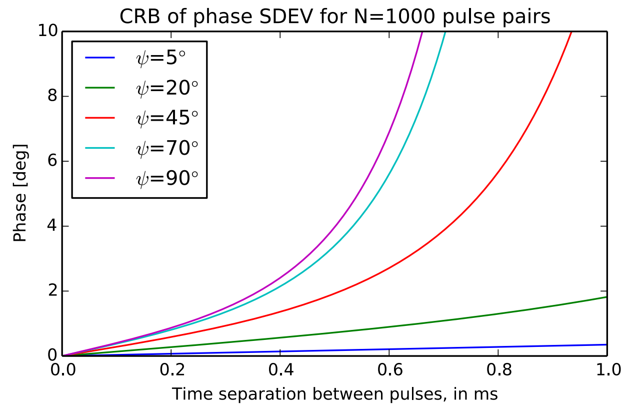


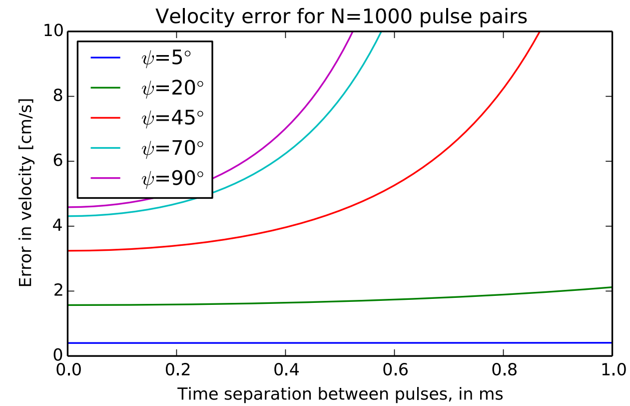


Chirped System Preliminary Performance: Decorrelation Sources

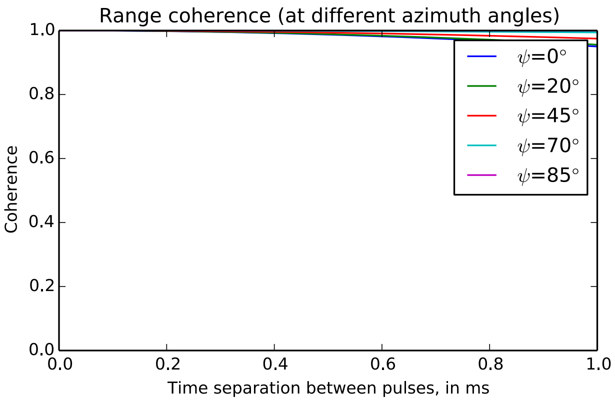
- Doppler decorrelation due to variation of the Doppler in azimuth direction.

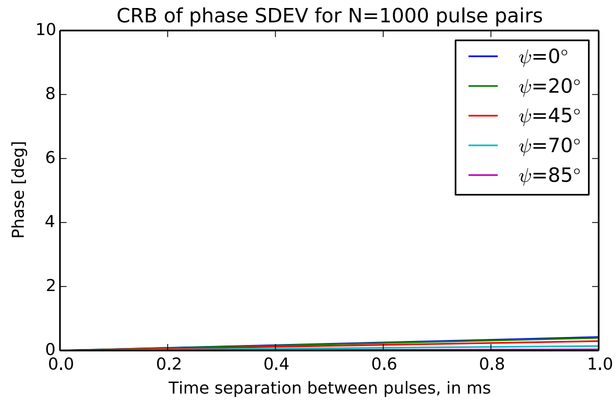


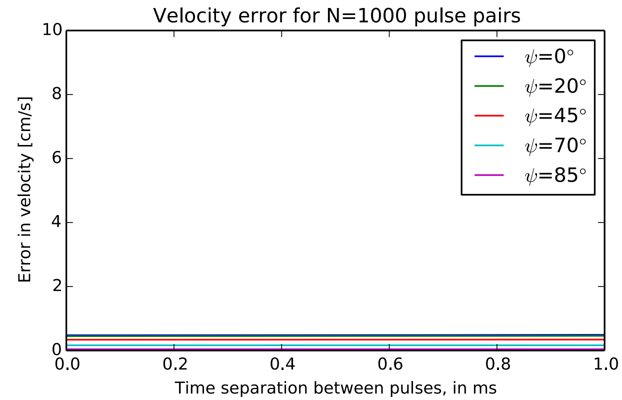




- Range decorrelation due to variation of the Doppler in the range direction.



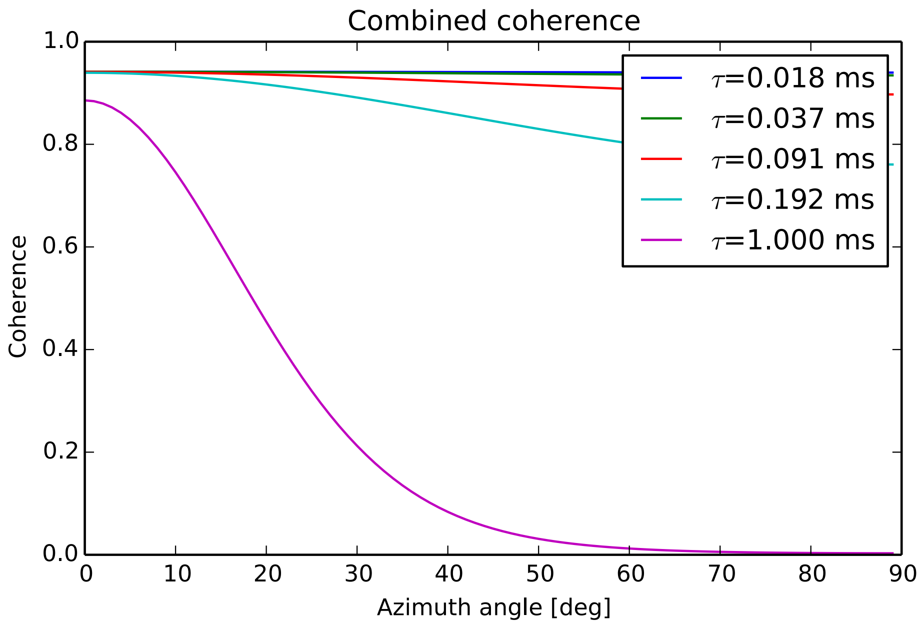


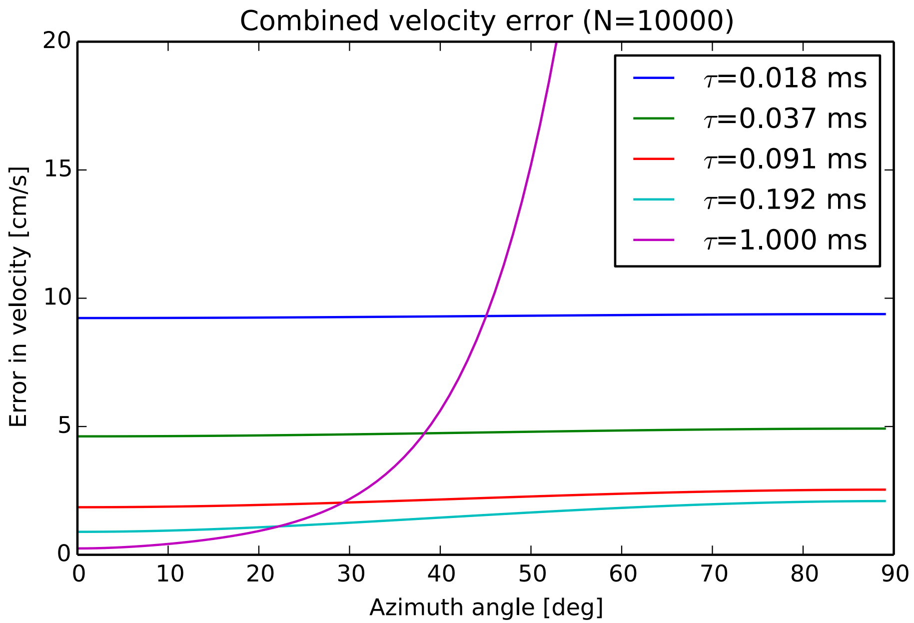


Chirped System Preliminary Performance: Decorrelation Sources Combined

- Individual times and azimuth angles

$$\gamma = \gamma_{temp}\gamma_{therm}\gamma_{doppler}\gamma_{range}\gamma_{quant}$$

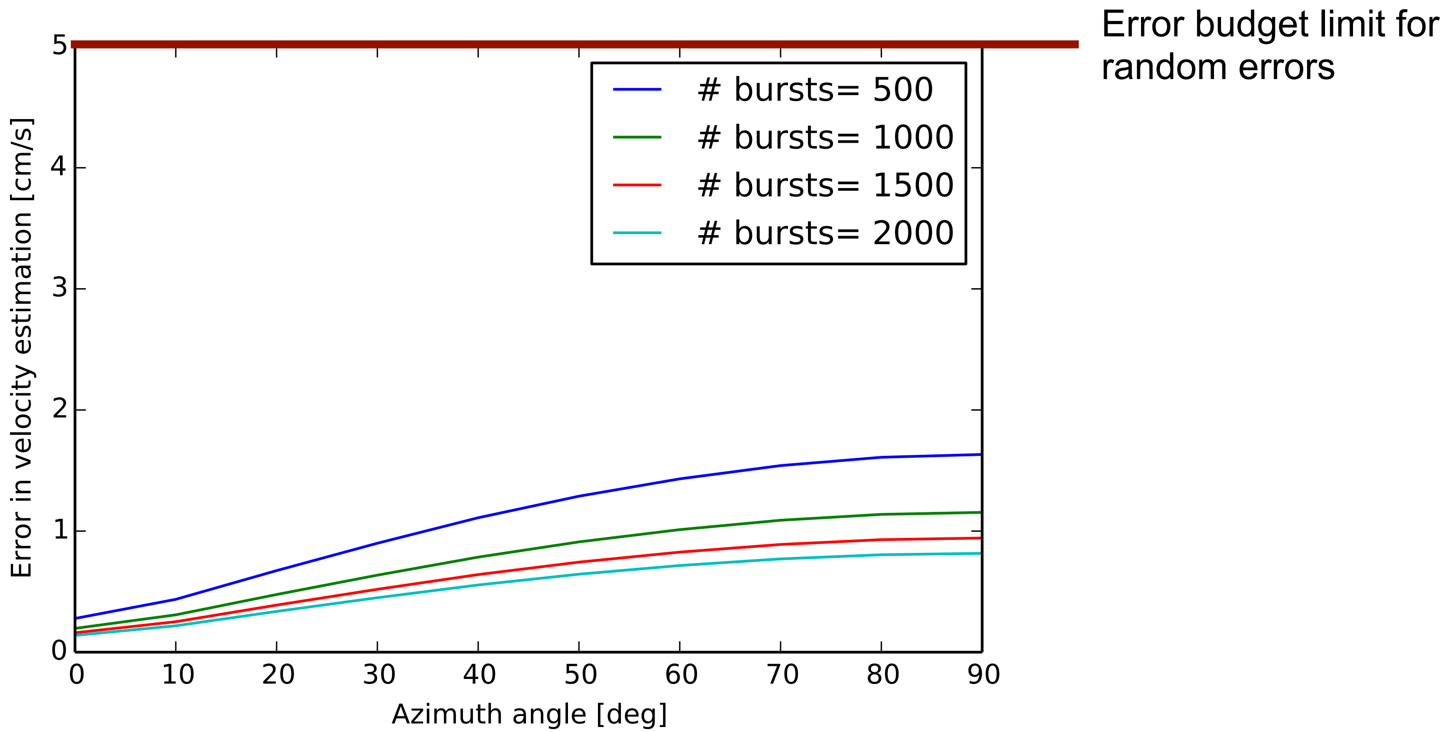




- Maximum number of pulses inside a resolution cell: > 56,000 (same azimuth), > 113k (both azimuth)
- Phase and coherence are non-linear functions of pulse combinations
- Enables cross-correlating pulses with short and long time intervals, enhancing the estimation

Chirped System Preliminary Performance: Decorrelation Sources Combined

- Combining cross-correlating pulse pairs with different time intervals:
  - > 56,000 pulses (> 2,200 bursts) per rotation over the cell
  - > 4 rotation scans over the cell



- Maximum number of pulses inside a resolution cell: > 56,000 (same azimuth), > 113k (both azimuth)
- 10 range bins per pulse
- Phase and coherence are non-linear functions of pulse combinations
- Enables cross-correlating pulses with short and long time intervals, enhancing the estimation

DopplerScatt Simulation and Performance Analysis

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Backup Slides

Why Measure Ocean Currents?

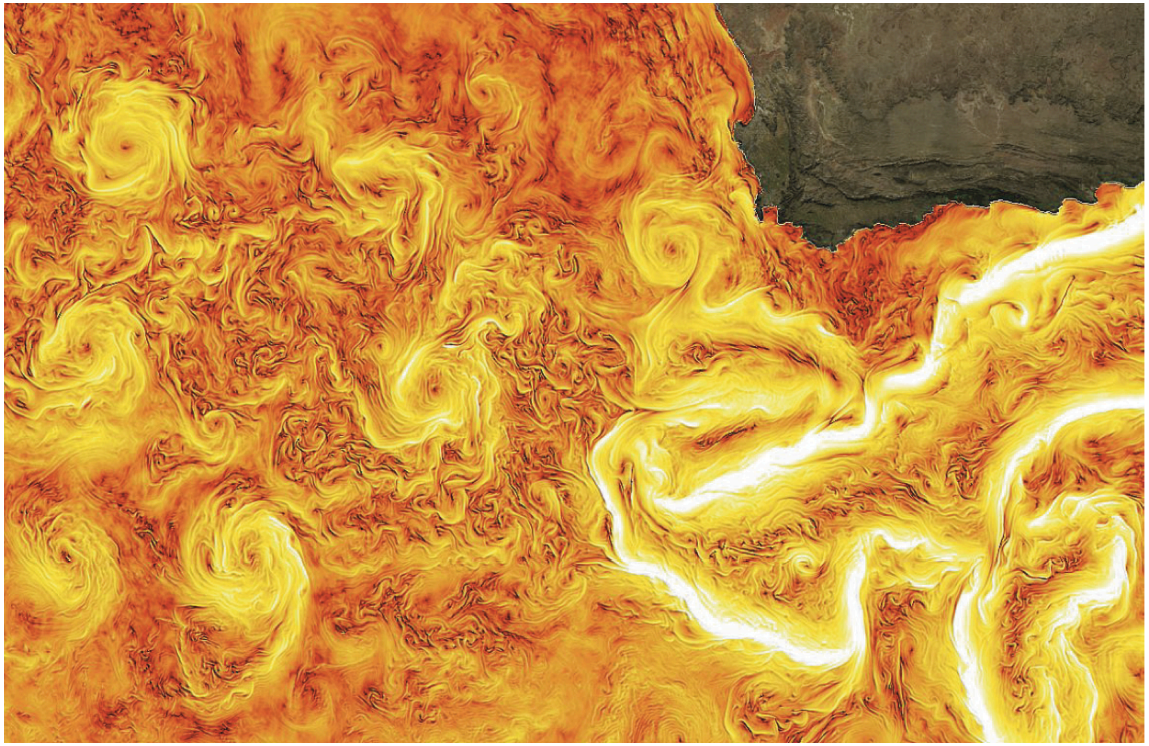


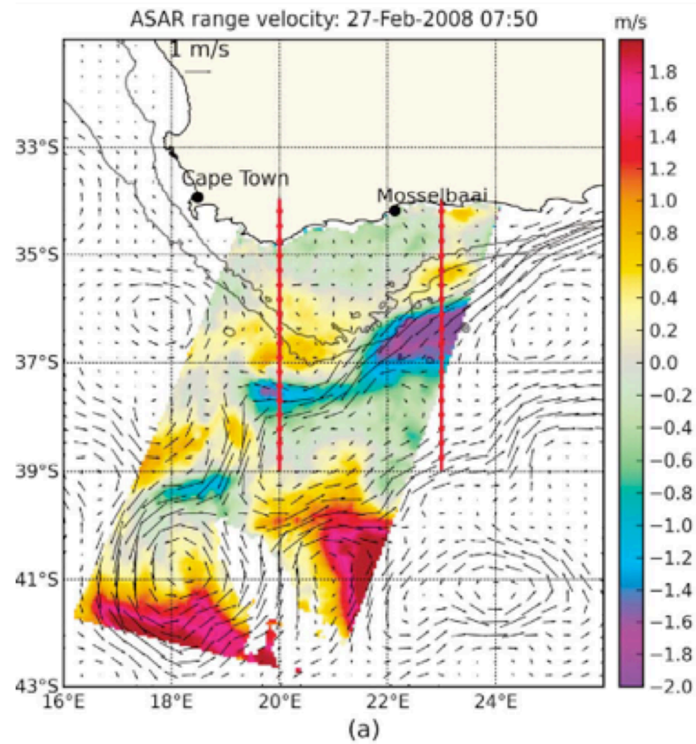
Image of modeled ocean surface currents from the high resolution ECCO2 model (courtesy D. Menemenlis, JPL).

Currently, we have no way to validate these results at high resolution.

- Ocean surface currents are an essential climate variable
- Knowledge of ocean surface currents will improve our knowledge of energy transfer between the atmosphere and the ocean and our understanding of the advection of heat, nutrients, and pollutants in the ocean.
- Ocean surface currents are a unique complement to the geostrophic currents measured by the forthcoming SWOT mission.

The DopplerScatt Concept

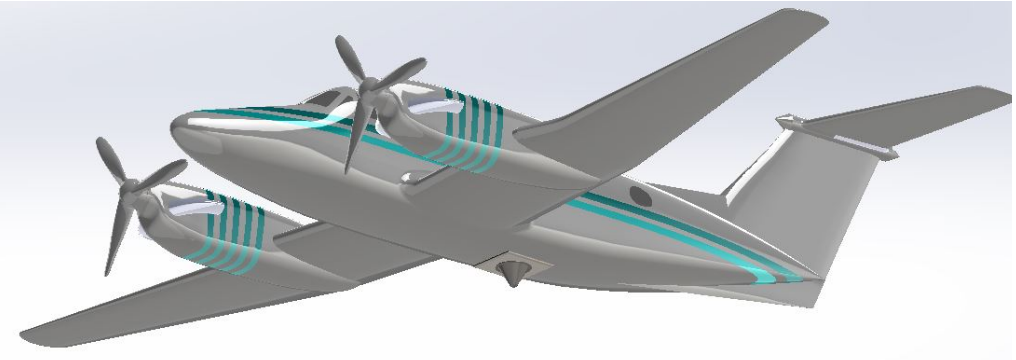
- Coherent radars can measure radial velocities by measuring Doppler shifts.
- The use of Doppler for one component of the surface current velocity has been demonstrated from space using SAR's.
  - Since SAR only looks in one direction, only one component of the velocity is retrieved.
  - Swath width and data rate limitations make SAR's impractical for global coverage
- Rodríguez (2012, 2014) has extended the concept to be able to measure ***both*** components by using a pencil-beam scanning scatterometer.
  - A wide swath coverage would enable global coverage in one day
  - The same instrument would also measure high resolution winds
- The DopplerScatt IIP will demonstrate the feasibility and accuracy of this concept using an airborne instrument and the results will be applicable to future spaceborne missions.

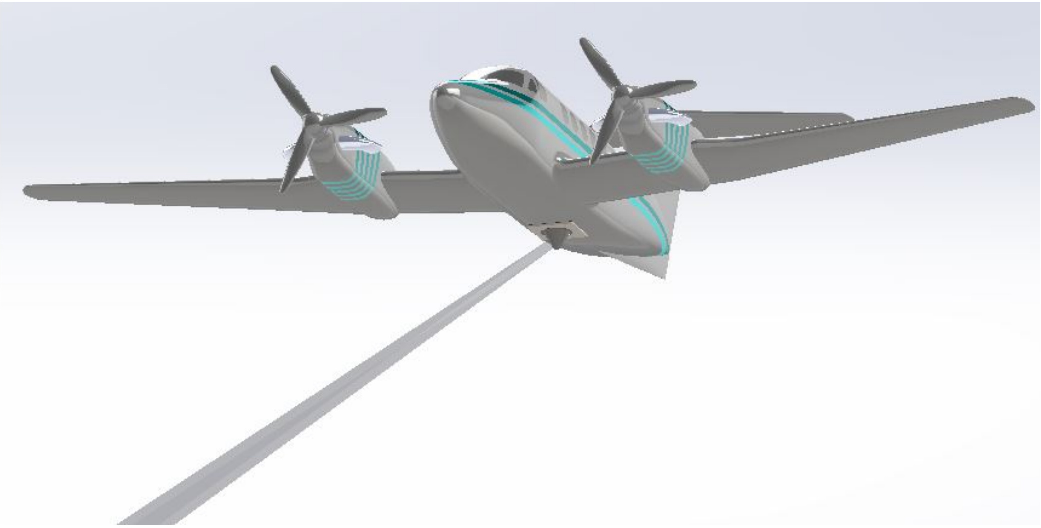


Comparison of surface current radial component measured by ASAR and geostrophic currents from the AVISO altimetry product. Rouault, M. J., Mouche, A., Collard, F., Johannessen, J. A. & Chapron, B. Mapping the Agulhas Current from space: An assessment of ASAR surface current velocities. Journal of Geophysical Research 115, (2010).

Driving Requirements

Parameter	Value
Center Frequency	35.75 GHz
Peak Transmit Power	90 W
Burst Repetition	8 kHz (max)
System Noise Figure	10 dB (max)
Antenna Rotation Rate	5-25 rpm
Antenna Beamwidth	2.9 deg
Velocity Bias	1.0 cm/s
Velocity Precision	10 cm/s
Wind Speed Accuracy	2 m/s (3-20 m/s) 10 % (20-30 m/s)
Wind Direction Accuracy	20 deg
Resolution cell size	5 km



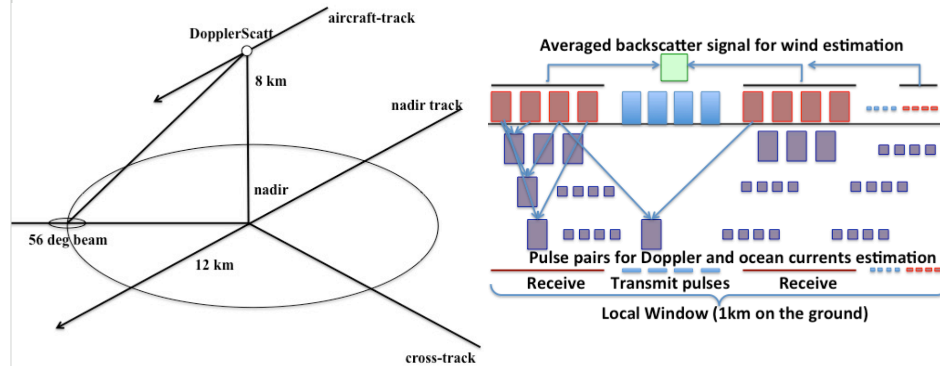


Ka-band Doppler Scatterometer for Measurements of Ocean Vector Winds and Surface Currents (DopplerScatt)

PI: Dragana Perkovic-Martin, JPL

Objective

- Develop a proof-of-concept Ka-band Doppler scatterometer (DopplerScatt) to demonstrate simultaneous direct measurements of ocean vector winds and surface currents over a wide swath for future spaceborne scatterometer.
    - These coupled measurements will enable improved understanding of relevant air-sea interactions and their influence on heat transport, surface momentum and gas fluxes, ocean productivity and marine biology .
- Demonstrate the concept and performance of DopplerScatt in lab tests over temperature and in airborne test flights (co-fly with UW synthetic aperture radar).



Pencil-beam concept for airborne DopplerScatt, with wide-swath coverage (left) and combination of burst measurements for estimation of phase shift and power (right)

Approach

- Development of loopback calibration capabilities.
- Development of a scanning 56 deg antenna subsystem and its airborne accommodation with a custom radome.
- Laboratory testing of functions and performance at subsystem and system end-to-end levels over airborne thermal environment.
- Integration of instrument into a stand-alone package, coupled to a precision inertial measurement unit (IMU).
- Flying engineering flights on the DoE King Air B200 aircraft.

Co-Is/Partners:

Mauricio Sanchez-Barbetty, Maxim Neumann, Ernesto Rodriguez, JPL; Gordon Farquharson, APL/U. Washington

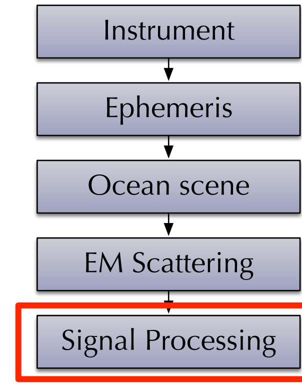
Key Milestones

	Original	Current
• Develop system requirements	08/14	09/14
• Develop system design and architecture	09/14	08/14
• Integrate and test calibration loop over temperature	05/15	08/15
• Integrate and test antenna subsystem (including spin mechanism, rotary joint and antenna)	03/16	09/15
• Complete spaceborne system study and technology readiness assessment	05/16	
• Complete instrument integration and end-to-end testing in a thermal chamber	12/16	
• Complete engineering test flights	04/17	
• Complete measurement validation	05/17	

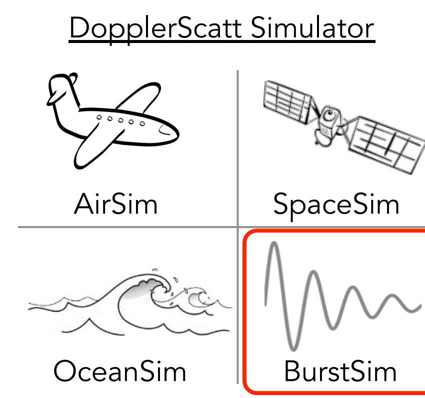
$TRL_{in} = 3$ $TRL_{current} = 3$

BurstSim: Overview

- Primary tasks:
  - Generation of transmitted pulses
  - Illumination of the simulated ocean surface
  - Receiving the scattered (echo) signal
  - Raw data processing



- Features:
  - High-frequency sampling (1 GHz)
  - Fine sampling of the footprint (0.1 deg in azimuth and elevation)
  - Allows simulation of noise from several sources, which can be modified to simulate real hardware:
    - » transmit and receive losses
    - » local oscillator noise
    - » thermal noise



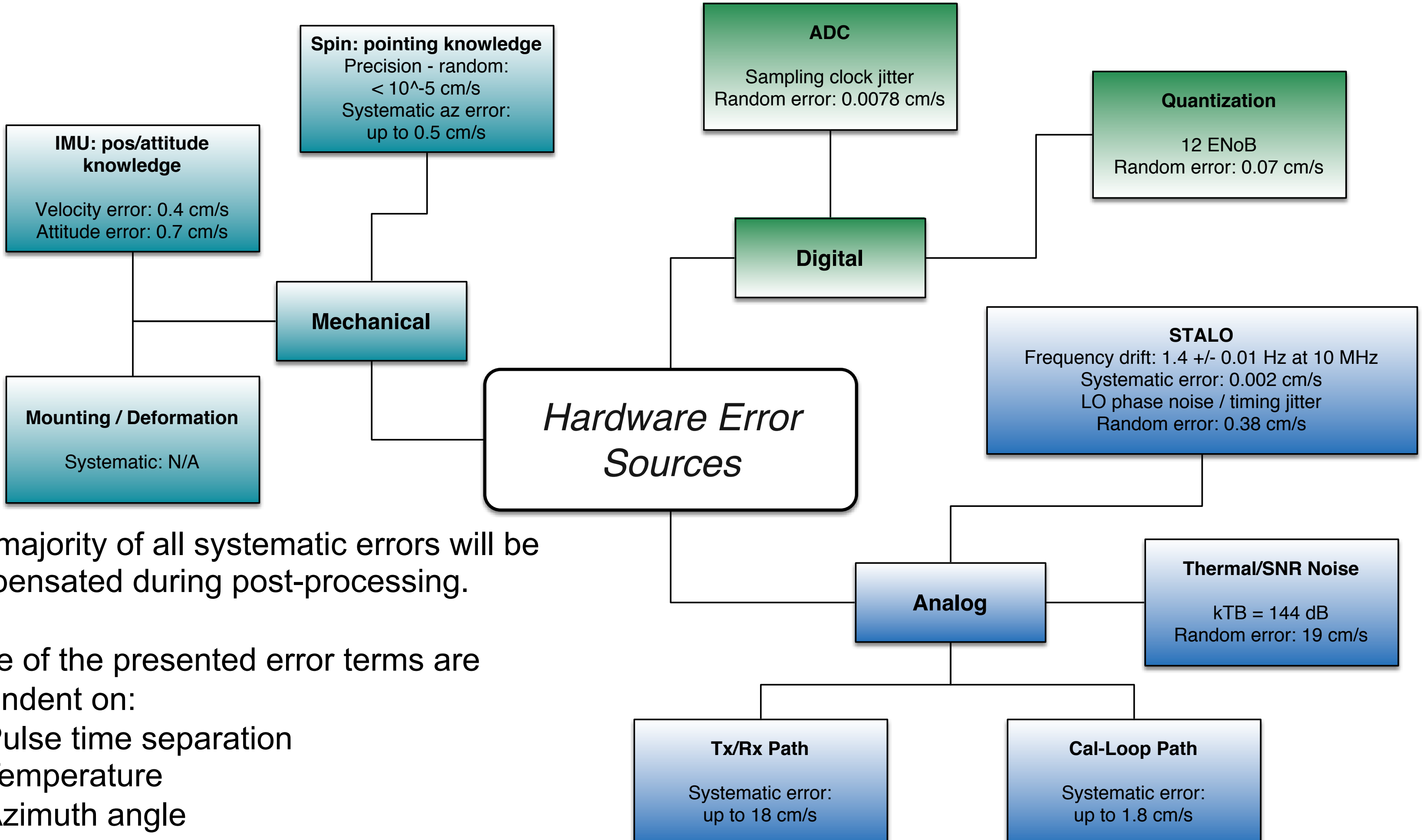
Error Budget

- Total error budget for Doppler velocity estimation: 10 cm/s

Error Source	Velocity error	Current design expected error
Random phase errors	5 cm/s	1-3 cm/s
Frequency	<0.1 cm/s	0.002 cm/s
Timing	<0.1 cm/s	0.0017 cm/s
Platform velocity	0.5 cm/s	0.4 cm/s
Look angle	0.5 cm/s	0.32 cm/s
Azimuth angle	1 cm/s	0.65 cm/s
Velocity gradients, random variation due to wave interactions, and asymmetry bias	3 cm/s	data / model dependent

* We will be refining the error allocations as the system components get tested and built.

Hardware Error Sources



The majority of all systematic errors will be compensated during post-processing.

Some of the presented error terms are dependent on:

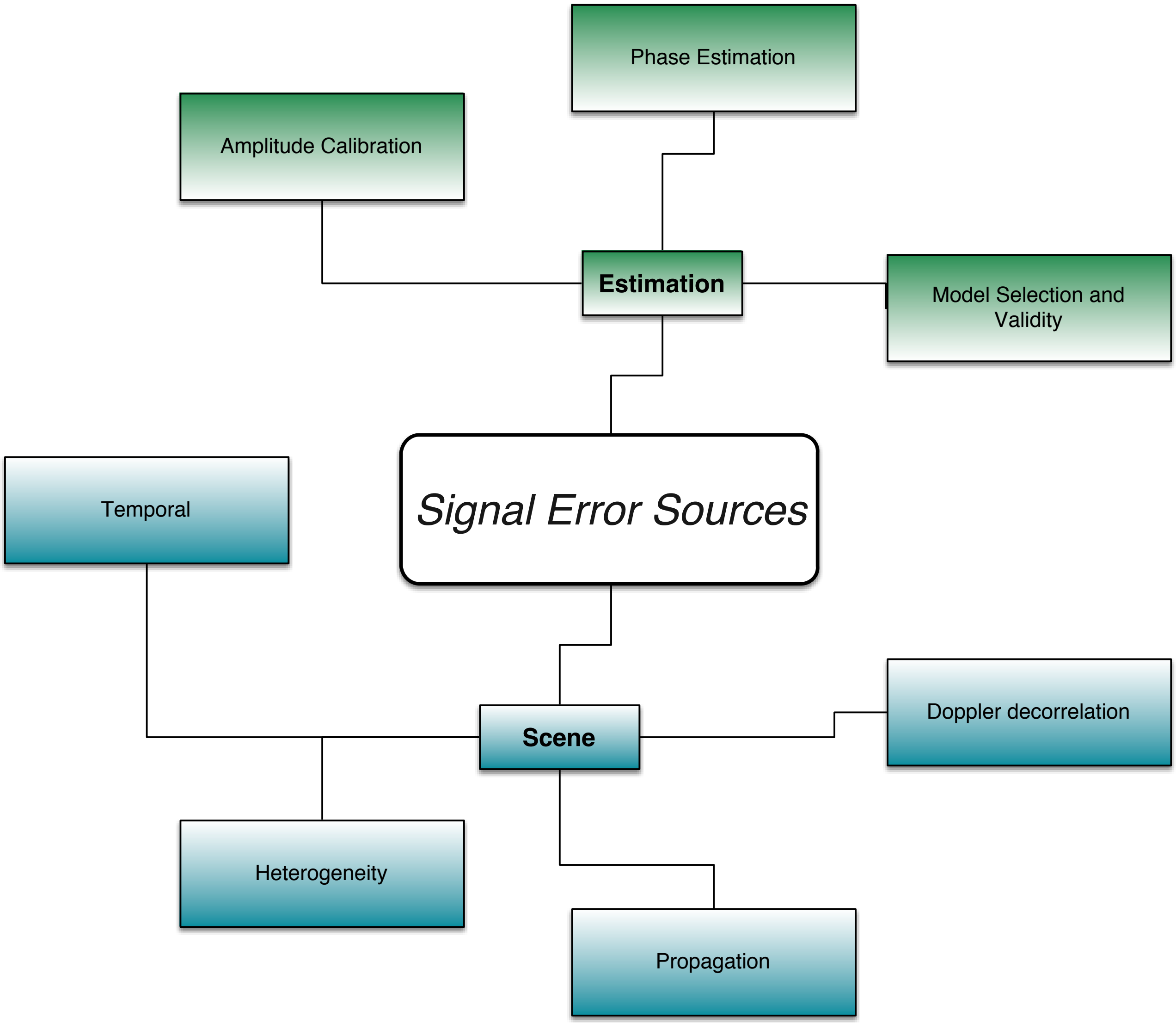
- Pulse time separation
- Temperature
- Azimuth angle
- Wind strength

Velocity errors are given for a single pulse-pair on the time scale of a burst: $\tau = BRI = 192\mu s$

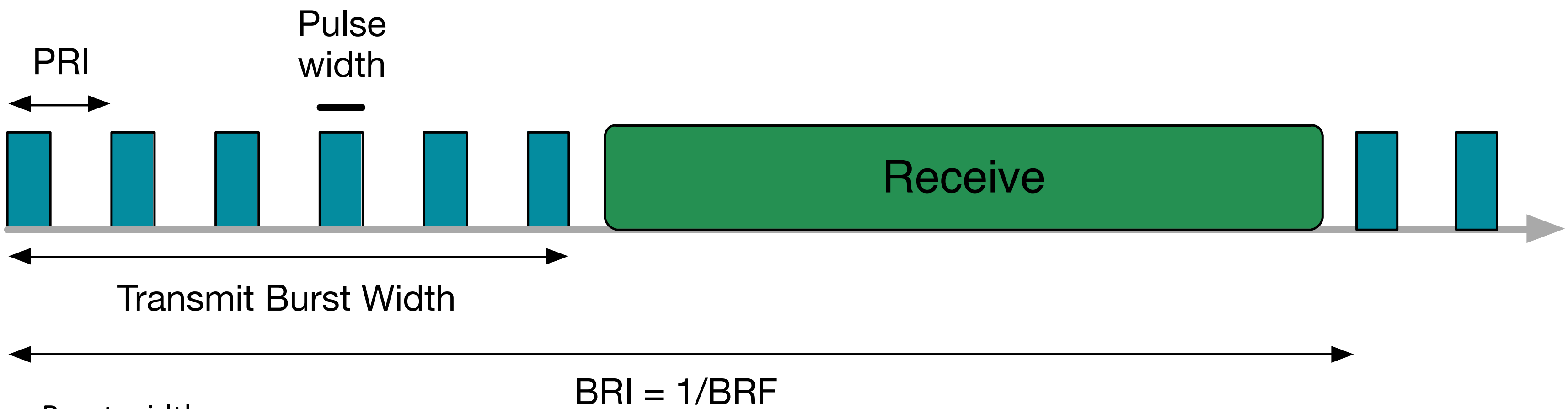
Random errors are reduced with the number of N independent samples: $\propto \frac{1}{\sqrt{N}}$

Signal Error Sources

- Scene terms mainly contribute to decorrelation noise:
  - Temporal decorrelation due to changes in the illuminated cell between the pulses
  - Doppler decorrelation due to variability of the Doppler frequency inside the footprint
  - Scene heterogeneity is accounted for via gradients inside the cell and random variations
  - Propagation effects are assumed to be negligible over time scale of pulse pair separations



Design Trade: Timing Scheme Constraints



- Burst width
  - Max burst width = round-trip-time at near range, but not more than the duty cycle (47 %) * BRI
  - Min BRI = 2 x burst-width + round-trip-time + beam-fill-time
- Pulse width
  - Min (hardware): 0.5 us; Max (round-trip-time): 97 us
- PRF
  - Constrained by range and azimuth ambiguities
  - Range ambiguities arise when the round trip time is longer than the PRI
    - » Multiple echoes are returning from the ground at the same time
  - Azimuth ambiguities arise when the spectrum overlaps
    - » Spectrum aliasing causing wrapping the velocity contributions (with respect to the surface currents velocity)

$$PRI = \frac{1}{PRF} \geq \tau + \text{beam-fill-time}$$

$$PRF \leq \frac{c}{2R}$$

$$PRF \geq \frac{2v}{\lambda} \sin\theta$$

- Rotation Rate
  - Minimum rate is limited by required along-track overlap of consecutive rotations
    - » Choose slowest rotation rate to minimize decorrelation, but still providing full coverage
- Number of Pulses in a Burst
  - To optimize velocity estimation from pulse-pairs, we want to get as many pulses as possible

Pulsed System Preliminary Performance: SNR

$$SNR = \frac{P_t G_t G_r \lambda^2 A \sigma^0}{(4\pi)^3 R^4 k T f_s L}$$

Resolution cell area:

$$A = \pi \Delta_{az} \Delta_{elv}$$

Thermal noise power is a product of the receiver bandwidth, the Boltzmann's constant, and the system temperature

$$T = T_0(NF - 1)$$

Losses account for transmit, atmosphere propagation, receive, and signal processing.

$$L = L_{Tx} L_{atm} L_{Rx} L_{sp}$$

- The only adjustable parameters are:
  - » Footprint area (elevation resolution, via pulse width)
  - » Receiver bandwidth

- Optimal SNR $SNR \propto \frac{\tau}{f_s} \propto \tau^2$
  - » Maximum resolution at the order of the elevation footprint size
  - » Pulse width:

$$\tau \approx \frac{2}{c} \frac{R\Delta\theta}{\cos(\theta)}$$

Pulsed System Preliminary Performance: SNR

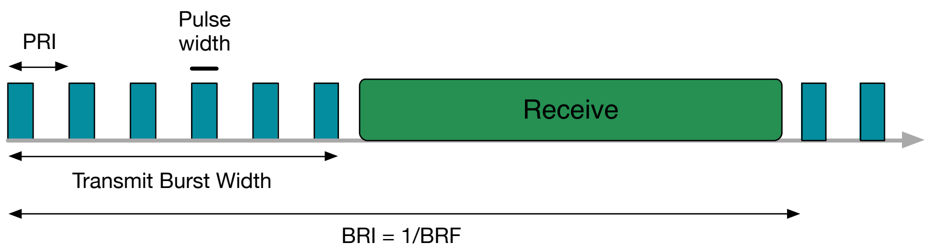
$$SNR = \frac{P_t G_t G_r \lambda^2 A \sigma^0}{(4\pi)^3 R^4 k T f_s L}$$

```
               power         19.542           90
                area         59.905       978385
           -(4pi)^3         -32.976   0.00050393
                G^2          70.000        1e+07
               -R^4        -166.630  2.17288e-17
               wl^2         -41.529  7.03217e-05
=========================================
    Gains (Total):          -91.688   6.7803e-10

                 N0        -197.138  1.93291e-20
  Receive Bandwidth          52.159       164384
              La(R)           1.172      1.30971
            Rx_Loss           4.000      2.51189
            Tx_Loss           3.000      1.99526
=========================================
   Losses (Total):         -136.808  2.08566e-14
              NESZ:         -45.120 dB
```

Nominal height:	8.2 km	Rotation rate:	9 rpm
Nominal velocity:	180.0 m/s	Transmit burst width:	81 us
Look angle:	55.9	Pulse width:	7.3 us
Incidence:	54.6–57.5	Pulses in burst:	6
Footprint size (az):	741 m	PRF:	67.8 kHz
Footprint size (gr) :	1328 m	BRF:	5.2 kHz
Round-trip time:	97.7 us	Transmit bandwidth:	137 kHz
		Receive bandwidth:	164 kHz

Chirped System Preliminary Performance: Timing & SNR



power	19.542	90
area	48.400	69175.4
-(4pi)^3	-32.976	0.00050393
G^2	70.000	1e+07
Bandwidth	61.367	1.37e+06
-R^4	-166.630	2.17288e-17
pulse_width	-48.861	1.3e-05
wl^2	-41.529	7.03217e-05
Gains (Total):	-90.686	8.53796e-10
N0	-197.138	1.93291e-20
La(R)	1.172	1.30971
Rx_Loss	4.000	2.51189
Receive Bandwidth	62.159	1.644e+06
Tx_Loss	3.000	1.99526
Losses (Total):	-126.807	2.08587e-13
NESZ:	**-36.121 dB**	

Nominal height:	8.2 km	Rotation rate:	9 rpm
Nominal velocity:	180.0 m/s	Transmit burst width:	81 us
Look angle:	55.9	Pulse width:	13 us
Incidence:	54.6–57.5	Pulses in burst:	6
Footprint size (az):	741 m	PRF:	67.8 kHz
Footprint size (gr) :	1328 m	BRF:	5.2 kHz
Round-trip time:	97.7 us	Transmit bandwidth:	1.37 MHz

Pulsed System Preliminary Performance: Decorrelation Sources

- Thermal decorrelation:

$$\gamma_{therm} = \frac{SNR}{SNR+1}$$

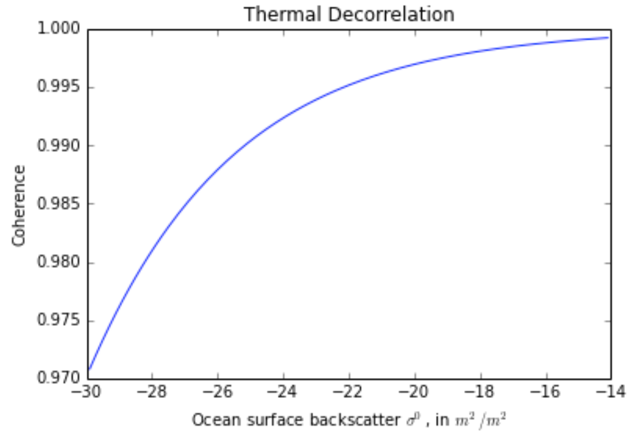
$$SNR = \frac{P_t G_t G_r \lambda^2 A \sigma^0}{(4\pi)^3 R^4 k T f_s L}$$

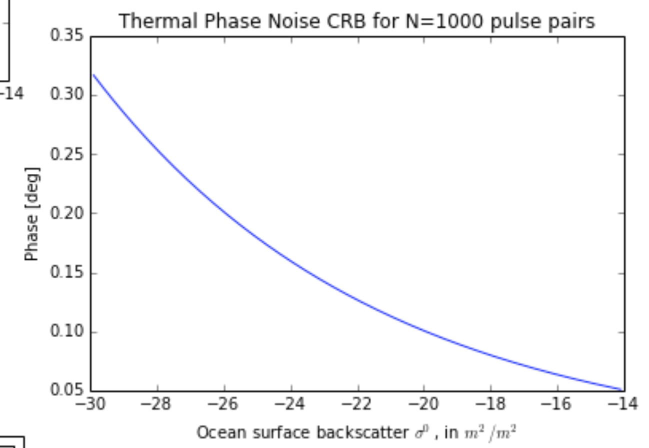
- Cramer-Rao Lower Bound for phase SDEV for N independent pulse pairs (N>4):

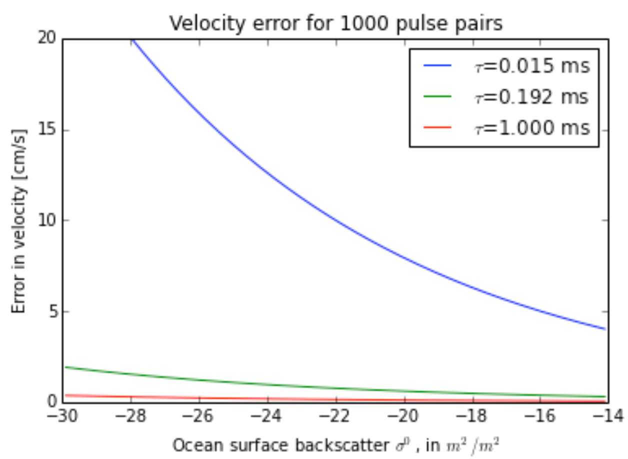
$$\sigma_\phi = \frac{1}{\sqrt{2N}} \frac{\sqrt{1-\gamma^2}}{\gamma}$$

- Radial velocity error:

$$\delta v_{rs} = \frac{\lambda}{4\pi\tau}\delta\phi$$

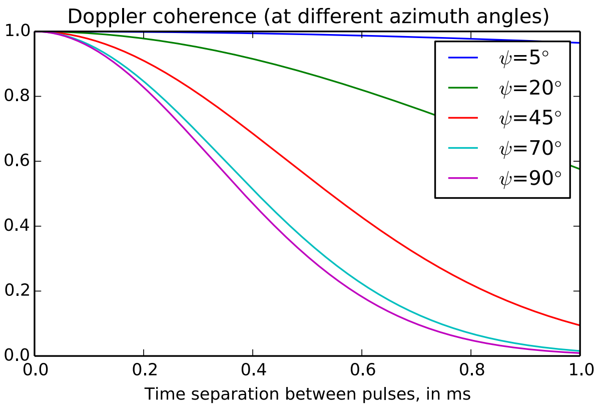


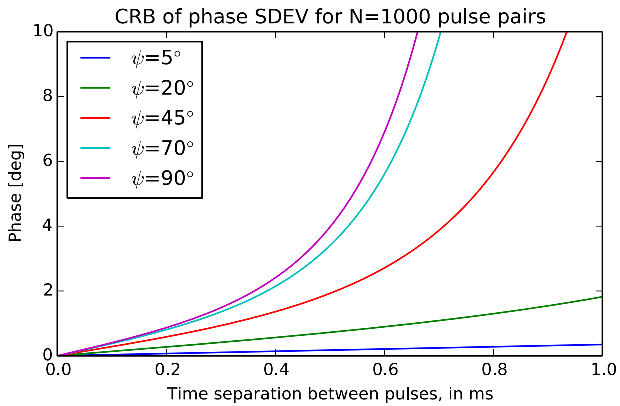


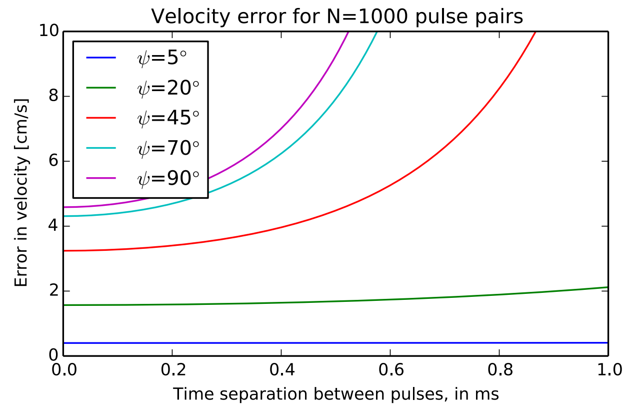


Pulsed System Preliminary Performance: Decorrelation Sources

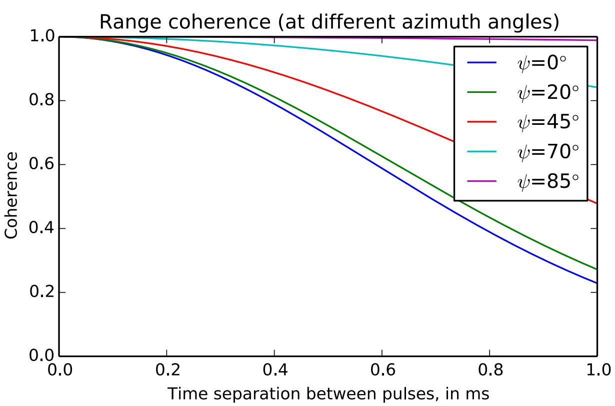
- Doppler decorrelation due to variation of the Doppler in azimuth direction.

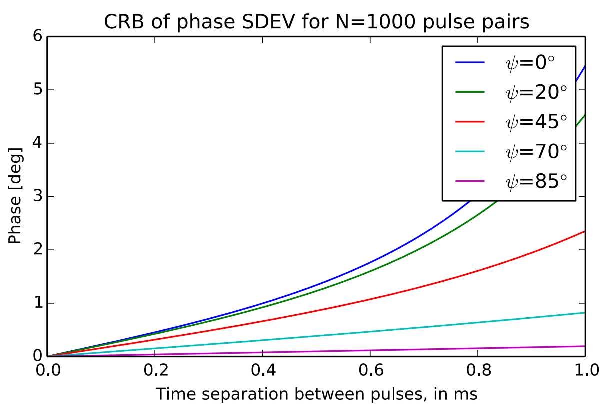


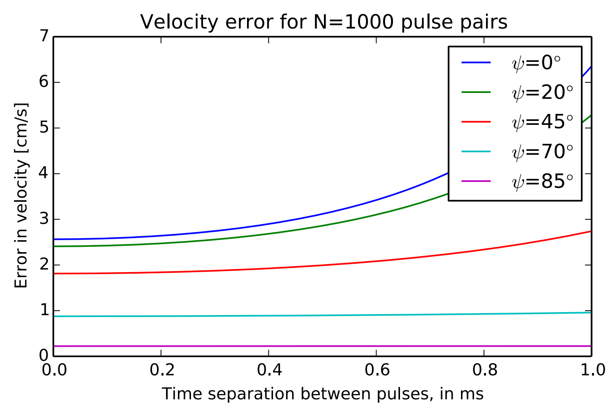




- Range decorrelation due to variation of the Doppler in the range direction.



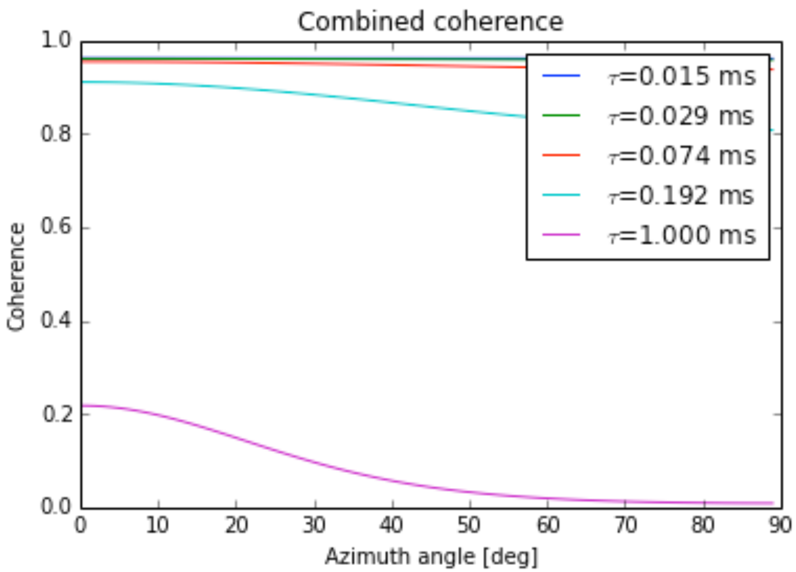


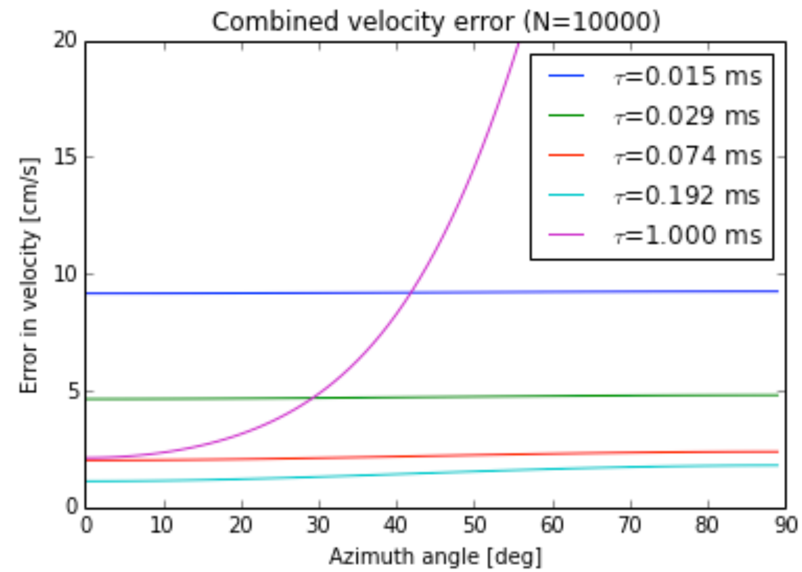


Pulsed System Preliminary Performance: Decorrelation Sources Combined

- Individual times and azimuth angles

$$\gamma = \gamma_{temp}\gamma_{therm}\gamma_{doppler}\gamma_{range}\gamma_{quant}$$

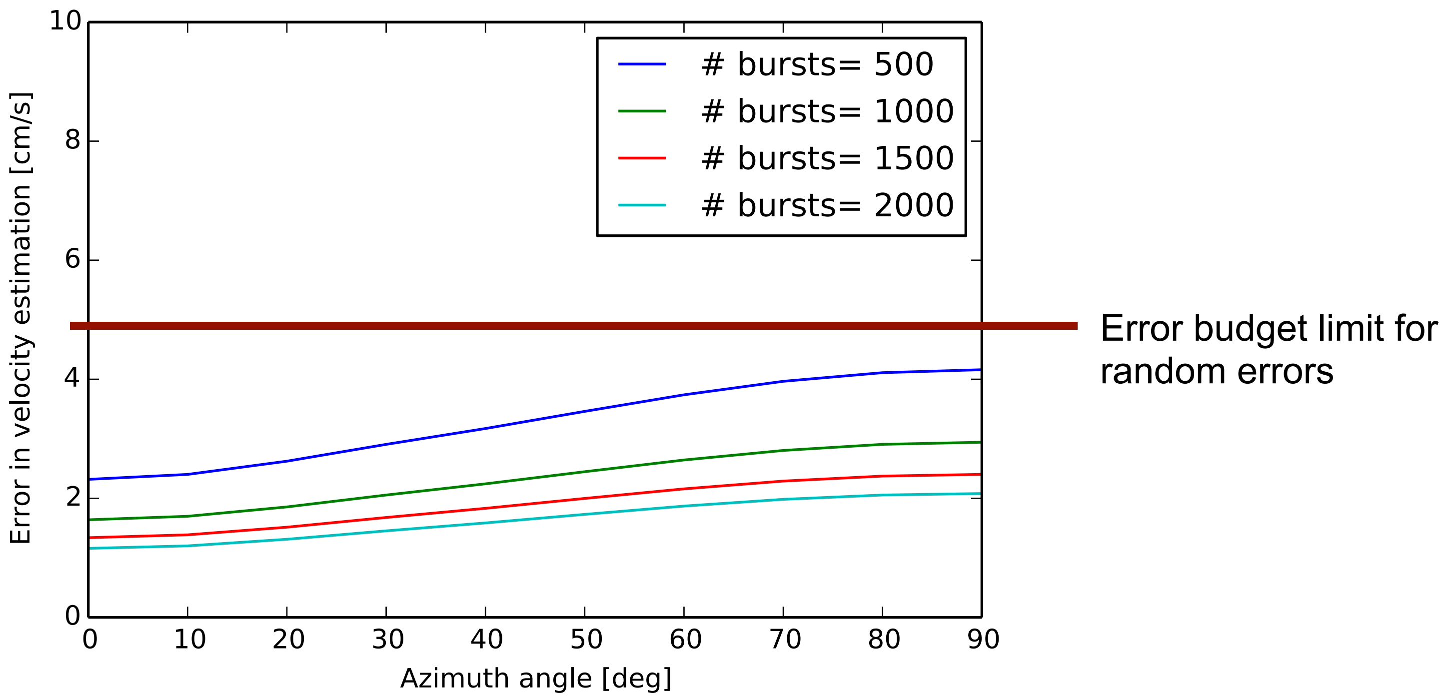




- Maximum number of pulses inside a resolution cell: > 56,000 (same azimuth), > 113k (both azimuth)
- Phase and coherence are non-linear functions of pulse combinations
- Enables cross-correlating pulses with short and long time intervals, enhancing the estimation

Pulsed System Preliminary Performance: Decorrelation Sources Combined

- Combining cross-correlating pulse pairs with different time intervals:
  - > 56,000 pulses (> 2,200 bursts) per rotation over the cell
  - > 4 rotation scans over the cell



- Maximum number of pulses inside a resolution cell: > 56,000 (same azimuth), > 113k (both azimuth)
- Phase and coherence are non-linear functions of pulse combinations
- Enables cross-correlating pulses with short and long time intervals, enhancing the estimation