International Ocean Vector Wind Science Team Meeting
Kailua-Kona, Hawaii USA
6-8 May 2013

CYGNSS Wind Retrieval Performance

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For more information: http://cygnss-michigan.org

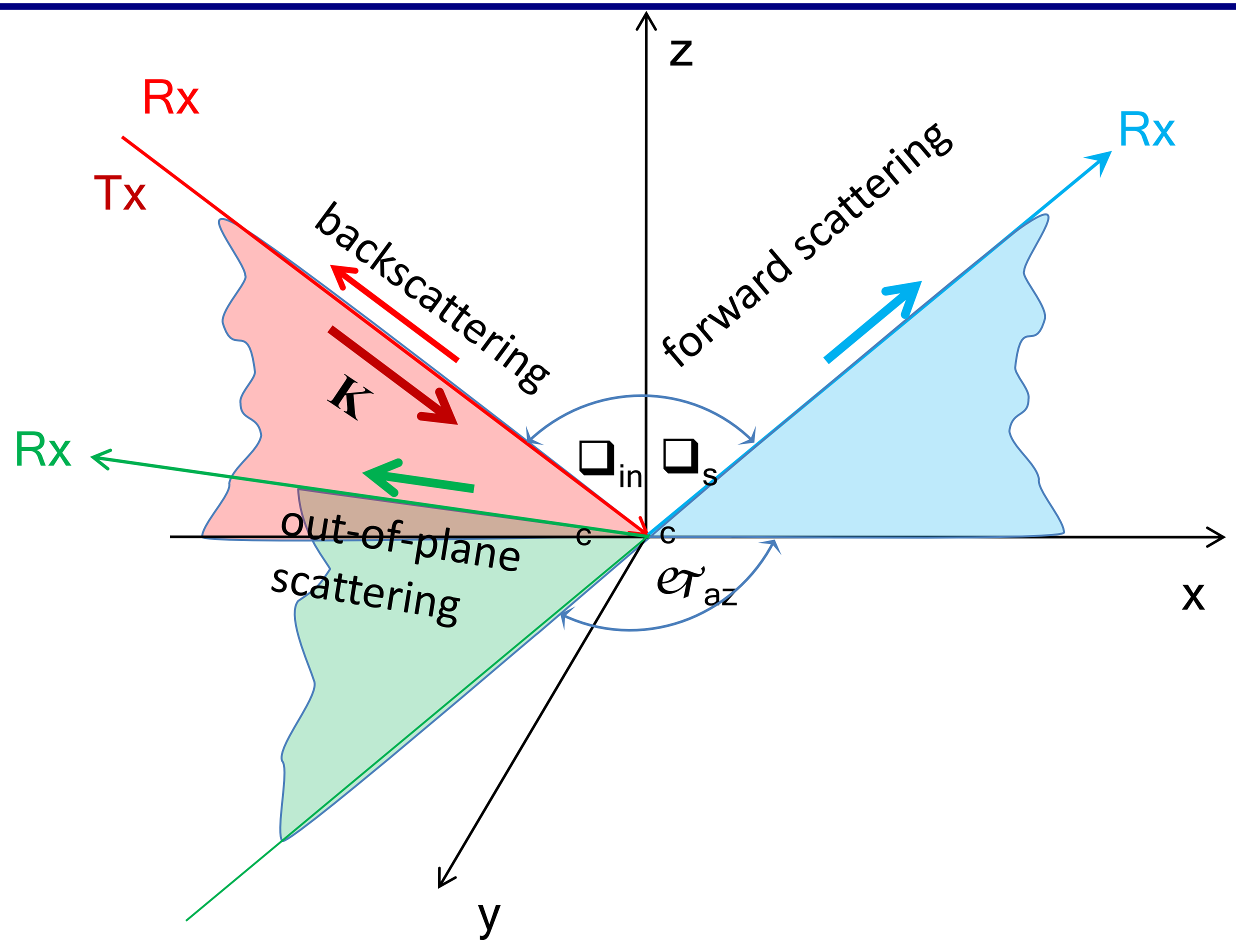
Outline

- **Description of End-to-End Simulator**
- **Properties of Level 1 Data Product, the Delay Doppler Map (DDM)**
  - Transformation from **Delay** (i.e. relative time-of-flight between direct and reflected signal) and **Doppler** (L1 carrier doppler shift of reflected signal) coordinates to **spatial** coordinates
  - Sensitivity to non-uniform wind speed distribution
- **Wind speed retrieval algorithms**
  - Use of average scattering cross-section ("scatterometer mode")
  - Use of delay waveform rising edge ("altimeter mode")
  - Retrieval performance (**preliminary**)

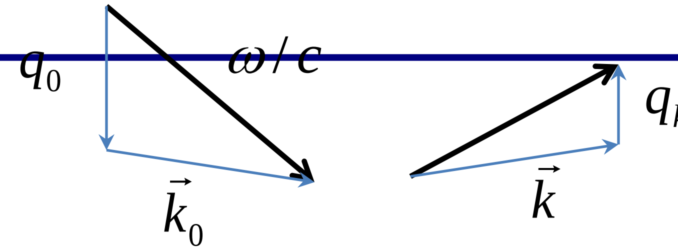
CYGNSS End-to-End Simulator

- Orbit propagators for GPS and CYGNSS constellations establish measurement geometry
- Nominal GPS transmission properties assumed
- Free space propagation with precip optical depth included
- Bi-static rough surface forward scattering from the ocean surface
  - Small slope approximation using semi-empirical roughness spectrum (tuned to fit aircraft GNSS-R hurricane overflight data)
  - Speckle noise modeled by Monte Carlo approach with geometrics optics approximation over coherent integration time
  - (modeling led by V. Zavorotny and J. Johnson)
- Baseline CYGNSS antenna and receiver designs
  - Thermal noise
  - DDM sampling characteristics

Geometry of Bi-static Scattering



Voronovich's small-slope approximation of the 1st order



Bistatic Radar Cross Section (BRCS)

$$\sigma_{\alpha\alpha_0}\left(\vec{k},\vec{k}_0\right)=\frac{1}{\pi}\left|\frac{2q_kq_0}{q_k+q_0}B_{\alpha\alpha_0}\left(\vec{k},\vec{k}_0\right)\right|^2 e^{-(q_k+q_0)^2W(0)}\int\left(e^{-(q_k+q_0)^2W(\vec{r})}-1\right)e^{-i\left(\vec{k}-\vec{k}_0\right)\vec{r}}d\vec{r}$$

Correlation function of roughness function → $W(\vec{r})=\int S\left(\vec{\xi}\right)e^{i\vec{\xi}\vec{r}}d\vec{\xi}$ Roughness spectrum

Statistics of the elevations is assumed to be Gaussian with spectrum *S* and corresponding correlation function *W*; indices *α, α0 =1,2* correspond to vertical and horizontal polarization, correspondingly.

DDM Sampling Information

- DDM mode delay resolution and range:
  - 128 pixels @ 250 ns per pixel (~4/chip) in delay
  - 20 pixels @ 500 Hz per pixel in Doppler
  - Delay and Doppler step sizes consistent with ~50% drop in ambiguity function given CYGNSS orbit geometry
  - On board integration: 1 ms coherent, 1 s incoherent

- 4 simultaneous DDMs per satellite per second

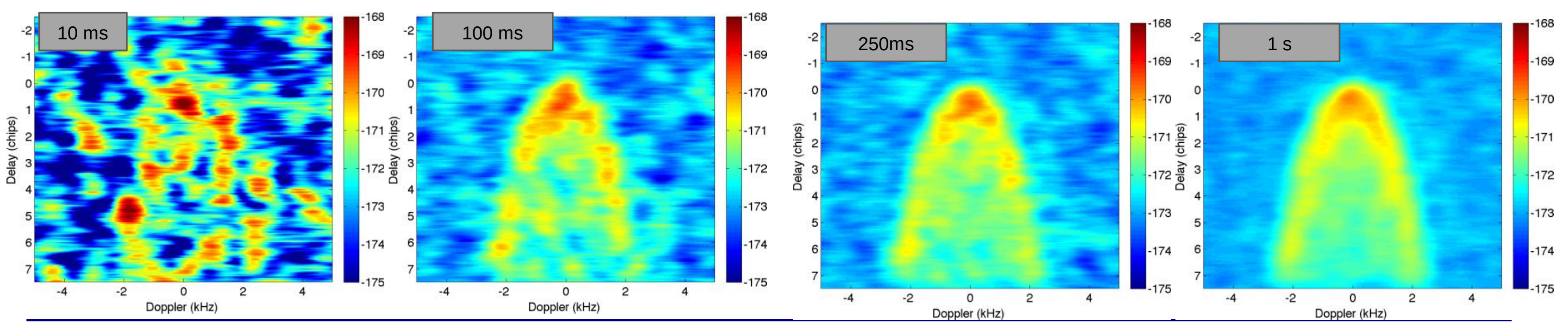
What is computed?

$$SNR(\tau, f_{dop}) = \frac{P_T G_T \lambda^2 G_R}{(4\pi)^3 k T^* B_D} \times \iint F(\vec{\rho}) \Lambda^2(\tau, \vec{\rho}) \left| S(f_{dop}, \vec{\rho}) \right|^2 R_0^{-2} R^{-2} \sigma_0(\vec{\rho}) d^2\rho.$$

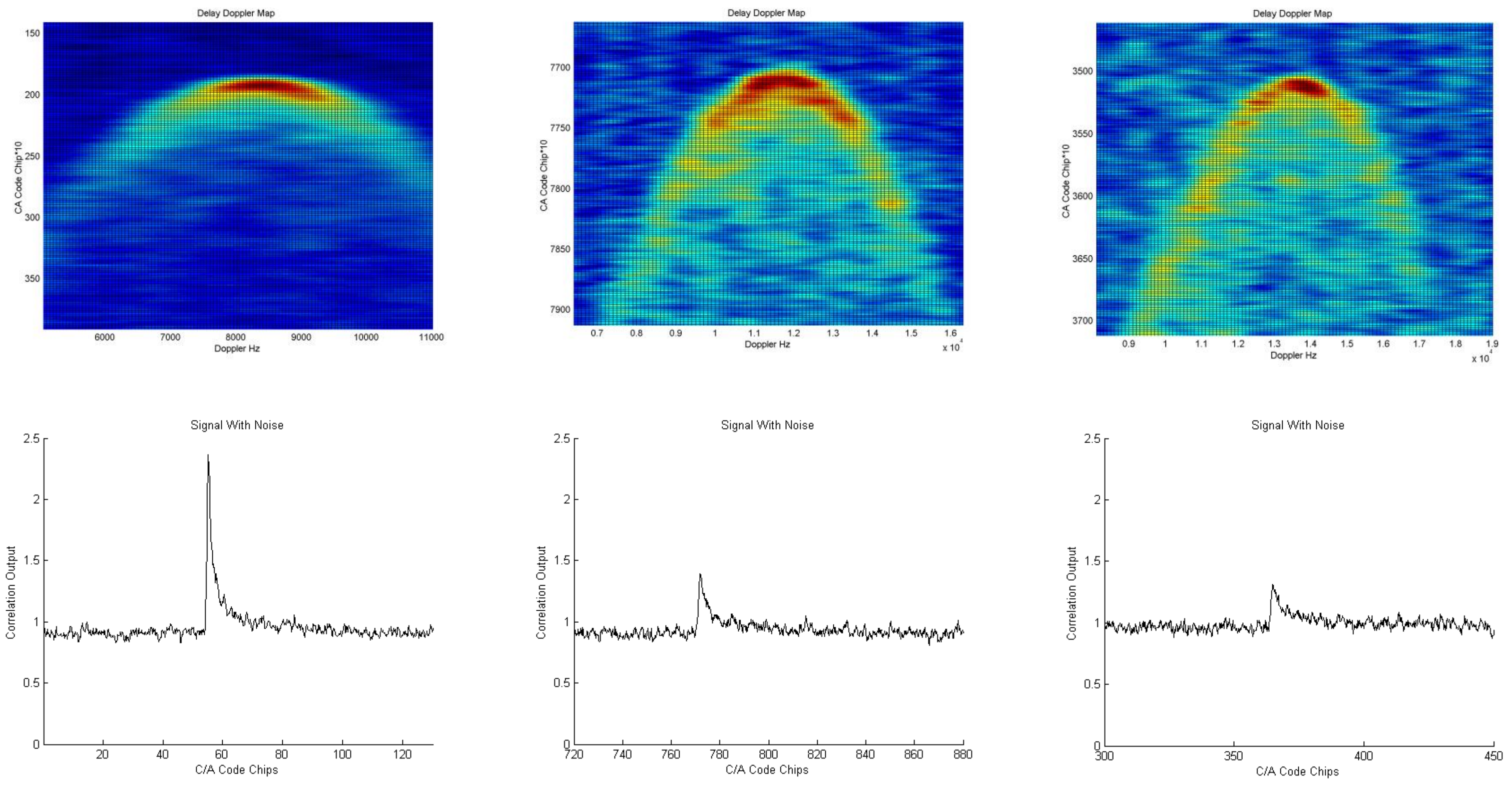
- Pt is GPS transmit power 14.25 dBw (metadata)
- Bd is 1/coherent integration time 1 kHz (fixed)
- T0 is 290 * Noise Figure 580 K (metadata)
- Gt is GPS antenna gain 13 dBi (metadata)
  - Needs attitude/geometry information?
- Gr is CYGNSS antenna gain var dBi (metadata)
- F is CYGNSS receive antenna pattern var (ancillary)
  - Needs attitude/geometry information
- R0, R, GPS/CYG lat/long/alt/velocity, specular point location (metadata)
- Sigma0 from GO; needs slope variances and reflection coeff

Example of DDM produced by E2ES

- **Coherent integration produces 1 ms data product**
- **Thermal noise added to 1 ms product**
  - thermal noise created by generating white Gaussian noise and convolving ambiguity function to create correlation wrt delay and Doppler
- **Incoherent integration to 1 sec final DDM**



Example of Actual DDMs measured by UK-DMC-1 mission



- Winds ~ 2 m/s
- Winds 7 m/s
- Winds 10 m/s

The Higher the wind and waves the lower the return and greater the signal spreading over the surface

E2ES Model Validation Using Airborne TC Overflights and UK-DMC-1 Spaceborne Obs

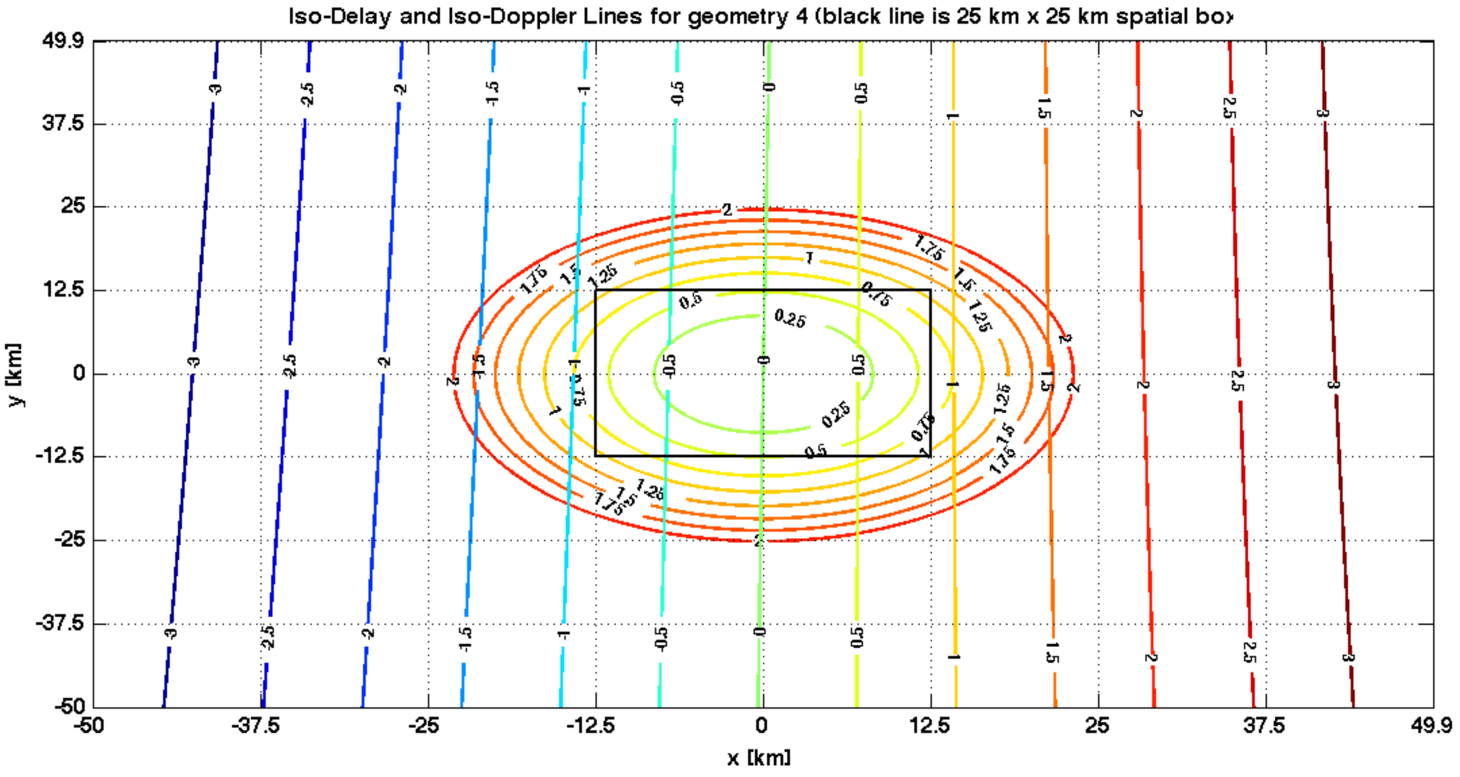
- Airborne (P-3) flights demonstrations for WS<40 m/s
- Spaceborne (UK-DMC-1) flight demo for WS<10 m/s
- Significant unknown with CYGNSS version of E2ES: High wind response at orbital altitudes (wind non-uniformity)

CYGNSS Simulator Validation and Performance Predictions

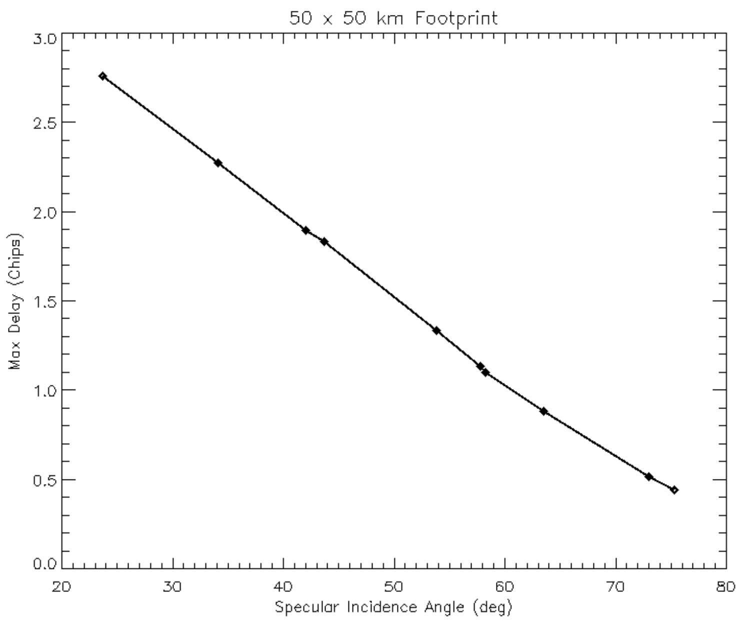
Platform	Altitude (km)	Wind speed (m/s)	Science antenna gain (dBi)	Incidence angle of specular point (°)	Empirical wind speed uncertainty (m/s)	Model wind speed uncertainty (m/s)
P-3	3	10	3	45	±1.2	±0.9
P-3	3	40	3	45	±4.8	±3.7
UK-DMC-1	680	10	11	45	±2.3	± 2.0
CYGNSS	500	10	11	45	To be completed after CYGNSS on-orbit cal/val	±0.7*
CYGNSS	500	33 (Cat 1)	11	45		±4.23*
CYGNSS	500	50 (Cat 3)	11	45		±5.73*
CYGNSS	500	70 (Cat 5)	11	45		±6.8*

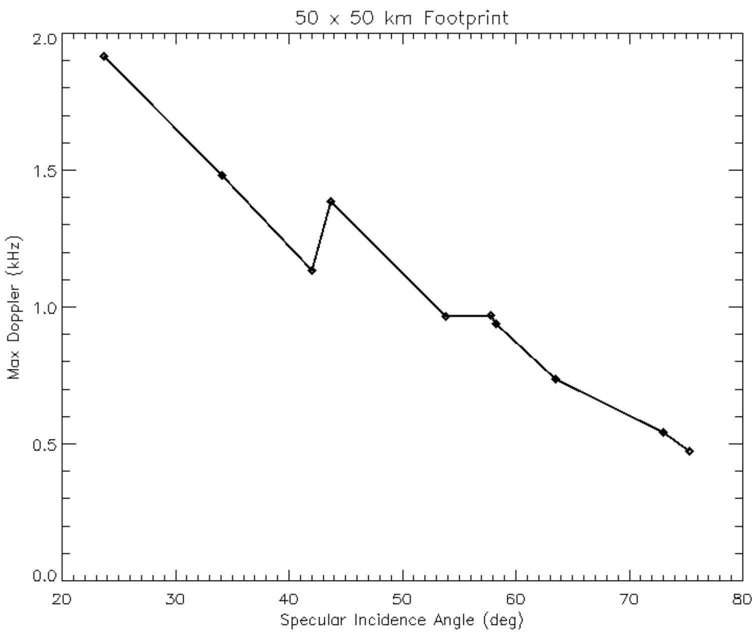
(* Assumes 25x25 km CYGNSS spatial resolution)

Relationship Between (Delay, Doppler) and Spatial Coordinates



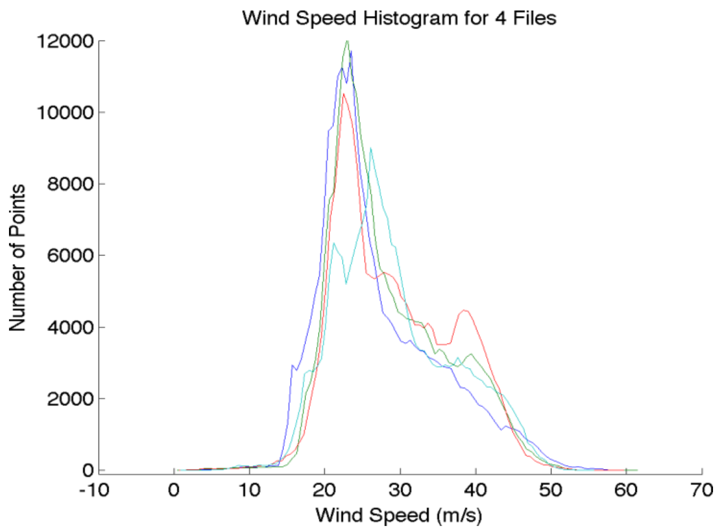
Maximum Extent of Delay and Doppler for 25 and 50 km Resolution

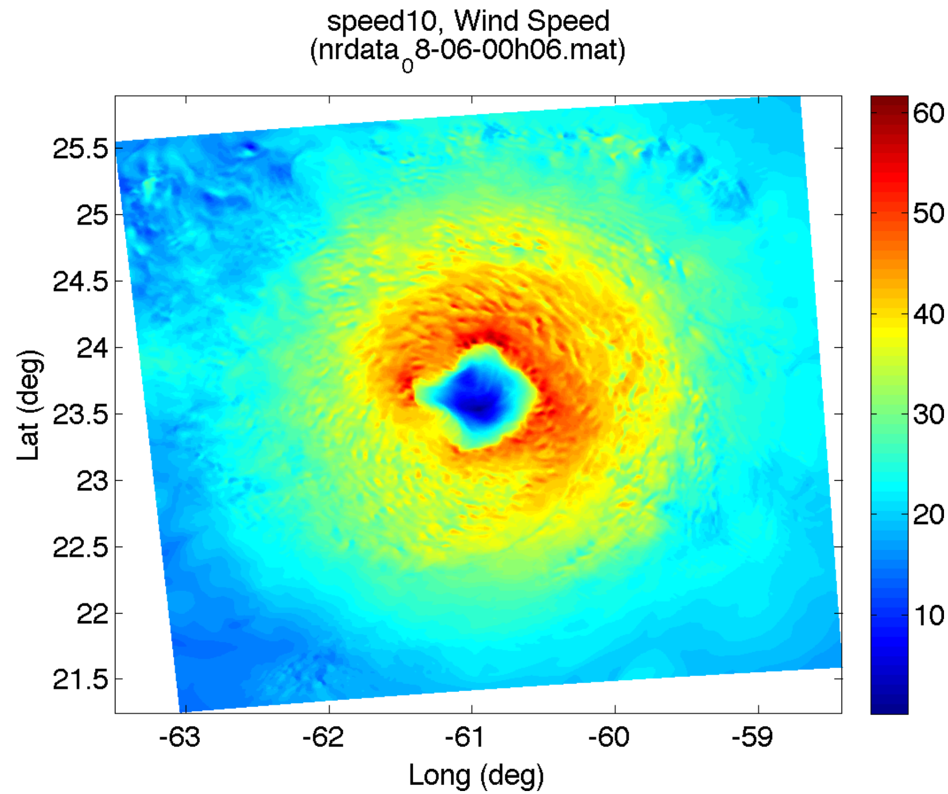


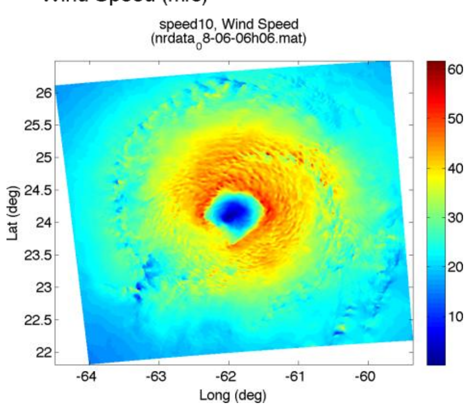


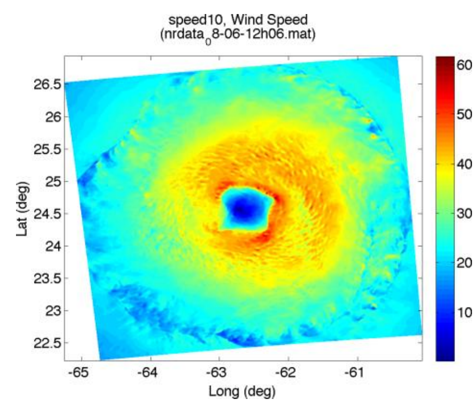
TC Nature Run Input Wind Fields (provided by Dave Nolan, U-Miami)

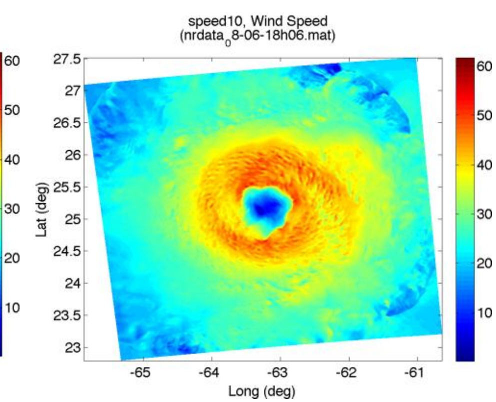
- 4 different times,
  6 hours apart
- 480x480 data points
- 1 km reporting grid, ~4 km effective resolution





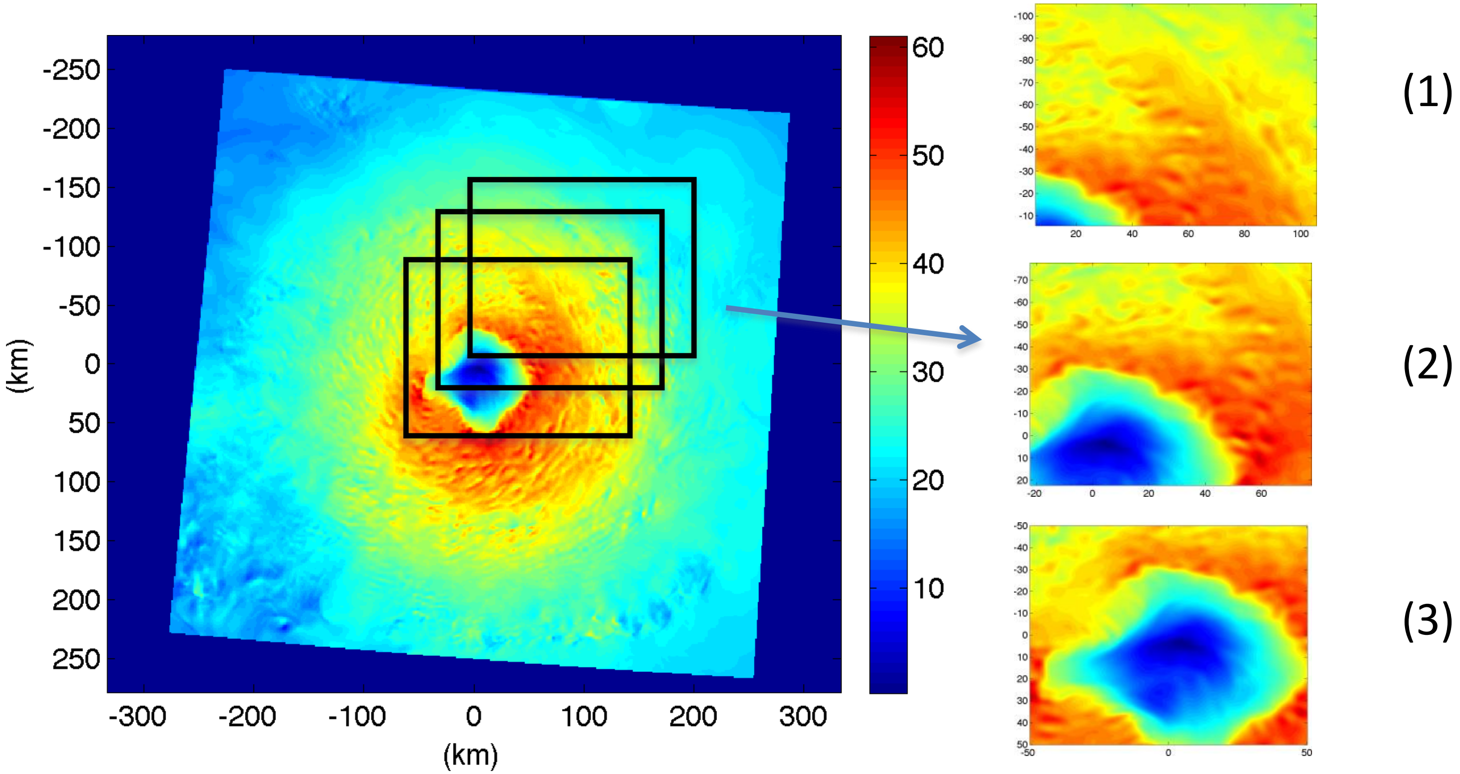




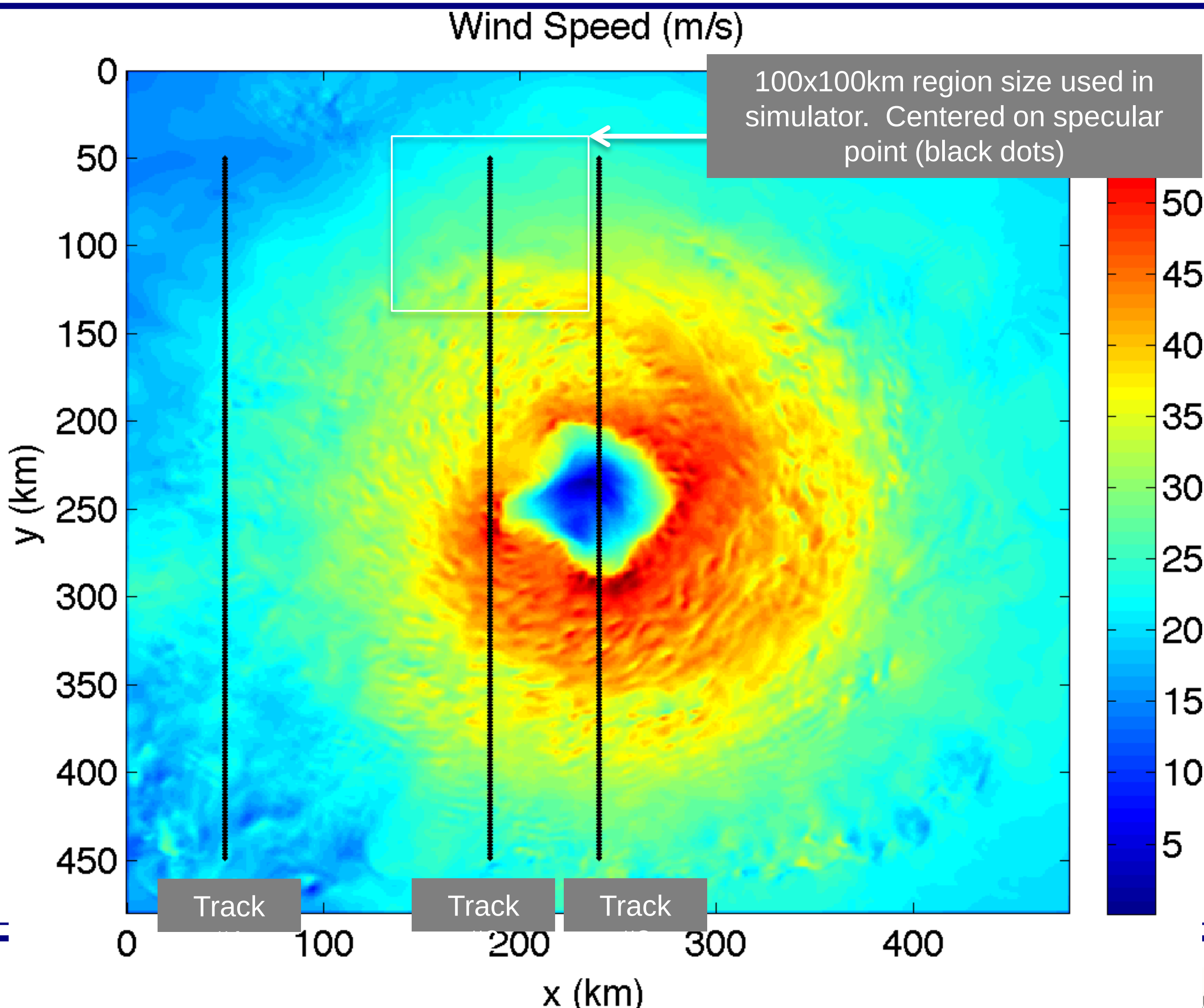


Domain of Nature Run for each DDM Computation

- 100 x 100 km domain

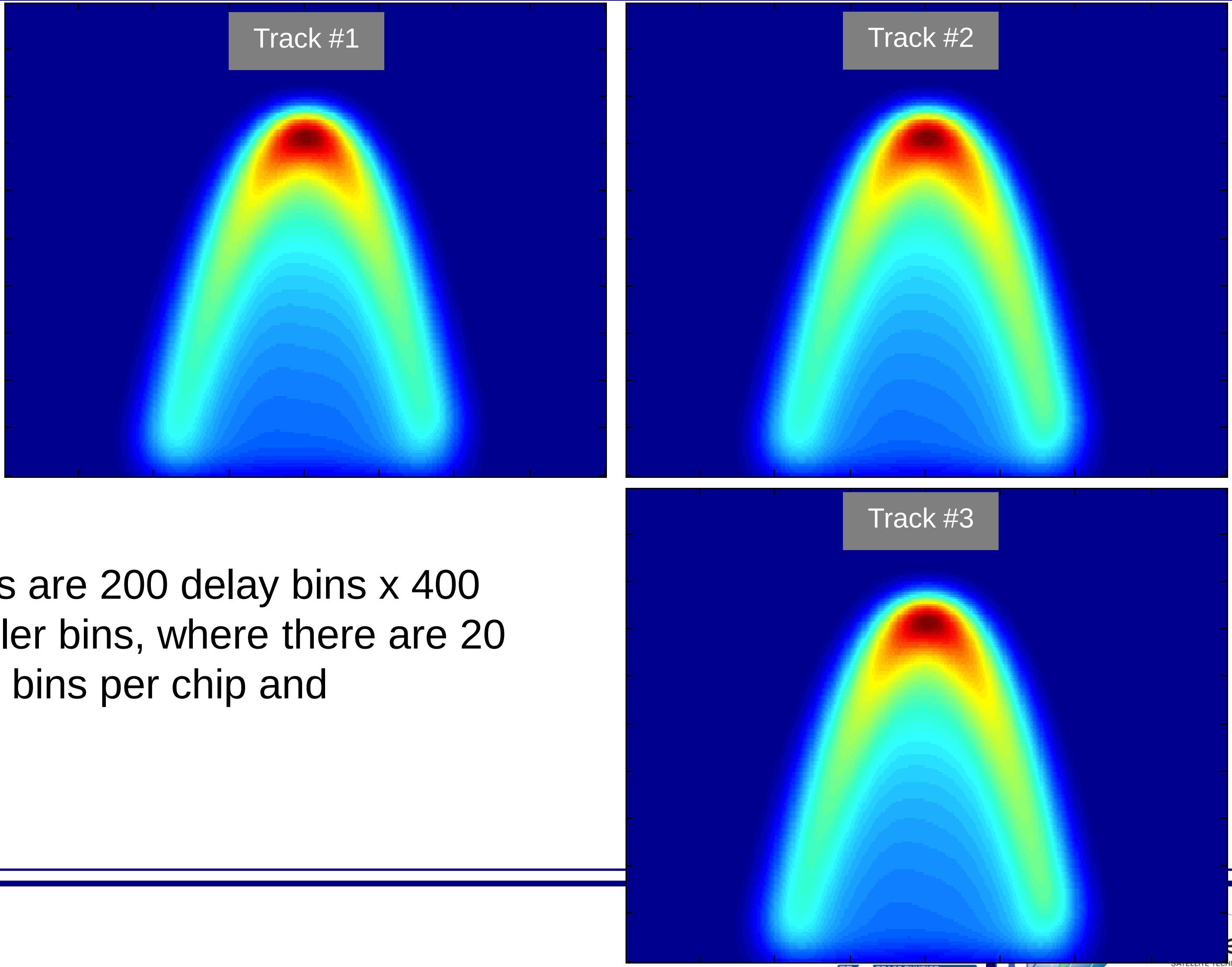


DDMs Computed Along TC Transects



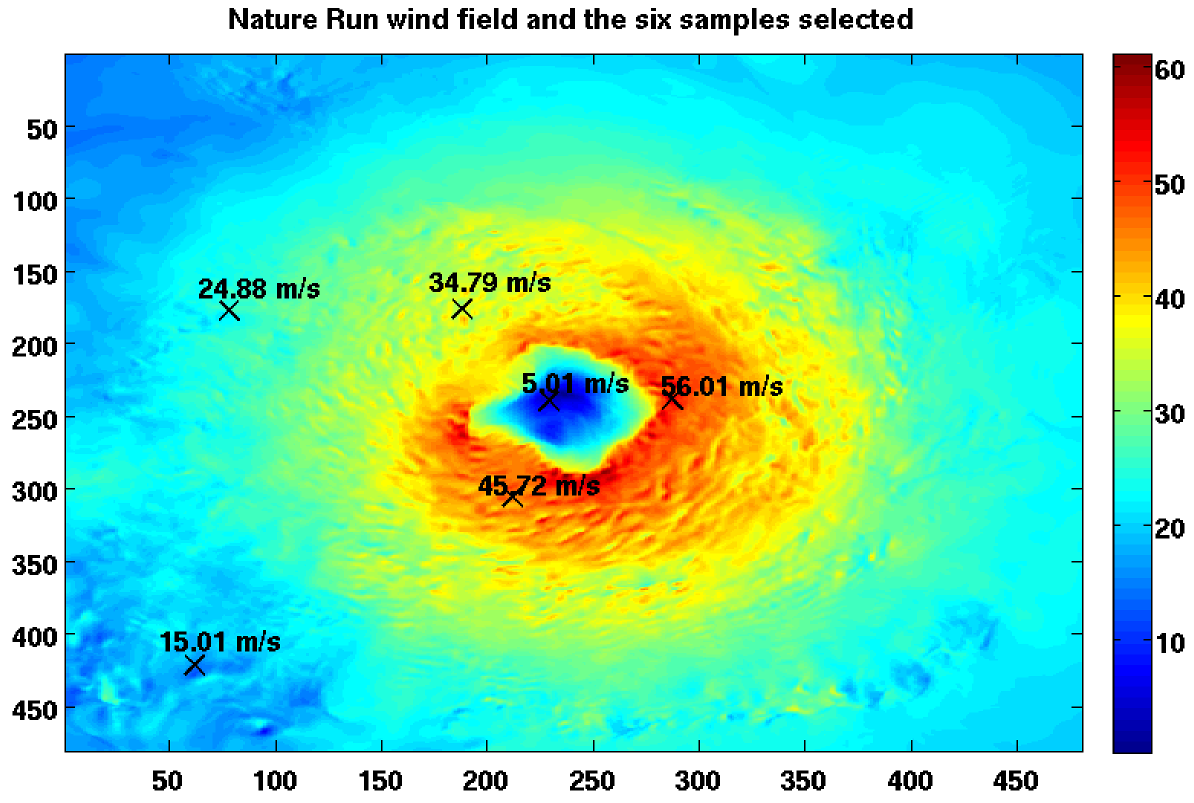
Example DDMs Along Tracks

DDM Animations (enter presentation mode to play animations)



DDMs are 200 delay bins x 400 Doppler bins, where there are 20 delay bins per chip and

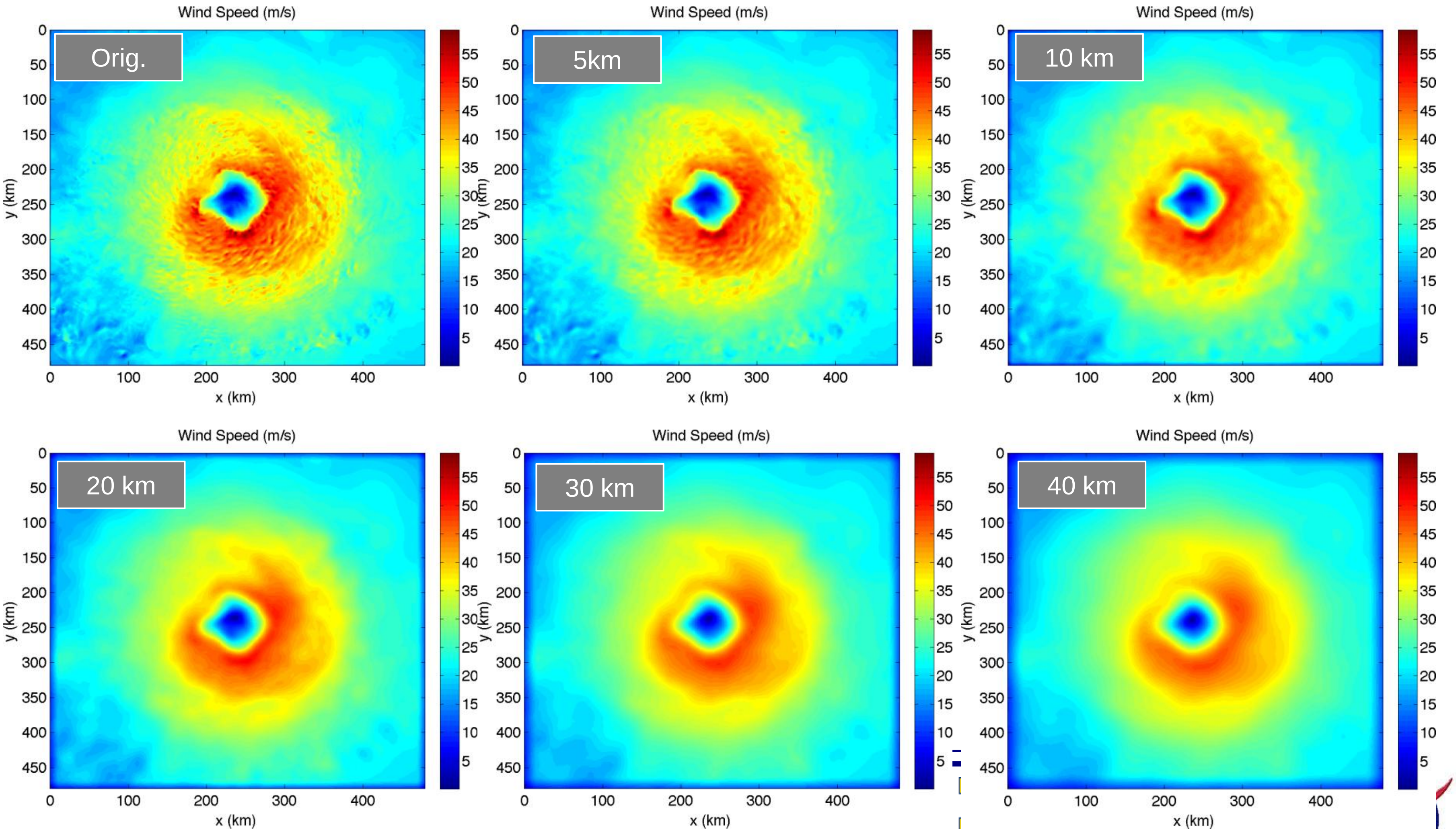
Wind Speed Retrieval Using Delay Waveform Slope (DWS) Nature Run Sample Locations



- Wind speeds shown are raw nature run values (not spatially averaged)

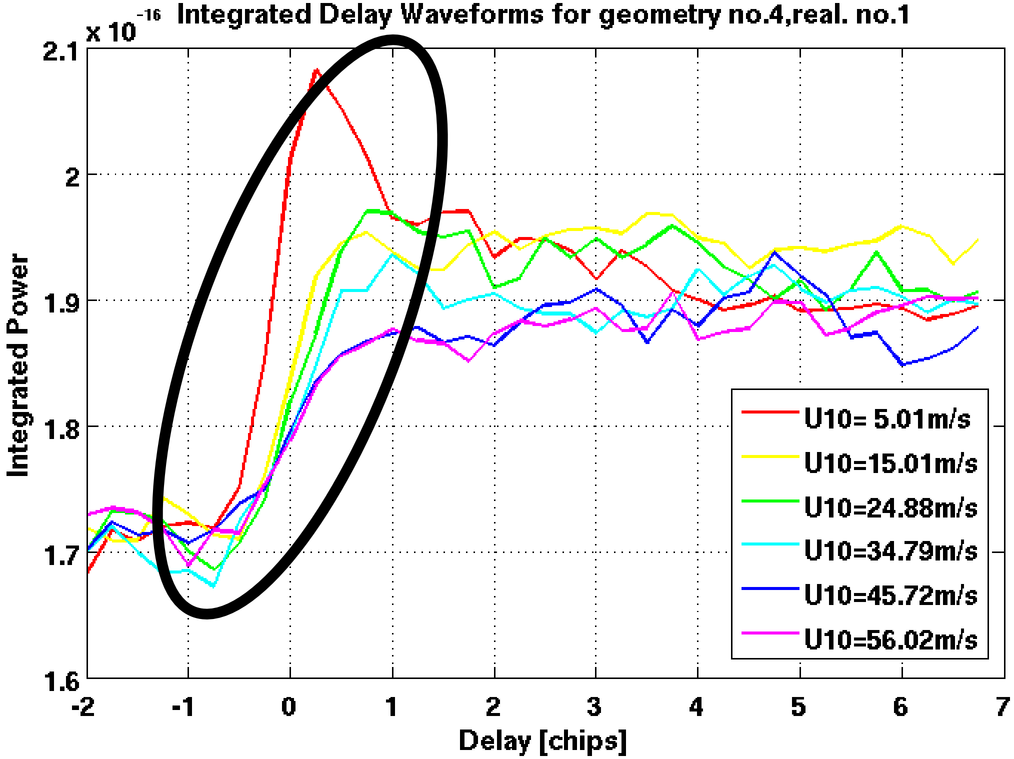
Spatially Smoothed Wind Fields

Ppatial filter of Nature Run. Top hat filter with a width of 10, 20, 30 and 40 km



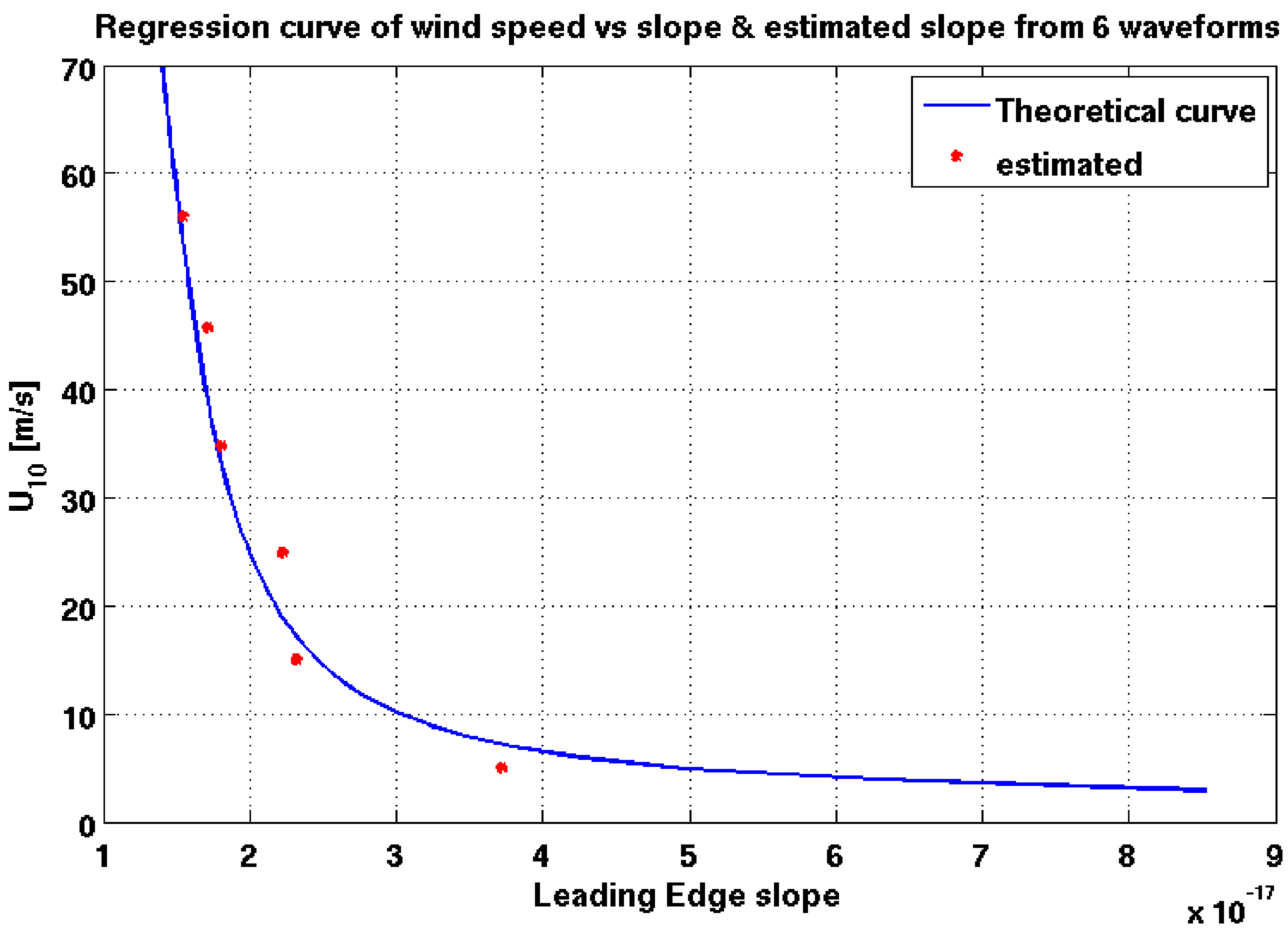
Wind Retrieval from DWS

- The integrated Delay Waveform Slope (DMS) is the leading edge slope of the DDM integration along the Doppler



❖ **For the 25x25 km2 case, select a DD range of [2 chip, 5 kHz].**

DWS vs. Wind Speed



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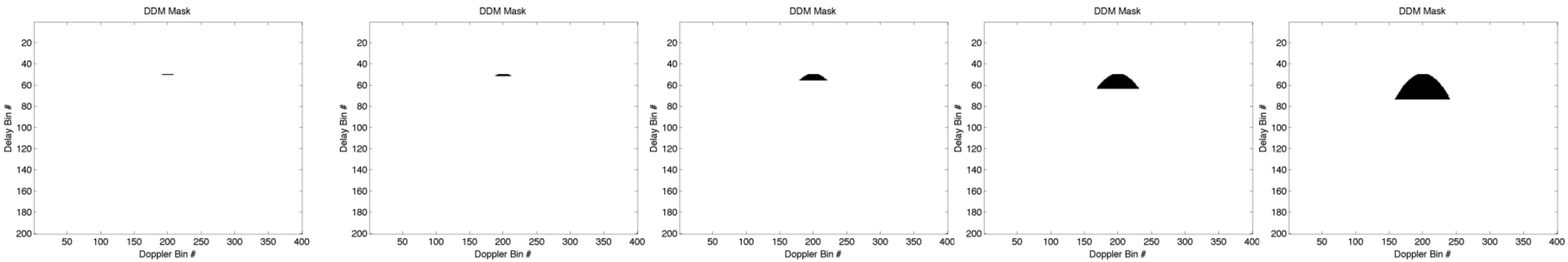
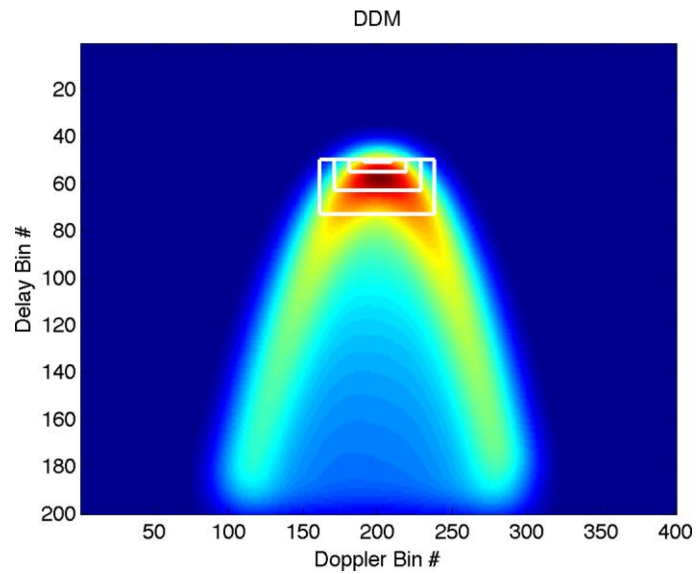
Spatial Integration of the DDMs

5 km | 10 km | 20 km | 30 km | 40 km

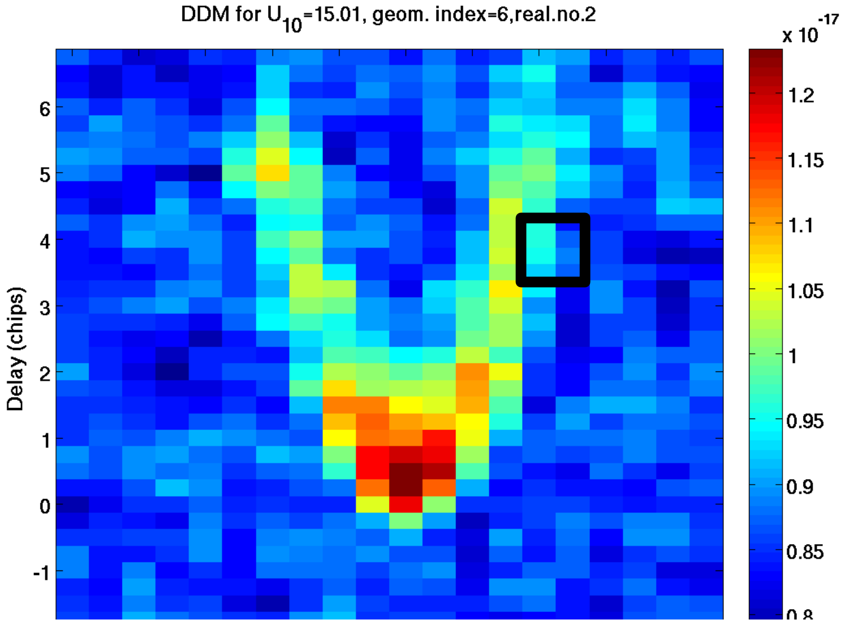


DDM integration regions chosen based on surface area covered by particular delay-Doppler bins



Wind Retrieval from DDMA

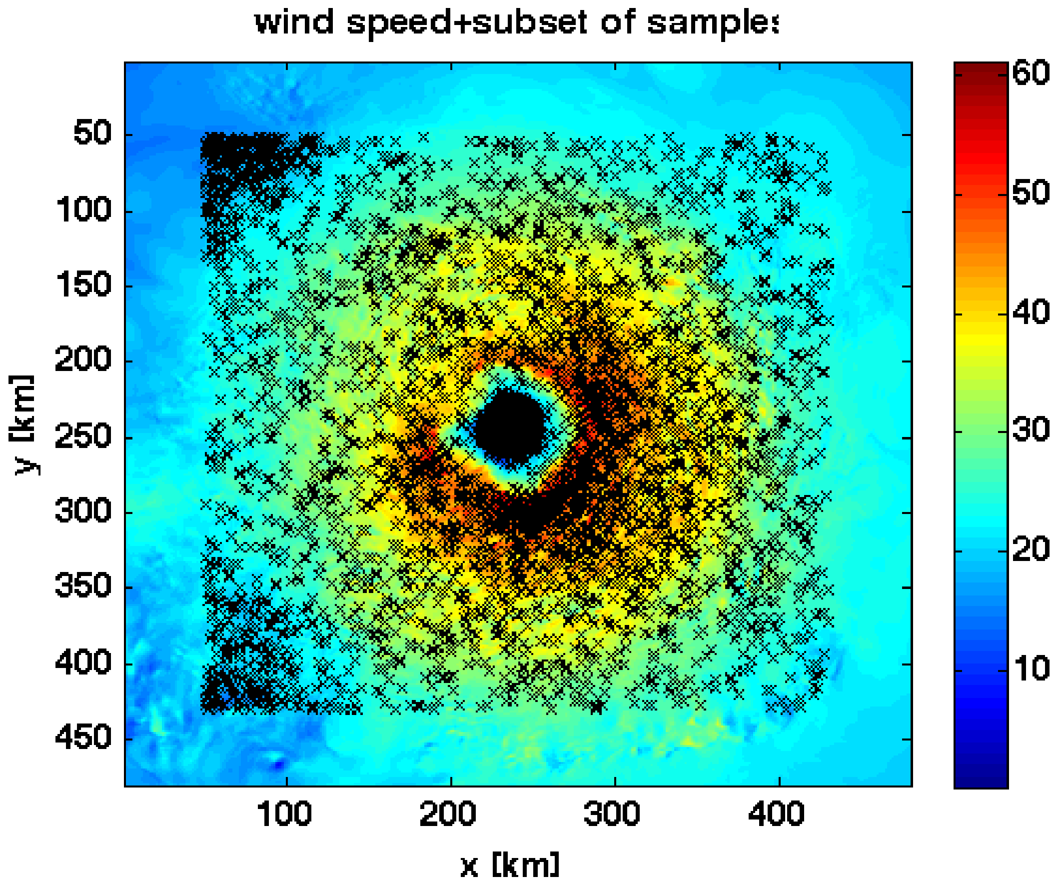
- DDMA is the average value of a "portion" of DDM;
- Select the DD range based on the spatial average we are considering



❖**For the 25x25 km2 case, we selected a DD range of [1 chip, 1 kHz].**

❖**For the 50x50 km2 case, we selected a DD range of [3 chip, 3 kHz].**

Sub-sampled Nature Run



DDMA vs. Wind Speed