Ocean current with DopSCA

New results, April 2019

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Context

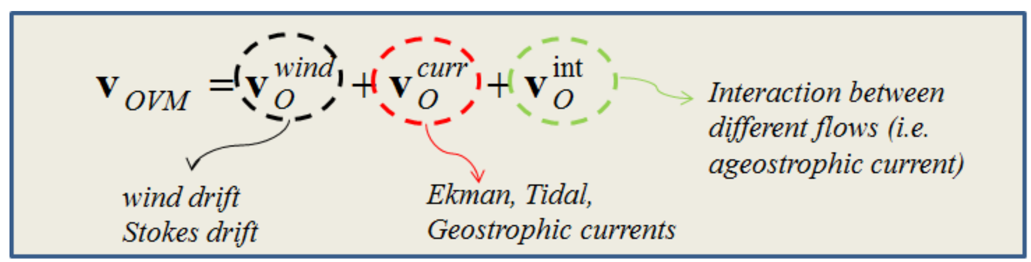
- ESA DopScat study 10 years ago suggested a dual chirp signal for ocean motion detection with a wind scatterometer
- Fois et al. 2014 published about the feasibility on MetOp-SG SCA with 0.2 m/s precision
- DopScat would provide accurate global stress-equivalent winds and ocean motion in one go
- KNMI, on request of the ocean currents community, requested EUMETSAT to consider DopSCA on MetOp-SG
- However, Schulte (Airbus) wrote a technical note elaborating on the **in**feasibility of DopSCA
- At a consolidation meeting on 15 March 2017 at ESTEC it was agreed to continue with a R&D project
- TU Delft kept preparing such R&D study
- ESA EE9 SKIM may now fly in convoy with SCA

EPS-SG

Ocean Surface Vector Motion (OSVM)

The OSVM is associated to the local scatterometer winds due to wave generation and other ocean wind drift processes, which are a matter of further air-sea interaction research, but which need to be well known to transform OSVM inferred from Doppler to OSVC, as pioneered by Mouche et al. (2011).

The accurate SCA wind measurements would allow accurate computation of the wind-associated part of the OSVM.



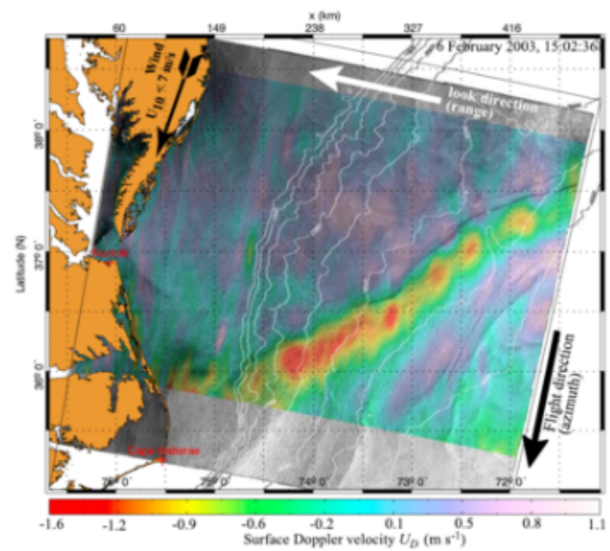
$$\mathbf{v}_O^{curr} \approx \mathbf{v}_{OVM} - \mathbf{v}_O^{wind}$$

Simplified relation between OVM and sea surface current Model

Scientific objectives: surface currents, waves & sea ice drift

The main objective of SKIM

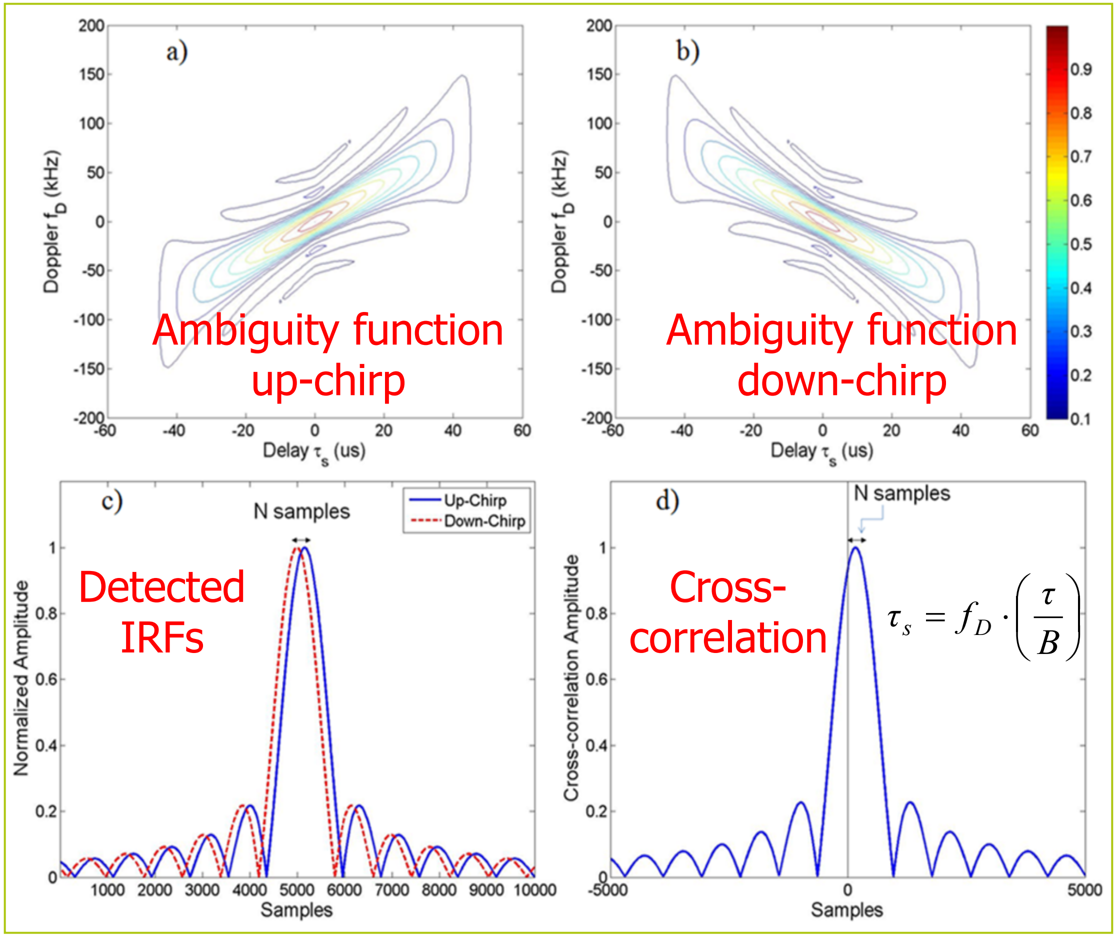
is to measure the **total surface current vectors** (TSCV). Each word here is important: the **total velocity** is the velocity of actual water parcels averaged over a few minutes (snapshots would include much stronger wind-wave signatures). This differs from altimeter-derived currents that generally miss most of the current variance. **Because SKIM includes a classic altimeter**, it will be able to **bridge the gap** between today's measurements and the more complete assessment of the TCSV. **Vector current** measurement on a single pass would be a first time ever measurement from space: previous ATI or Doppler centroid (as on this Envisat image) only give the current component perpendicular to the satellite track. Measurements of current shall be over the global ice-free and precipitation-free ocean and inland seas from 82°S to 82°N at a spatial resolution of ≤40 km (equivalent wavelength of ≤80 km) with a revisit of ≤ 10 days and a standard uncertainty of ≤0.1 m/s for each component.



Gulf Stream from Envisat Doppler

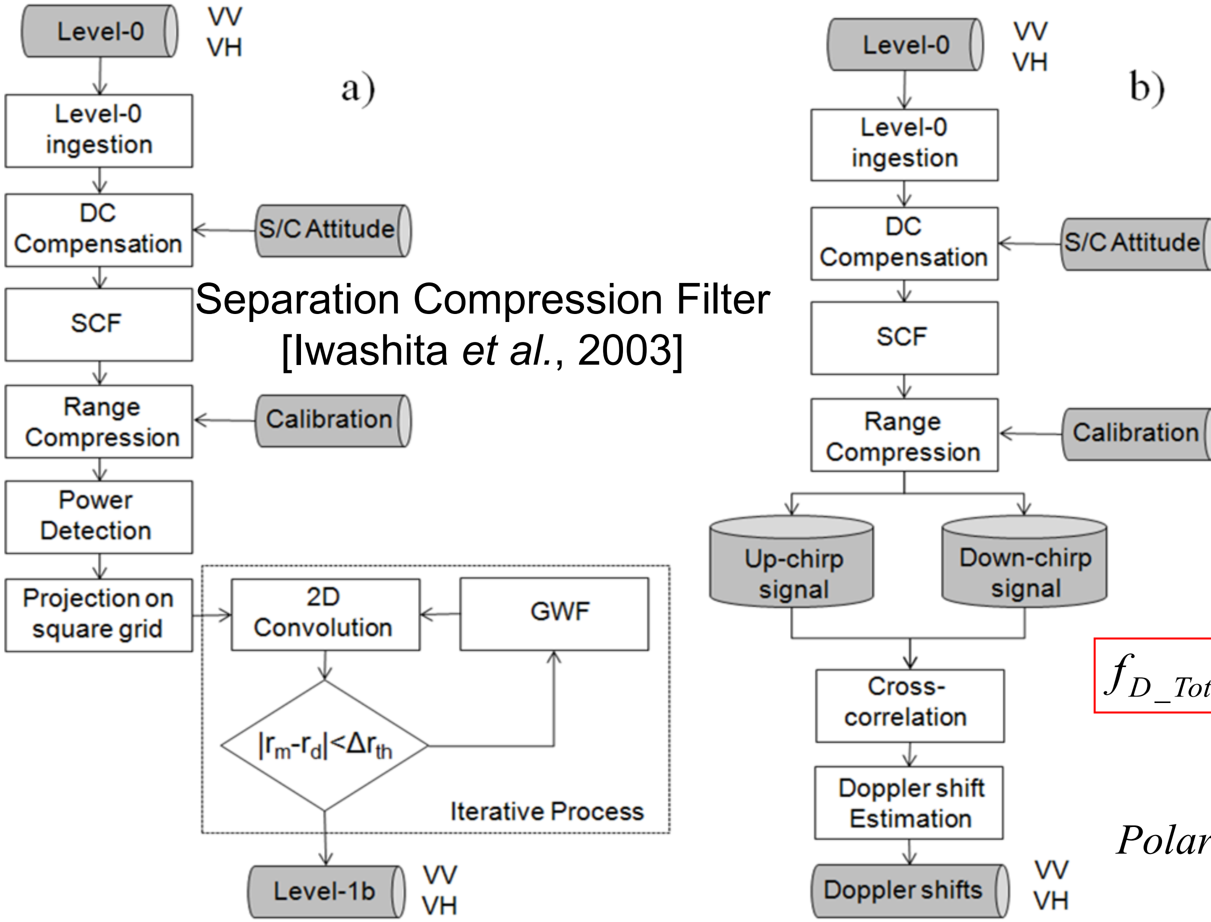
DopSCA Observation Principle (slide from Franco Fois)

- DopSCAT transmits a dual-chirp, that is a combination of an up-chirp, and a down-chirp.
- This waveform allows estimating not only the σ^o but also the Doppler shift of the ocean.
- The ambiguity functions of LFM pulses with opposite chirp rates are skewed in opposite direction, meaning that the introduced delay has an opposite sign.



$$s(t) = s_u(t) + s_d(t) =$$
$$= \left\{ A\exp\left[j2\pi\left(f_c t + \frac{1}{2}\frac{B}{\tau}t^2 \right)\right] + A\exp\left[j2\pi\left(f_c t - \frac{1}{2}\frac{B}{\tau}t^2 \right)\right]\right\} \mathrm{rect}_\tau(t)$$

Level-1 Processing (slide from Franco Fois)



- The Doppler shift measured by a space-borne active microwave instrument over the ocean can be expressed as the sum of three main terms:

$$f_{D\_Total} = f_{D\_wind} + f_{D\_curr} + f_{D\_geo}$$

Polarization dependent

Polarization independent

Level-1 data processing flow for the generation of Normalized Radar Cross section images (left) and for the estimation ocean's Doppler shifts (right).

Requested SCA instrument parameters for DopSCAT

- simultaneous up and down chirp (SCA uses only upchirps)
- Chirp duration 2 ms instead of 1 ms
- Chirp bandwidth 1 MHz (unchanged from SCA)

Some other points:

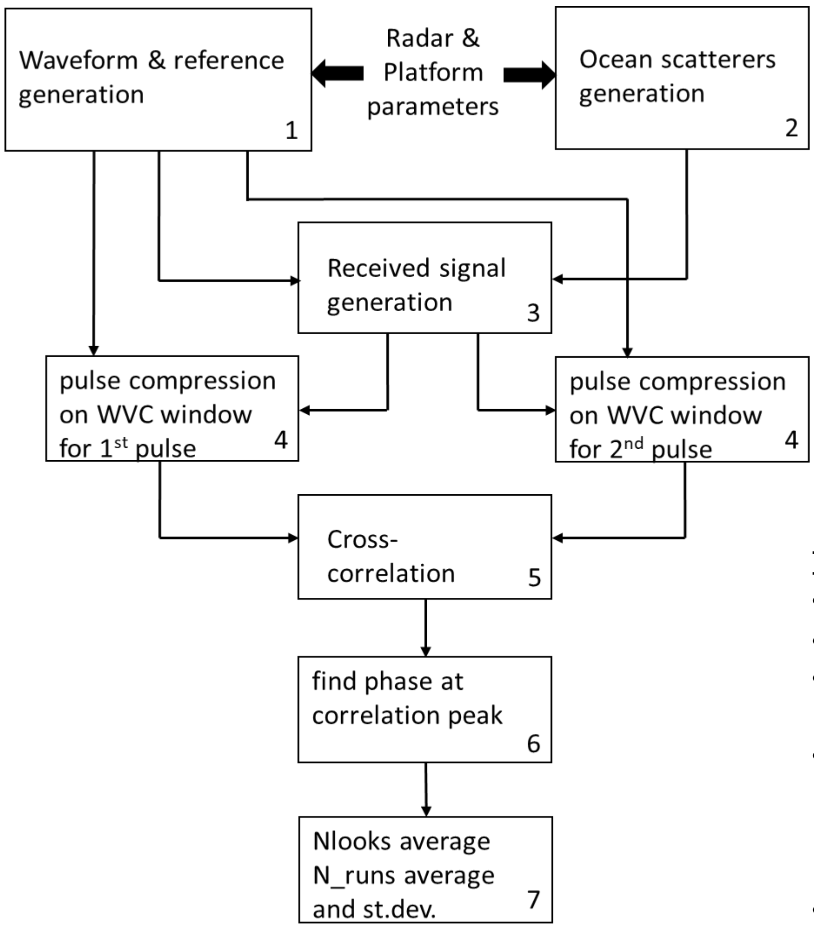
- Improved pointing analysis (cone metrics?)
- Doppler calibration over land
- We want to measure 0.1 – 1 m/s ocean current; 1 m/s is 35 Hz in Doppler
- 1 ms measurement time is 1 kHz in Doppler resolution
- PRF for a beam of SCA: 5 Hz; ocean decorrelation time 3 - 10 ms

Background

- Additional investigation showed that antenna motion effects were not fully taken into account in the studies, hence the results were far too optimistic
- In the consolidation meeting of March 2017 it was shown that there might be some opportunities for several waveforms, but a sufficiently detailed analysis lacked
- Today, a more detailed study with simulation results is available (draft manuscript), showing ocean motion measurement accuracy better than 1 m/s, with today's SCA instrument parameters. The well-known pulse-pair method is used, with relatively short pulses, using the SCA FORE and/or AFT beam

✓ Recently an echo cancellation method has been simulated, further improving performance

Simulation process



In the simulation:

- >7 scatterers per res.cell
- WVC of 166 resolution cells (25 km)
- Sufficiently large simulation surface, based on pulse lengths
- 64 / 128 runs of 16 look averages, a total of 1024/2048 independent realisations with 4000 – 7000 scatterers, (long processing times)
- 45 deg FORE and AFT beams considered

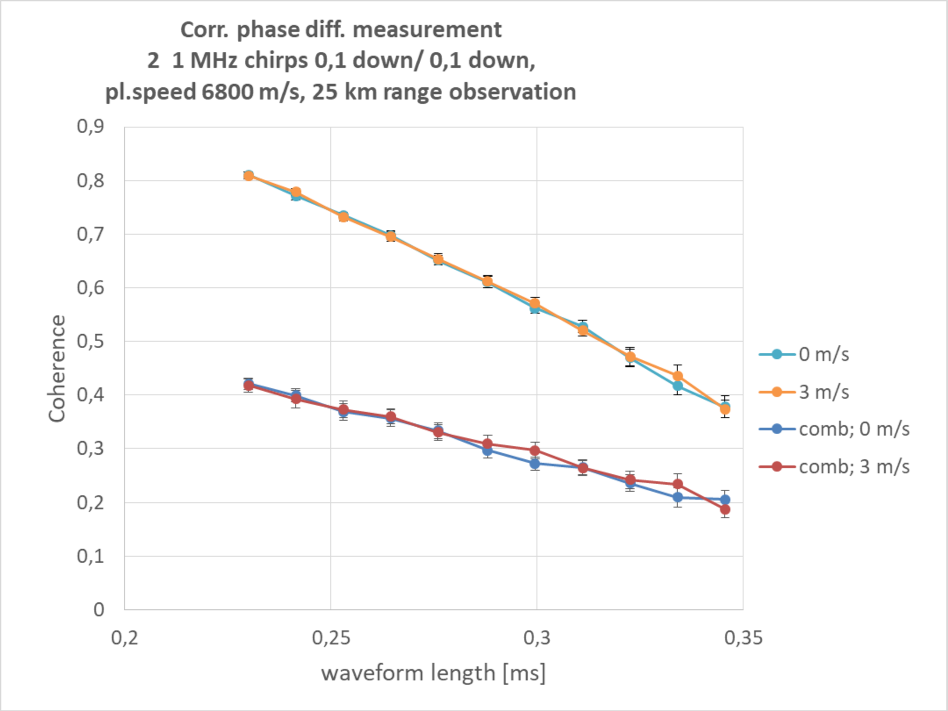
Performance Simulation

We aim to find the phase difference (Doppler shift) due to surface motion over Dt

The range response a(t) over a WVC is complemented by a similar response from the second pulse delayed by Dt: b(t+Dt)

The signals a and b overlap since the observation range is very long compared Dt and the responses over a given WVC are cross-correlated

Pulse-pair coherence and expected radial velocity measurement accuracy



Cramér-Rao bound:

$$\sigma_{vr}^2 = \left(\frac{1}{2k\tau_B}\right)^2 \frac{1}{2N_L}\frac{1-\gamma^2}{\gamma^2} \qquad \text{(Rodriguez)}$$

with:

$N_L = \frac{50}{0.15}\frac{50\ 4}{6.8} = 9800$ looks 50x50 km WVC

$\tau_B = 0.115\ ms$ time between pulses

$\gamma^2 = 0.168$ coherence squared

$k = \frac{2\pi}{\lambda}$=113 wavenumber

➔ $\sigma_{vr} = 0.61\ m/s$

Echo Cancellation

Improved coherence is sought by an echo cancellation method exploiting the known time delay Dt in Fourier domain to obtain a(t)/b(t) from s(t):
 $s(t) = a(t) + a(t+\Delta t)$

Fourier transform $F[s(t)] = F[a(t)] + F(a(t+\Delta t)]$

$F(a(t+\Delta t)] = A(j\omega)e+j\omega\Delta t$

$F[s(t)] = A(j\omega)(1+e+j\omega\Delta t)$

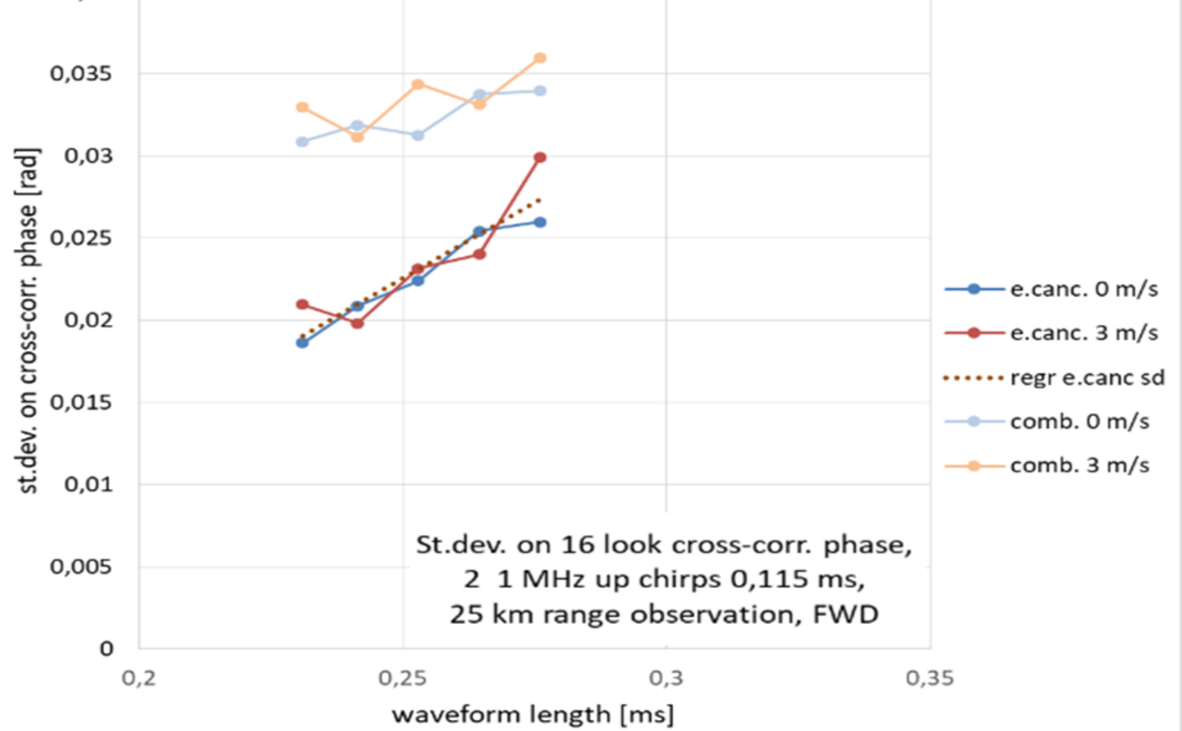
a(t): inverse Fourier transform of $F[s(t)]/(1+e+j\omega\Delta t)$

Since the complex ocean backscatter signal changes over Dt due to antenna motion, only partial echo suppression is achieved

A longer time series a(t) results in better suppression and 20 WVCs or 500 km is sufficient

The fore and aft antennae are used (L=3.6 m)

Results



Δt [ms]	Theoretical coherence a(t) and a(t+Δt) (separate signals)	Simulated coherence s(t) and s(t+Δt) (combined signal)	Simulated coherence a'(t) and a'(t+Δt) (echo cancelled signals)
0.115	85%	42%	55%
0.1265	82%	41%	52%
0.138	79%	40%	48%
0.1495	75%	38%	45%
0.161	72%	36%	42%

- Echo cancellation works to improve coherence and thus performance

SCA OSVM precision

Δt [ms]	Precision in m/s s(t) 25km x 25km WVC	Precision in m/s a'(t) 25km x 25km WVC	Precision in m/s a'(t) 50km x 50km WVC
0.1150	1,23	0,80	0,39
0.1265	1,09	0,67	0,34
0.1380	1,02	0,72	0,37
0.1495	1,03	0,73	0,36
0.1610	1,04	0,84	0,42

- Single-pass accuracies over a 50-km WVC better than 0.5 m/s.
- Time averaging over multiple passes and multiple scatterometers may further improve accuracy.

Ideas for follow-on activities

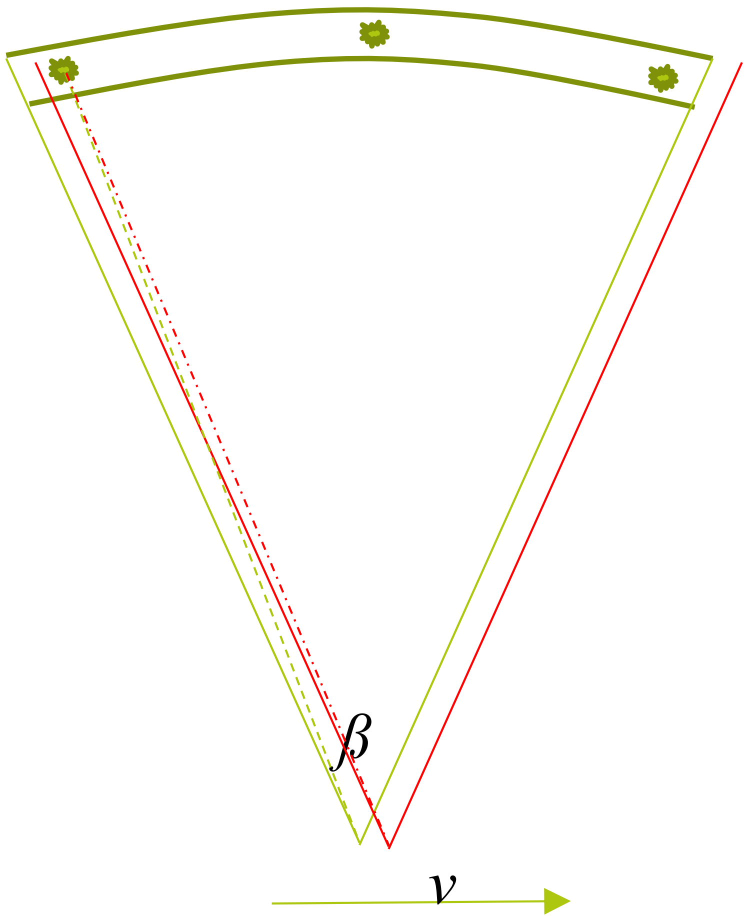
- The proposed method needs to be investigated and tested with real data. Two goals:
    1. Check the phase measurement method and its accuracy. Does it live up to the simulation results? What is furthermore needed in terms of instrument requirements?
    2. Investigate the geophysical aspects of the Ocean Current Measurement (aligns with GlobCurrent)
- Some ideas for experimental campaign:
    - Dedicated experiment with the pulse-pair waveform on TerraSAR-X
    - Airborne experiment (Metasensing?) with a scaled configuration (platform speed versus Doppler bandwidth) representative for the SCA configuration (also pulse-pair waveform required)
- Experiments should be carried out over land (zero current) and over oceans, preferably in areas with some in situ knowledge
- Investigations of the geophysical aspects could be performed with an instrument on a fixed platform, e.g. in collaboration with other projects (SKIM)
- Enhance simulation work
- Investigate instrument consequences (especially pointing)
- ….

Conclusions

- The high-quality wind scatterometer SCA is an excellent starting point for observing ocean motion, as accurate wind input is needed for waves and drifts
- DopSCA has been investigated and published as a viable concept for SCA, but the effect of the moving platform on the targets was underestimated
- The SCA development now continues WITHOUT DopSCA specs.
- SCA-1 and 2 thus likely have no optimal DopSCA capability, but:
- The digital signal transmitter may allow DopSCA waveforms
- Pointing knowledge may be proven adequate (TBC on ASCAT)
- Further simulation studies now provide a feasible concept on SCA with marginal, but potentially useful accuracy, e.g., in hurricane wind conditions or for weekly climatologies, particularly when complementing SKIM
- DopSCA studies/campaign(s) may be envisaged?

- Back-up slides

Antenna motion gives each scatterer in the resolution cell its own Doppler history



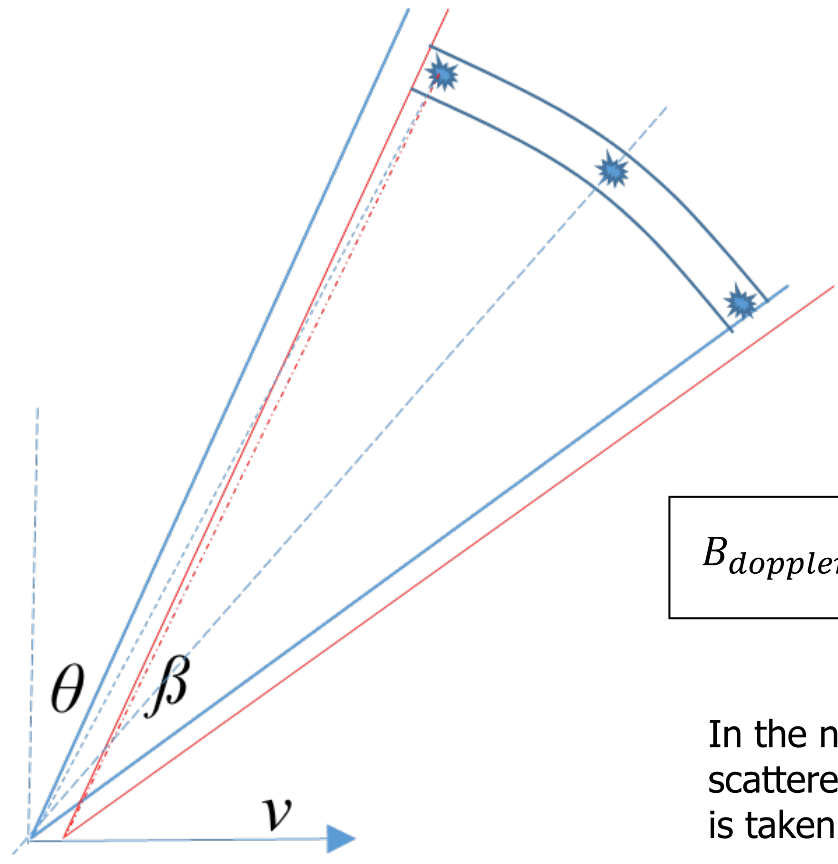
$$B_{doppler,azimuth} = \frac{2\beta v}{\lambda} \; [Hz]$$

- For SCA, DopSCAT:
  $B_{doppler,\, az} = 4250$ Hz
- Much larger than the ocean Doppler we are after! (Note that $1/B_{doppler,\, az}$ equals 230 μs, fits within the decorrelation time)
- There are two effects:
  1. We can and do compensate for the antenna motion between transmit and receive and over the pulse length (implemented in both simulation studies)
  2. Doppler spread from the distributed target cannot be compensated but has important effect (omitted in earlier DopSCAT study)

Approaches in the basic simulations with up and down chirps

- The proposed method of Franco Fois with cross-correlation to find the ocean current peak is simulated.
- Instrument parameters are taken from SCA, unless otherwise indicated.
- The platform (antenna) speed is 6800 m/s.
- An ocean surface of 17 km wide (azimuth) and 6 km long (range) is considered. It is represented by 600 randomly positioned scatterers of equal strength. The ocean current moves all scatterers in the same way. The analysis is limited to range cells within this area, so range-doppler ambiguities are well represented.
- In the simulation the transmit chirps can be generated and timed fully independent of each other. On reception the responses of the up and down chirps are kept separated (for simplicity the Separation Compression Filter as described and tested by Franco Fois has not been taken into account).
- Noise (SNR) has not been taken into account.
- In the simulations 256 independent realisations of the sea surface and of the received signals are generated. They are processed as 16 runs of 16 looks. So in a run, 16 independent measurements are averaged. The 16 runs are used to produce an average result and a standard deviation.
- In the graphs the pulse length, the time until the start of the second chirp and the bandwidth of the transmitted chirps are varied.

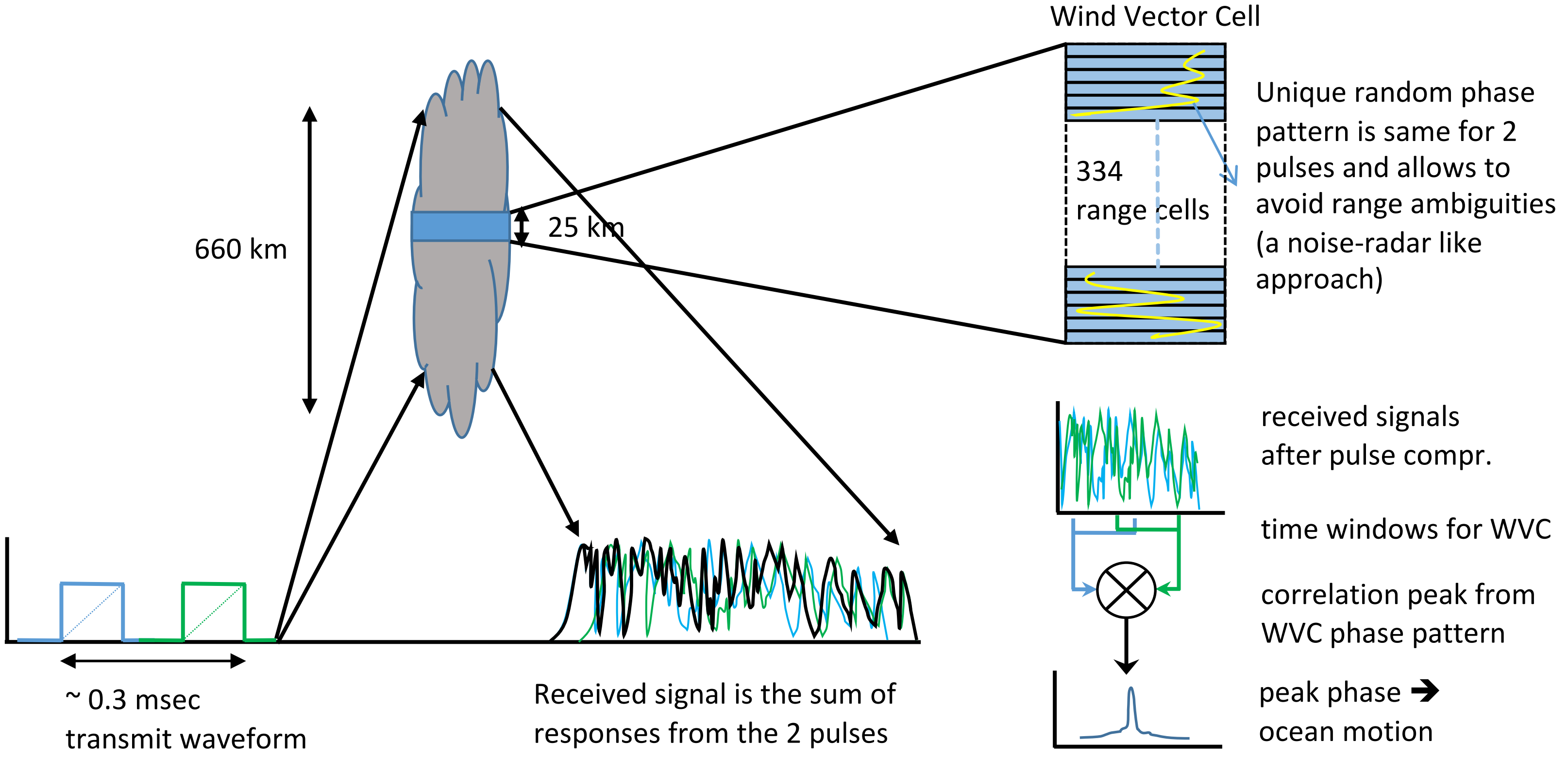
Scatterer Doppler history, squinted beam case used in the new study



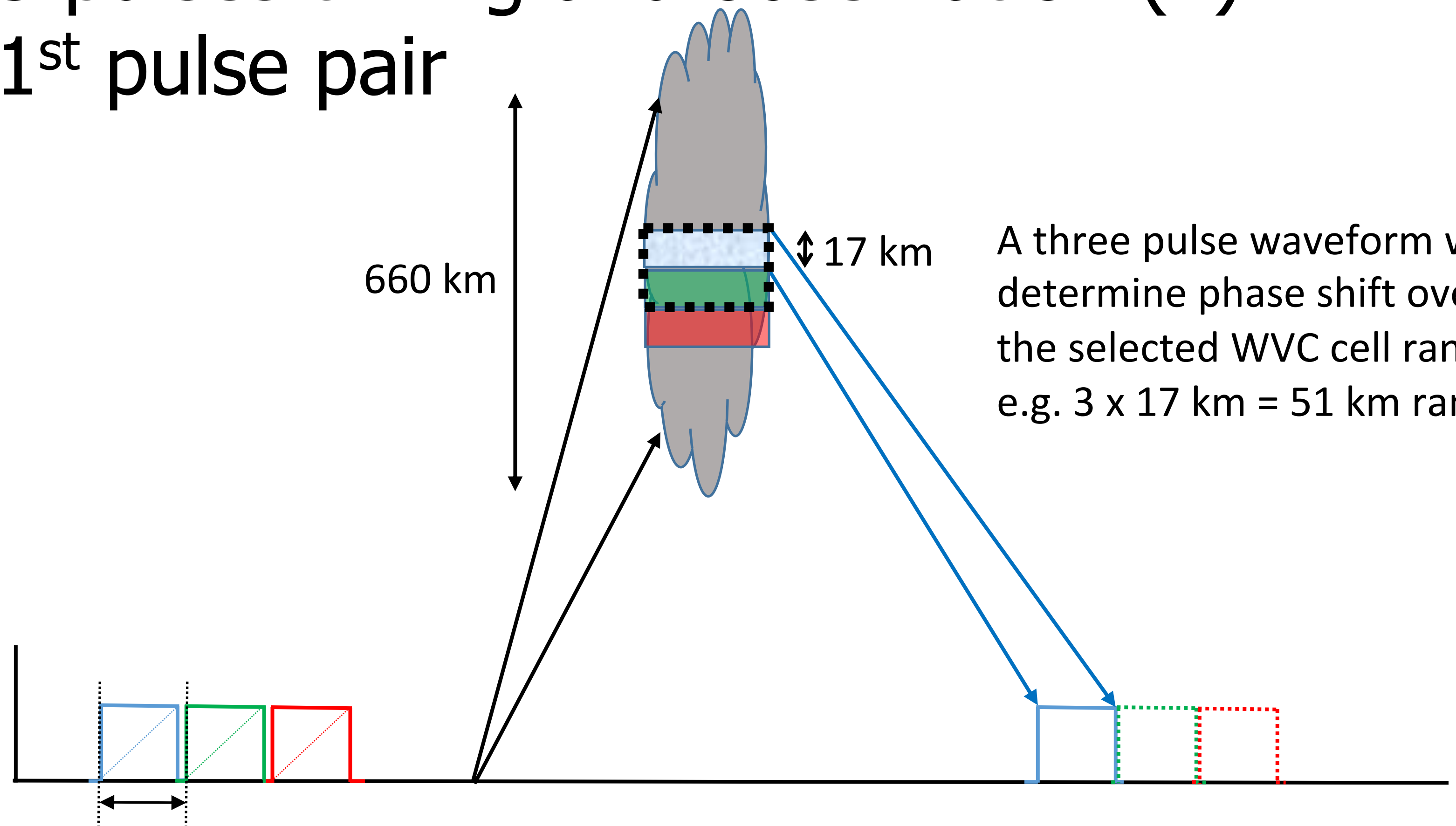
$$B_{doppler,az.} = \frac{4v}{\lambda} \cos\theta \sin\frac{\beta}{2} \text{ [Hz]}$$

In the new simulations for each scatterer the exact range history is taken into account

Ocean motion determination for a wide footprint wind scatterometer



3 pulses timing and observation (1)
1st pulse pair

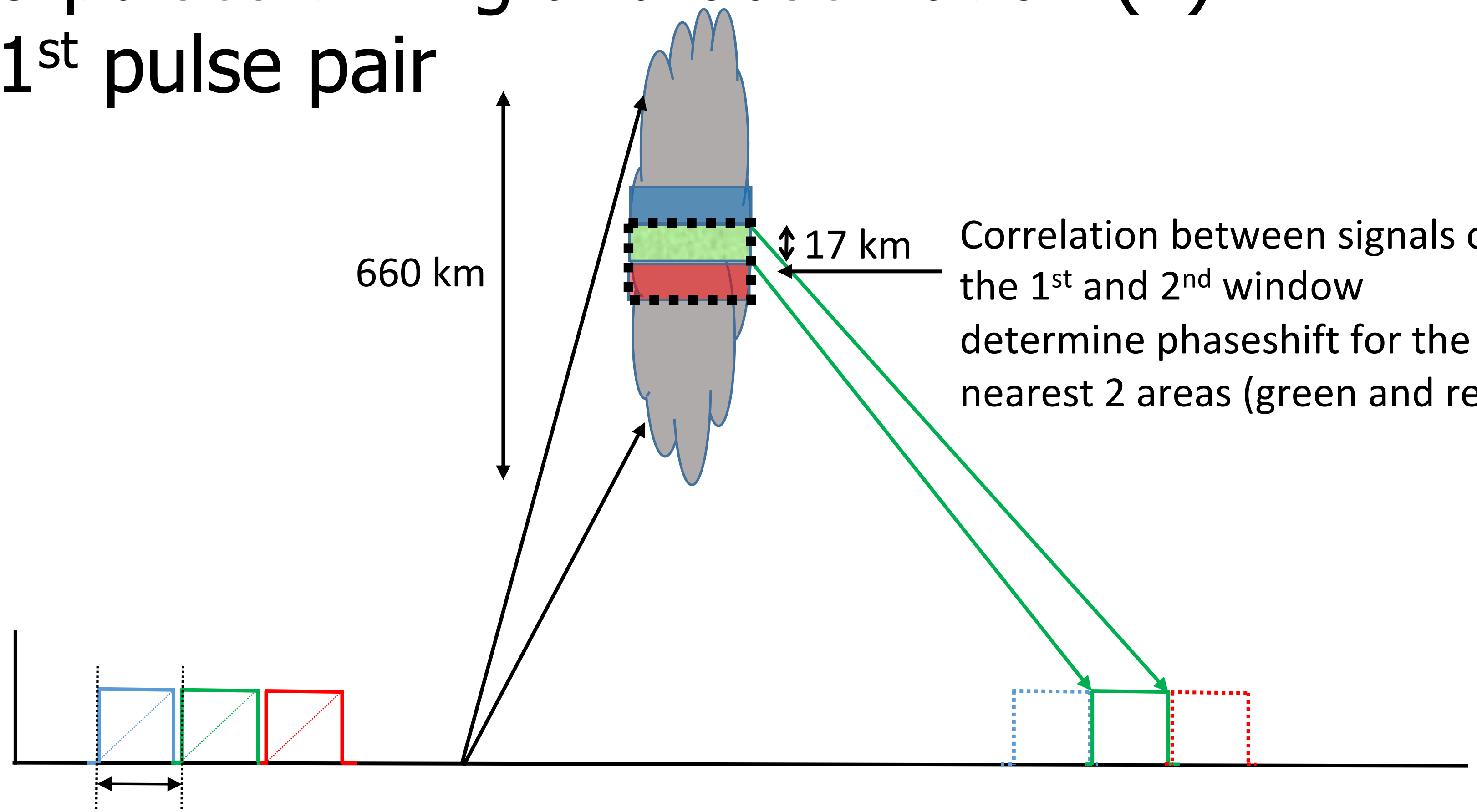


A three pulse waveform will determine phase shift over 3 x the selected WVC cell range, e.g. 3 x 17 km = 51 km range.

delay time between transmit waveforms, e.g. 0,115 ms = 17 km

Area of interest on the time axis selected for the 1st pulse. 2nd and 3rd pulse signals in this window come from areas 17 and 34 km nearer.

3 pulses timing and observation (2)
1st pulse pair

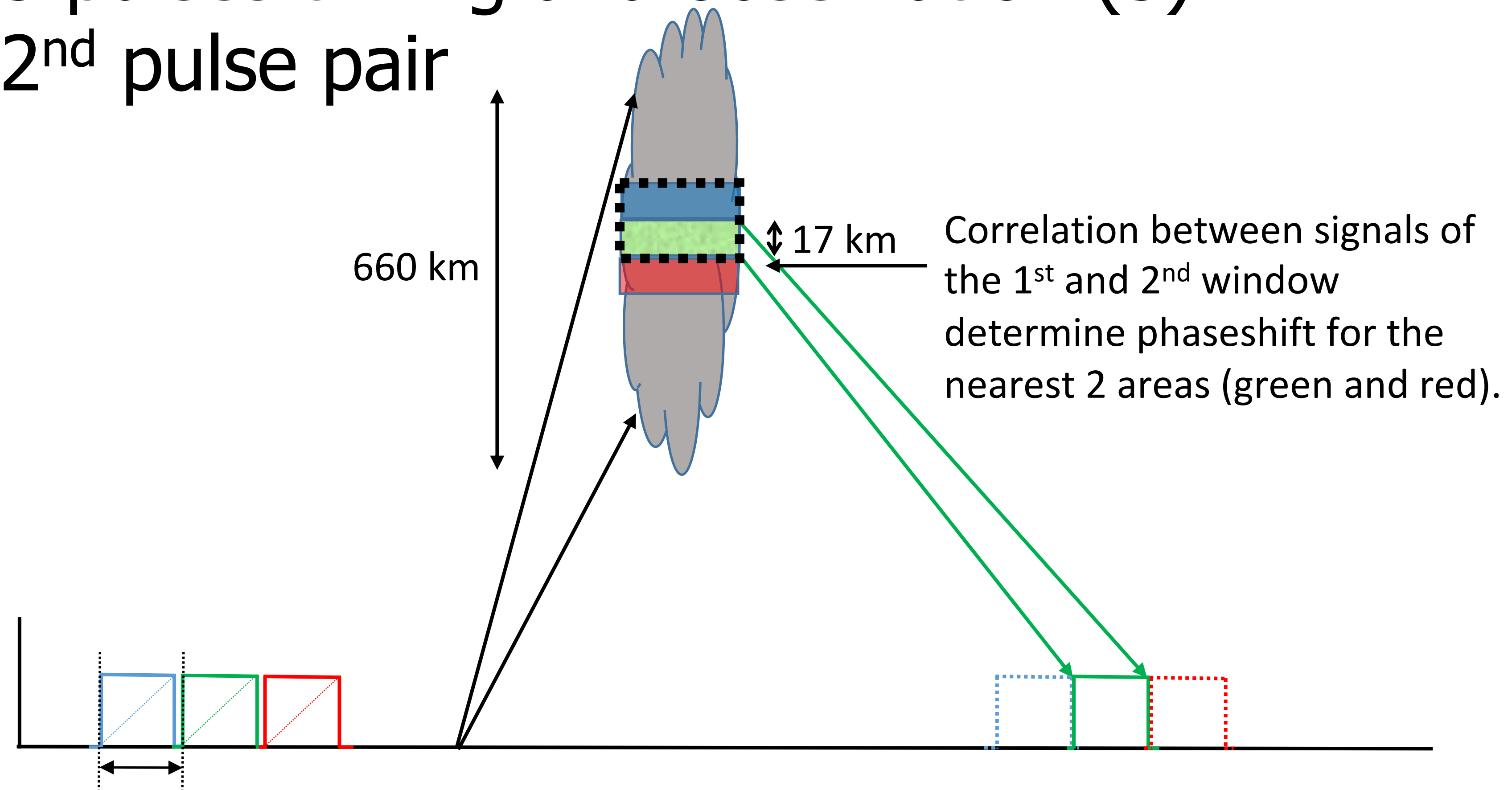


Correlation between signals of the 1st and 2nd window determine phaseshift for the nearest 2 areas (green and red).

delay time between transmit waveforms, e.g. 0,115 ms = 17 km

Area of interest on the time axis selected for the 2nd pulse. 1st and 3rd pulse signals in this window come from areas 17 km nearer and further away.

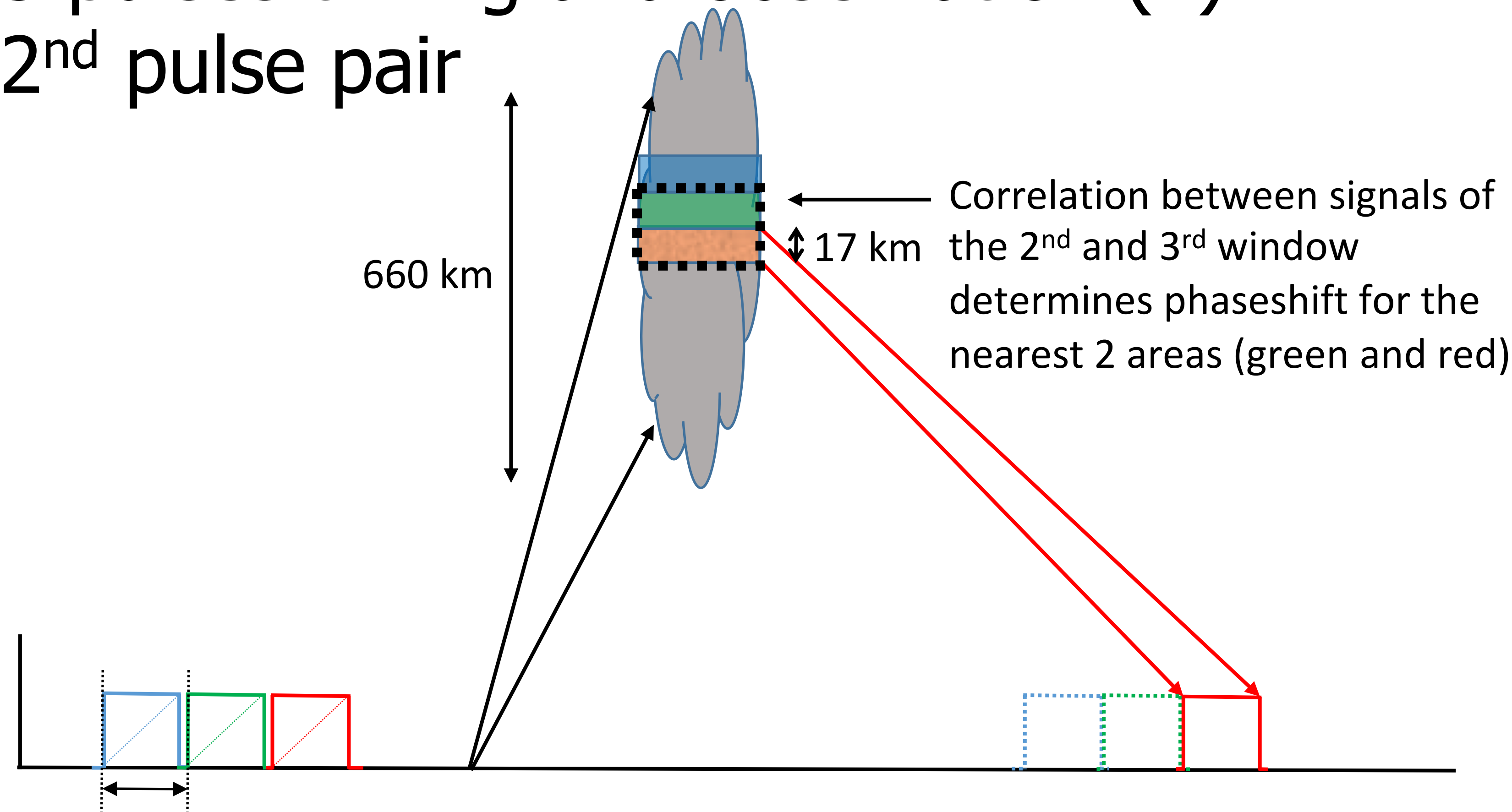
3 pulses timing and observation (3)
2nd pulse pair



delay time between transmit waveforms, e.g. 0,115 ms = 17 km

Area of interest on the time axis selected for the 2nd pulse. 1st and 3rd pulse signals in this window come from areas 17 km nearer and further away.

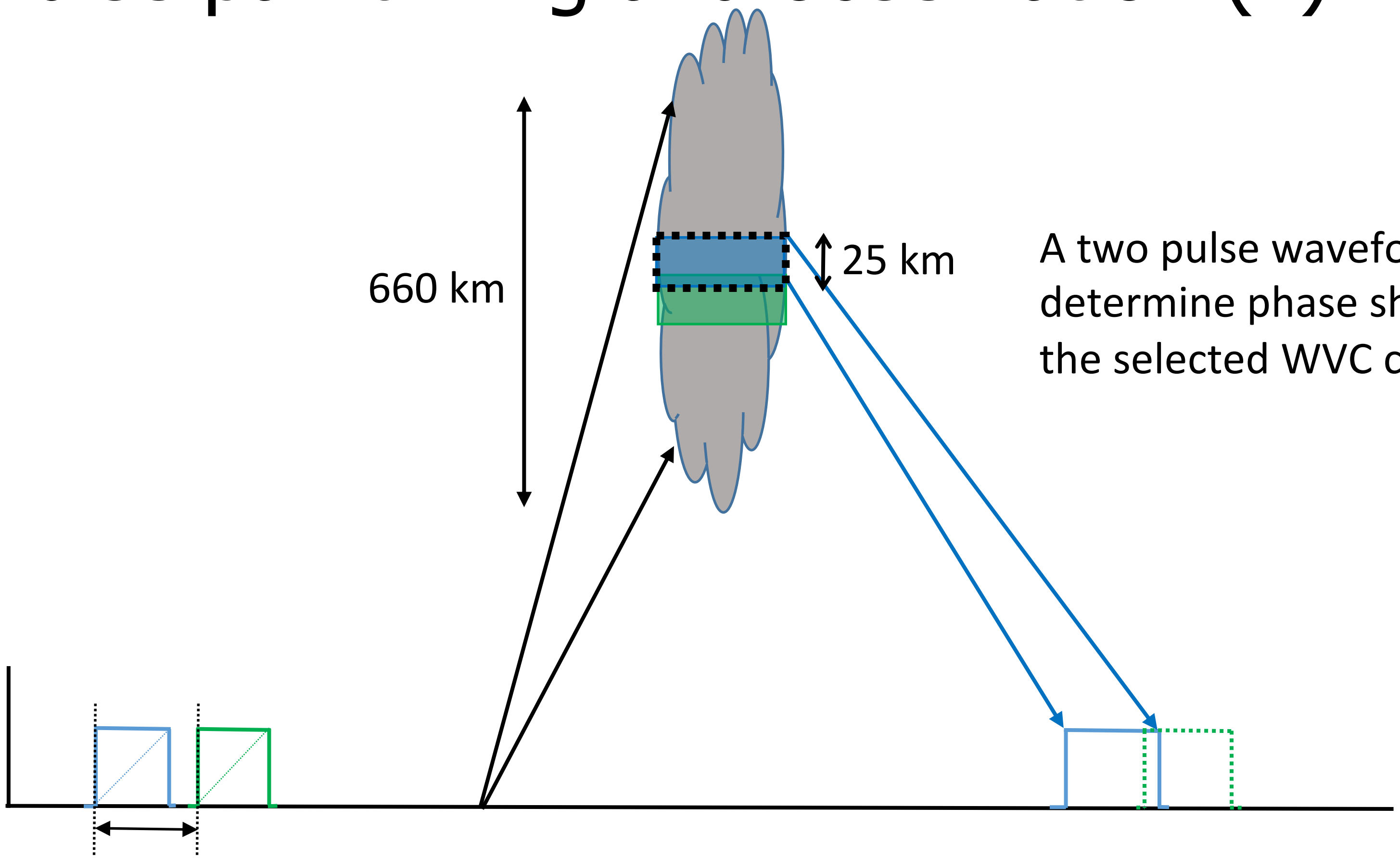
3 pulses timing and observation (4)
2nd pulse pair



delay time between transmit waveforms, e.g. 0,115 ms = 17 km

Area of interest on the time axis selected for the third pulse. 1st and 2nd pulse signals in this window come from areas 17 and 34 km further away

Pulse pair timing and observation (1)

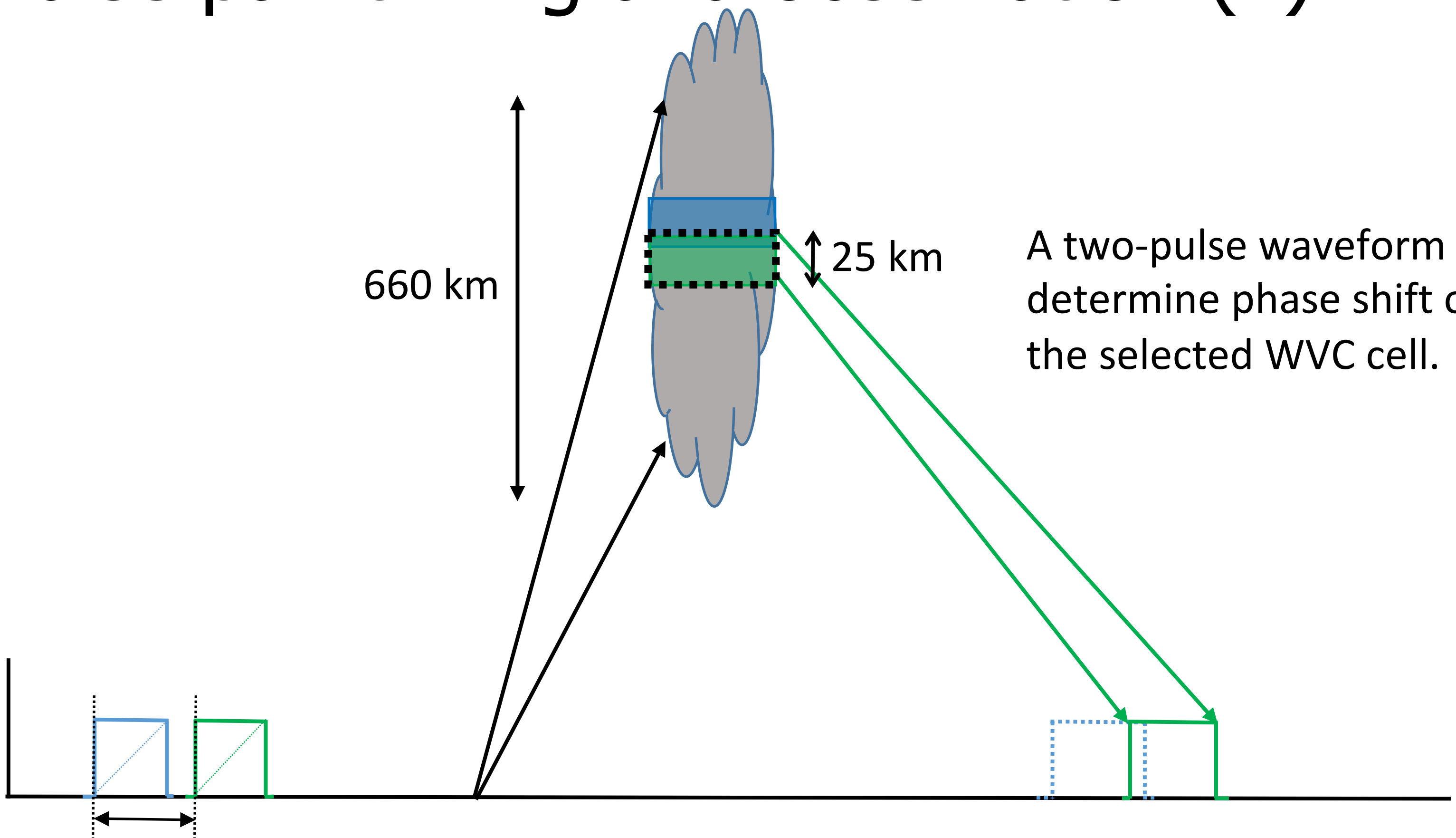


A two pulse waveform will determine phase shift over the selected WVC cell.

delay time between transmit waveforms, e.g. 0.14 ms = 21 km

Area of interest on the time axis selected for the 1st pulse. 2nd pulse signal in this window comes from an area 21 km nearer.

Pulse pair timing and observation (2)



A two-pulse waveform will determine phase shift over the selected WVC cell.

delay time between transmit waveforms, e.g. 0.14 ms = 21 km

Area of interest on the time axis selected for the 2nd pulse. 1st pulse signal in this window comes from an area 21 km further away.

Accuracy for 3 pulse chirps

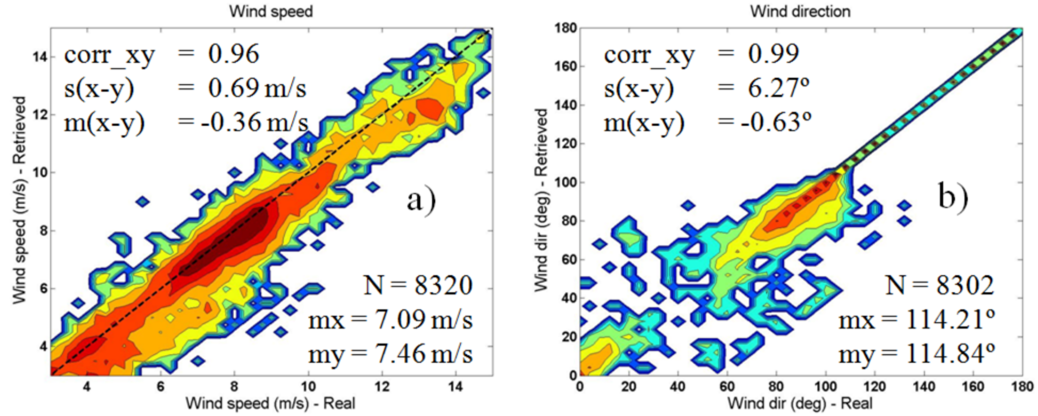
measurement time	Precision in m/s for 50 km WVC		
In ms	1st pulse pair	2nd pulse pair	Combined
Up-up-up 0,339	0,63	0,66	0,65
Dwn-dwn-dwn 0,339	0,74	0,72	0,66
Dwn-dwn-dwn 0,339	0,81	0,76	0,69
Dwn-dwn-dwn 0,345	0,84	0,76	0,65

Note: Simulation area in first two cases is 95 km long with 4500 reflectors. Last two cases have 155 km with 7500 reflectors.

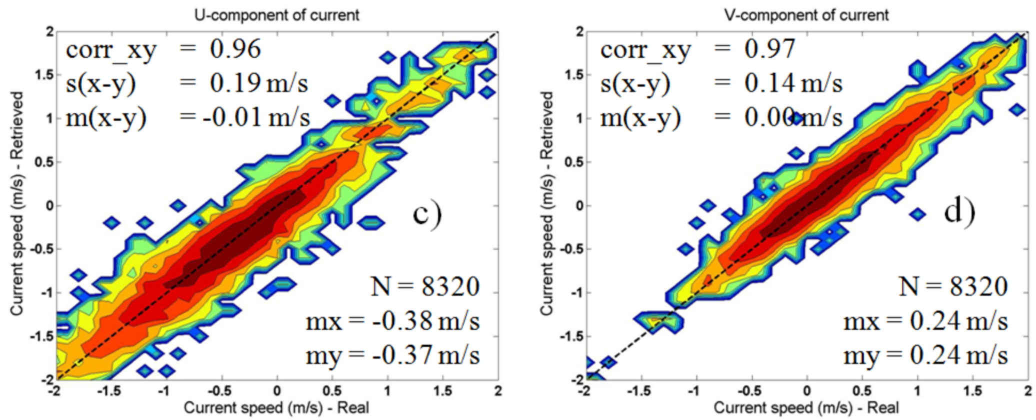
Processing & Performance Assessment Modules (slide from Franco Fois)

$$MLE(\vec{v} \mid z) = \frac{1}{\langle MLE \rangle} \sum_{i=1 \ldots N} \left| z_i - z_{GMF,i}(\vec{v}) \right|^2$$

- Extensive Monte-Carlo simulations show the capability of DopSCAT in estimating ocean currents with accuracy below 0.2 m/s, at a spatial resolution of 25 km (i.e. spatial sampling of 12.5 km) and a temporal resolution of 24 hrs.
- High-resolution products have accuracy worse than 1 m/s in ocean current estimates, which is only sufficient to meet the users' needs on a monthly time scale by performing temporal averages over stable currents.



$$MLE(\vec{v}_{OVM} \mid f_D) = \sum_{i=1 \ldots N} \left| f_{D,i} - \hat{f}_{D,i}(\vec{v}_{OVM}) \right|^2$$



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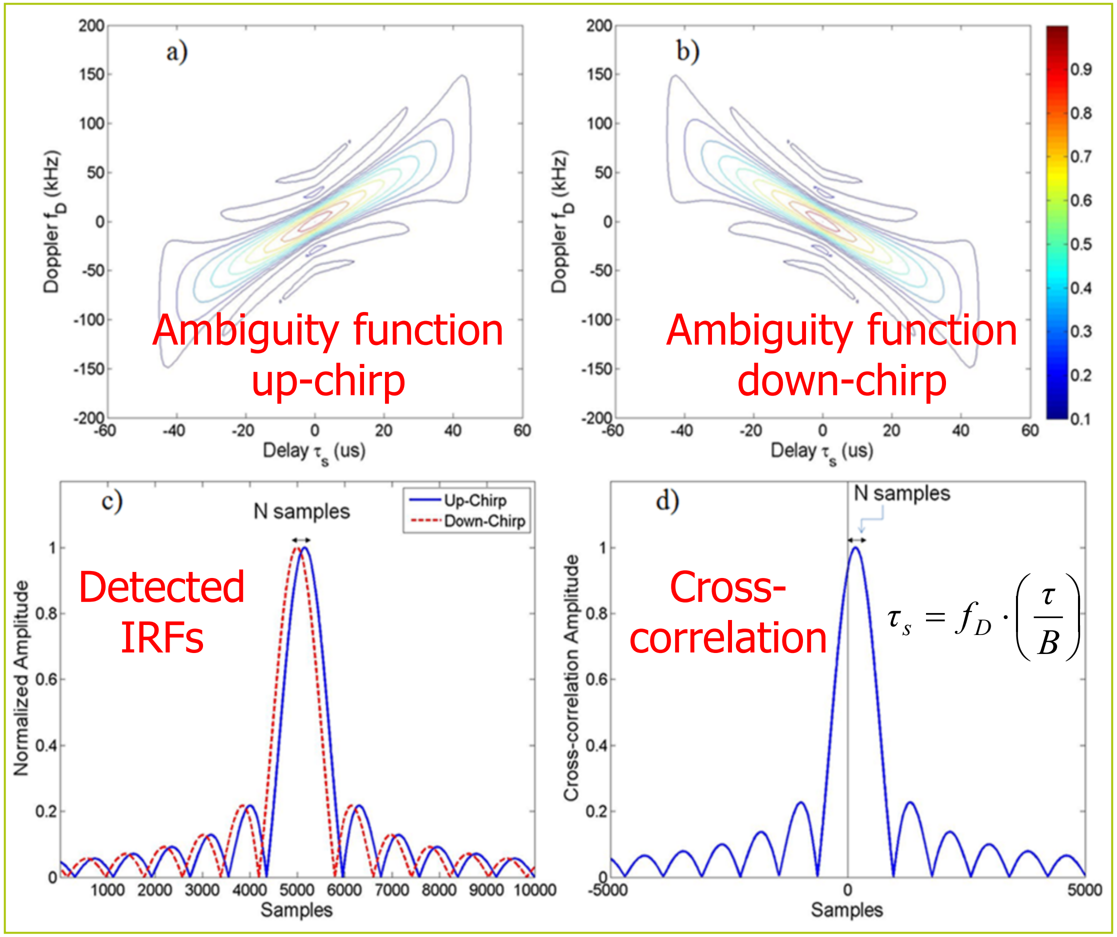

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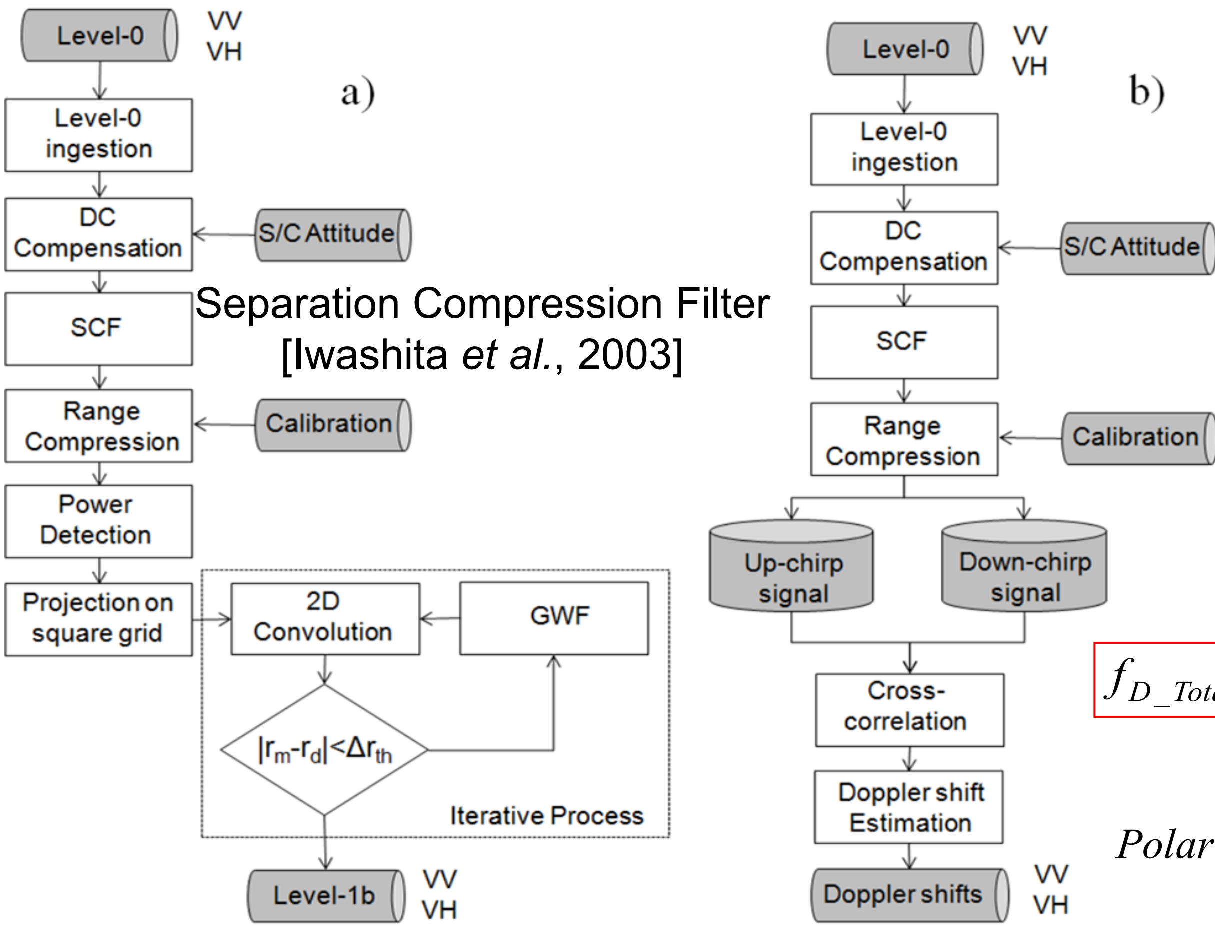
Level-1 Processing (slide from Franco Fois)



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2013 paper by Fabry et al with results from extensive study and simulation

FEASIBILITY STUDY OF SEA SURFACE CURRENTS MEASUREMENTS WITH DOPPLER SCATTEROMETERS

P. Fabry[1], A. Recchia[2], J. de Kloe[3], A. Stoffelen[3], R. Husson[1], F. Collard[1], B. Chapron[4], A. Mouche[1], V. Enjolras[5], J. Johannessen[6], C. C. Lin[7], F. Fois[7]

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ABSTRACT

We present the activity carried out in the framework of the ESA GSP study called "Feasibility Investigation of Global Ocean Surface Current Mapping using ERS, MetOp and QuikScat Wind Scatterometer”

Very short scale dynamical processes are emerging as vital for biogeochemical processes and mixing, and for the transfer of energy between scales. Consequently, observation requirements in terms of spatial resolution will certainly go even beyond the 25 km resolution. For coastal applications, the resolution issue is obviously

Important notes in this paper

Range compression: the received raw data are range-compressed with both the chirps (up and down) and two different range compressed images are obtained.
Relative shift estimation: the principle of the proposed Doppler estimation method is to measure the relative delay between the obtained up and down signals and readily convert this delay into a Doppler shift value. This operation is performed according to the well-known cross correlation technique which is used, for instance, for the coregistration of interferometric SAR images. The two signals obtained with the range compression operation are detected and the cross-correlation is computed via FFT and Inverse FFT. The relative shift is given by the location of the maximum of the cross-correlation function. To increase the accuracy of the estimation process an oversampling in the frequency domain can be performed.

4.4. Dual-chirp concept trade-offs

Two implementations of the dual-chirp system are possible:

1. Transmission of the sum of the two opposite chirps
2. Transmission of two chirps juxtaposed in time

The first solution is optimal from an ocean scene correlation point of view on both compressed signals but foresees the transmission of a non-constant amplitude pulse which may be an issue from technological point of view.

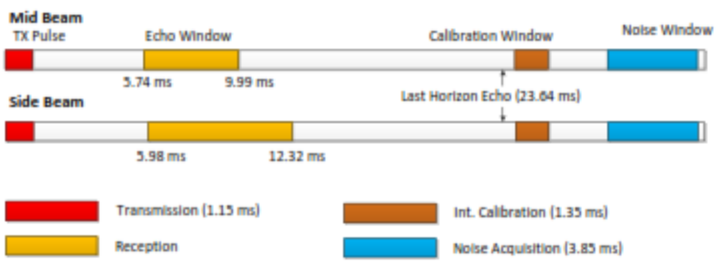
The second solution is optimal from a transmission point of view but the very quick de-correlation time of sea surface shall be considered during system design. Indeed the main issue related to the second approach would be that the two chirps would see two slightly different ground scenes, reducing the performances of the cross-correlation technique. This would not be a problem at all for scenes with coherence times much higher than the pulse length (e.g. land scenes), but for ocean scenes the impacts on the Doppler estimation accuracy should be assessed. A possible solution would

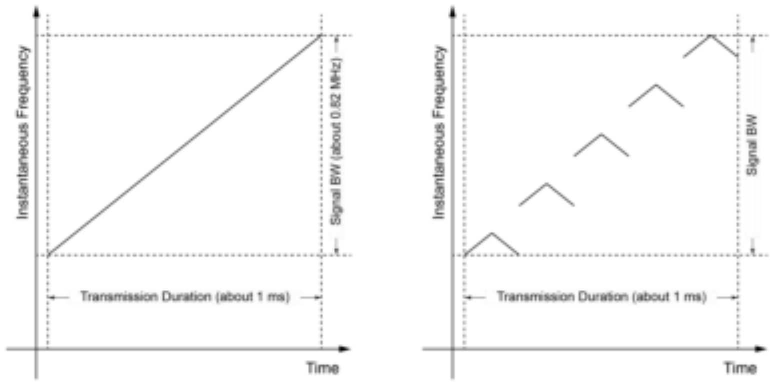
Ocean Current Measurement Principle (Compatible with the SCA instrument)

Measurement Principle:

- compare phases of two adjacent short pulses to estimate velocity
- the two pulses must cover the same frequency band
- discrimination between the two pulses of a pair by modulation parameters (e.g. up/down chirp)
- decoupling from other simultaneously received pulse pairs by using different frequency bands

The disadvantage of the proposed waveform is the non simultaneous measurement of the up and down chirps, which is really necessary.
It will be explained and demonstrated later on in this presentation.





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- We want to measure 0,1 – 1 m/s ocean current; 1 m/s is 35 Hz in Doppler
- 1 ms measurement time is 1 kHz in Doppler resolution
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Random Error inherent to the Measurement

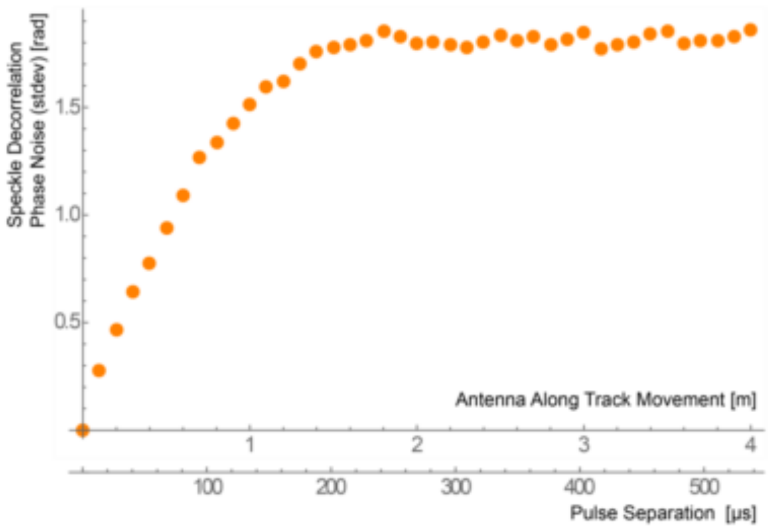
Speckle noise

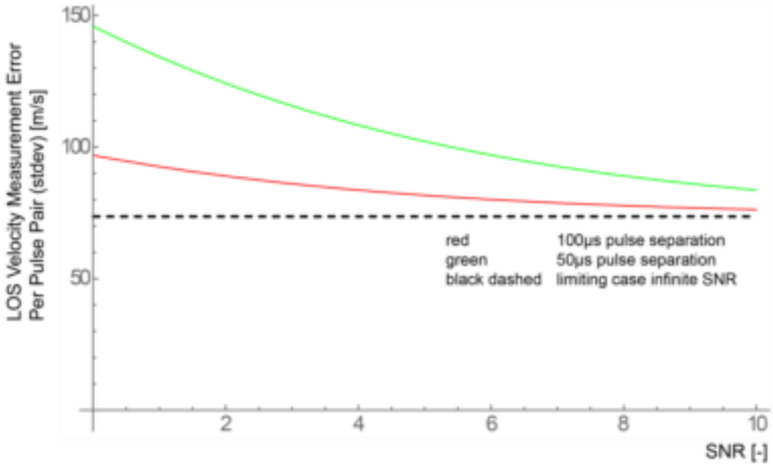
- Motion of the satellite causes de-correlation of the detected echo signals
- Separation between the pulses only indirectly affects velocity measurement noise (via SNR) for small separations
- There is there is a limitation for useful pulse separation given by complete de-correlation of the two detected signals
- The de-correlation is determined by antenna length and look angle

==> Independent from SNR and temporal variability of the sea surface the achievable measurement accuracy per pulse pair is limited.

Impact on RADAR parameters

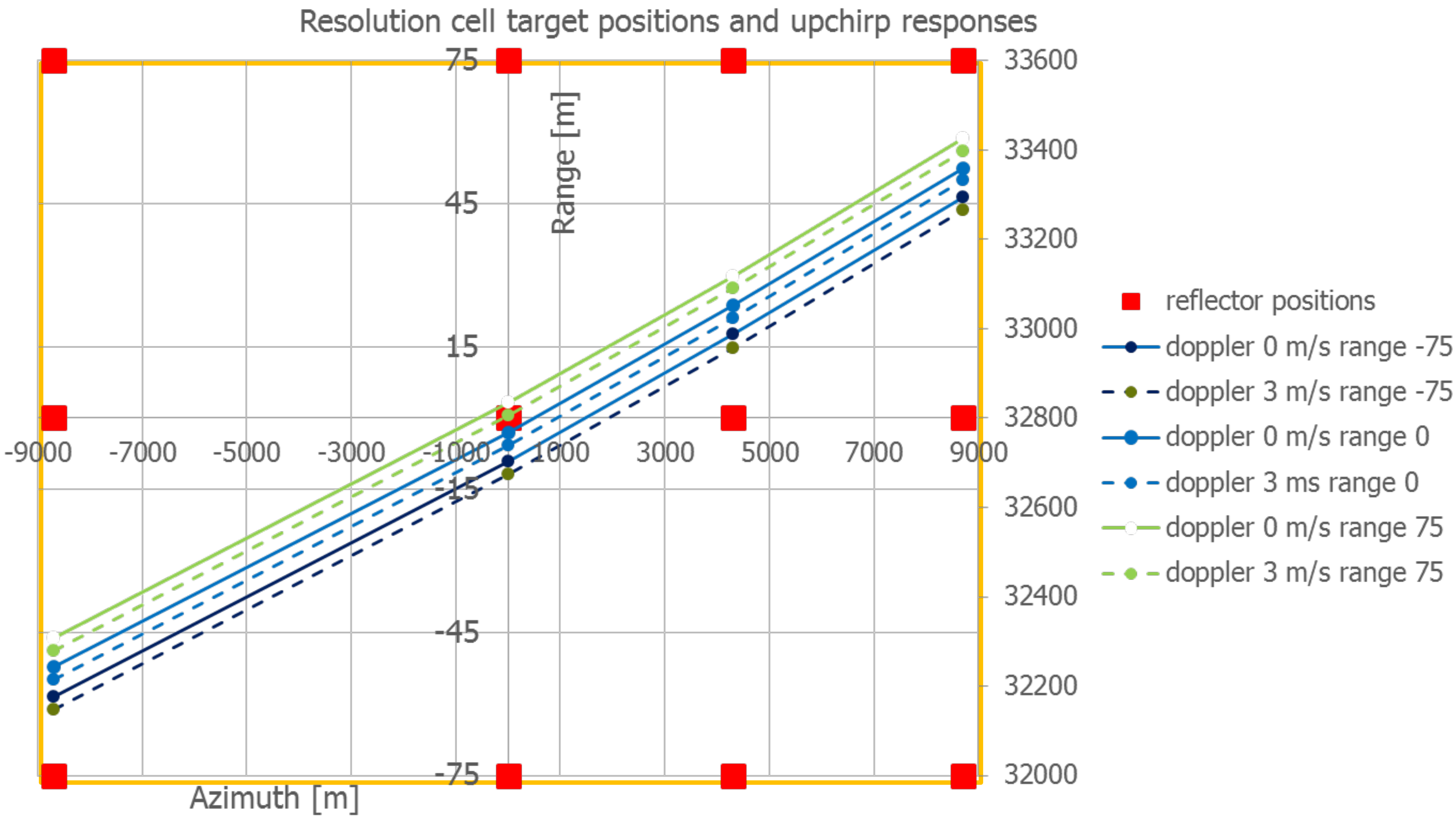
- It is required to maximise the number of looks at acceptable SNR
- The nominal SCA modulation (LFM) is well suited
  - processing of small slices of the echo pule is possible without loosing looks and affecting SNR (multi-look processing)
  - an approximate orthogonal waveform can be generated by inverting the slope
- The nominal chirp slope (defining overall bandwidth) is already driven by a goal to maximise the number of looks





AIRBUS DEFENCE & SPACE

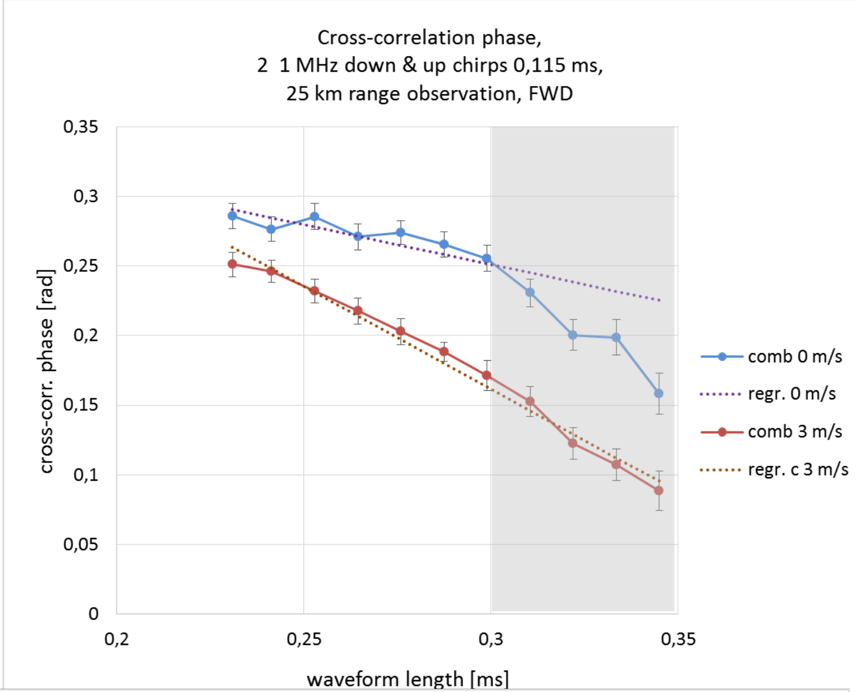
Range Doppler ambiguity within resolution cells

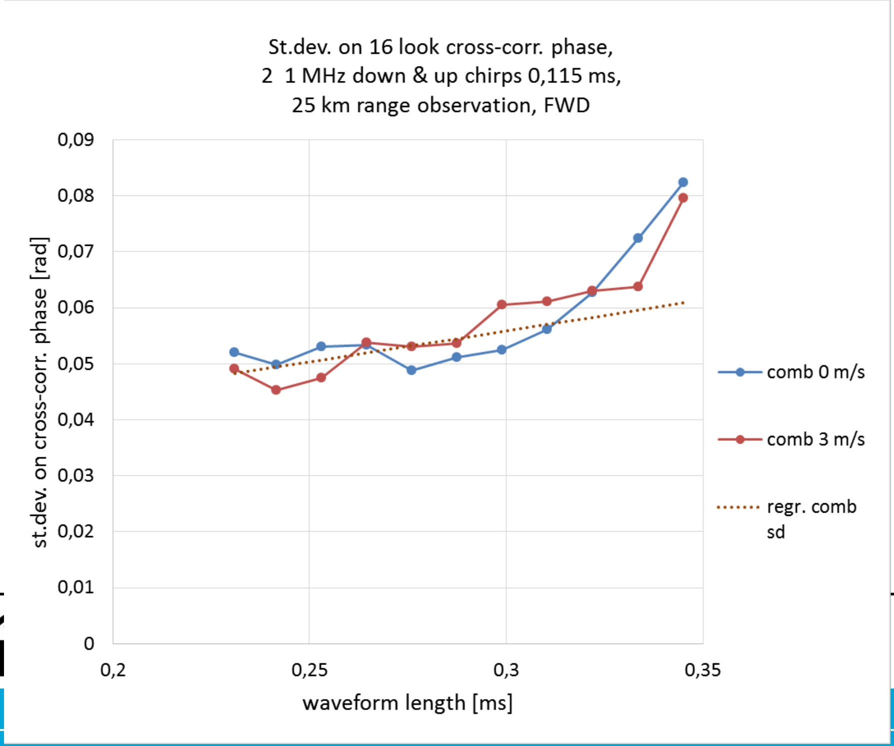


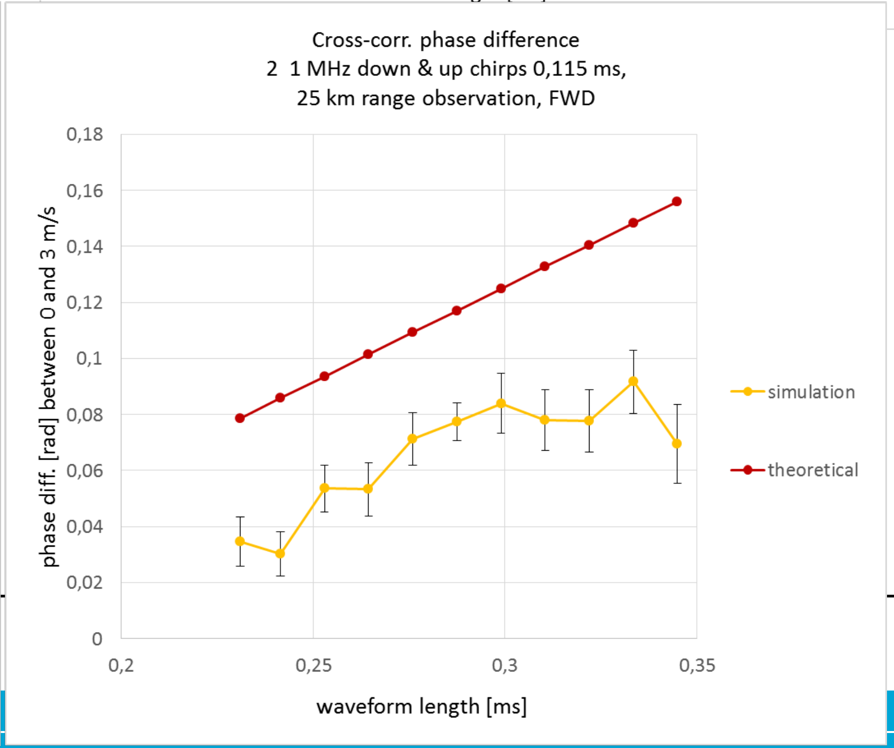
Approaches in the basic simulations with up and down chirps

- The proposed method of Franco Fois with cross-correlation to find the ocean current peak is simulated.
- Instrument parameters are taken from SCA, unless otherwise indicated.
- The platform (antenna) speed is 6800 m/s.
- An ocean surface of 17 km wide (azimuth) and 6 km long (range) is considered. It is represented by 600 randomly positioned scatterers of equal strength. The ocean current moves all scatterers in the same way. The analysis is limited to range cells within this area, so range-doppler ambiguities are well represented.
- In the simulation the transmit chirps can be generated and timed fully independent of each other. On reception the responses of the up and down chirps are kept separated (for simplicity the Separation Compression Filter as described and tested by Franco Fois has not been taken into account).
- Noise (SNR) has not been taken into account.
- In the simulations 256 independent realisations of the seasurface and of the received signals are generated. They are processed as 16 runs of 16 looks. So in a run, 16 independent measurements are averaged. The 16 runs are used to produce an average result and a standard deviation.
- In the graphs the pulselength, the time until the start of the second chirp and the bandwidth of the transmitted chirps are varied.

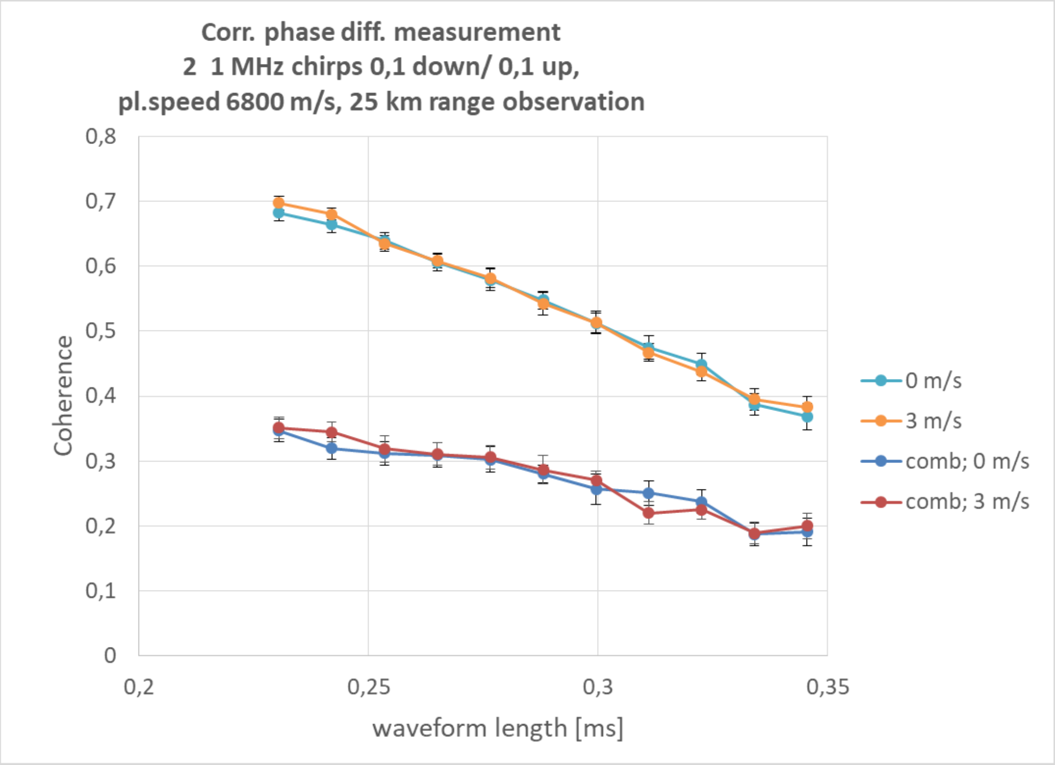
2 pulse-pair Up/Down chirps 0.115 ms







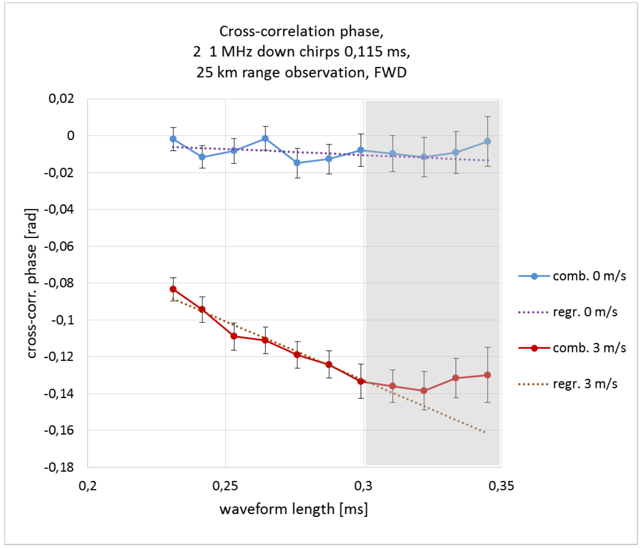
Coherence for up/down chirp

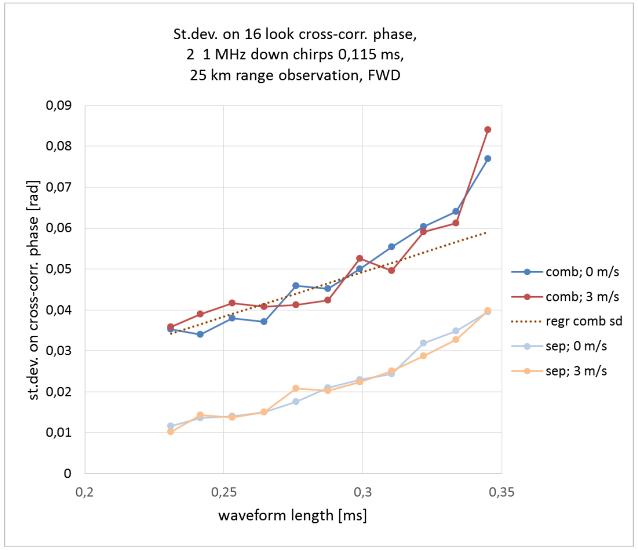


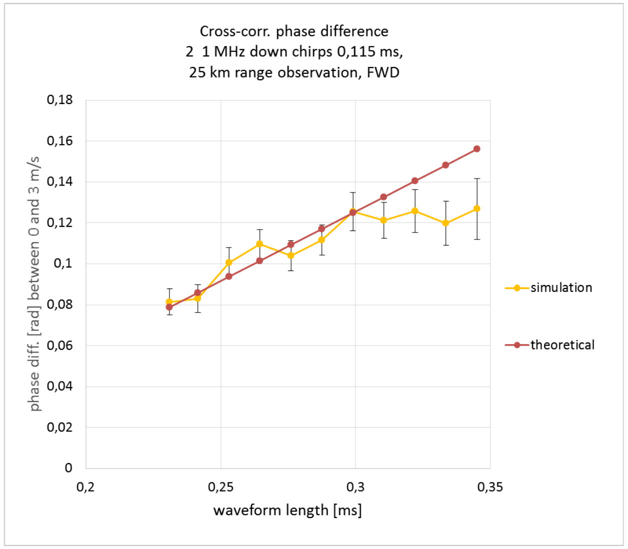
Measurement accuracy for up/down chirps

measurement time	pulse responses separate (theoretical)	pulse responses combined	include regression line phase	
In ms	Precision in m/s for 25 km WVC	Precision in m/s for 25 km WVC	Precision in m/s for 25 km WVC	Precision in m/s for 50 km WVC
0,231	1,67	4,25	3,74	1,87
0,2415	1,43	4,51	3,55	1,77
0,253	1,04	2,66	3,09	1,55
0,2645	0,92	3,02	3,00	1,50
0,276	0,75	2,24	2,57	1,28
0,2875	0,83	2,08	2,30	1,15
0,299	0,88	2,16	2,26	1,13
0,3105	0,91	2,35	1,98	0,99
0,322	1,00	2,43	1,63	0,81
0,3335	1,03	2,09	1,53	0,77
0,345	1,08	3,43	1,75	0,87

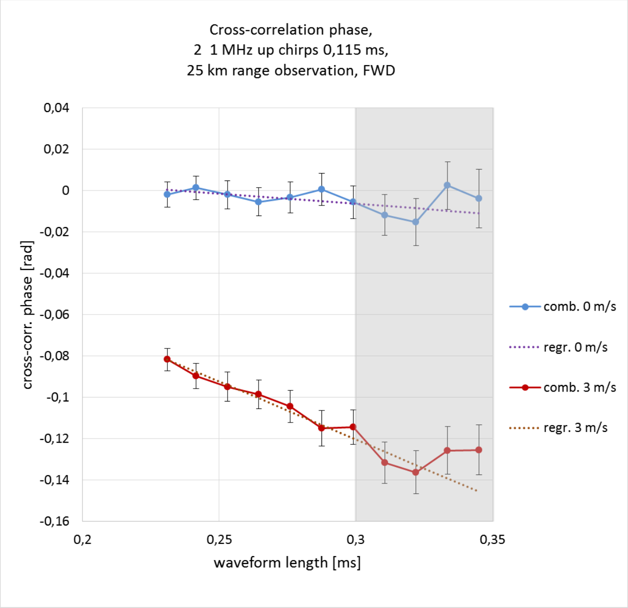
2 pulse pair down chirps 0.115 ms

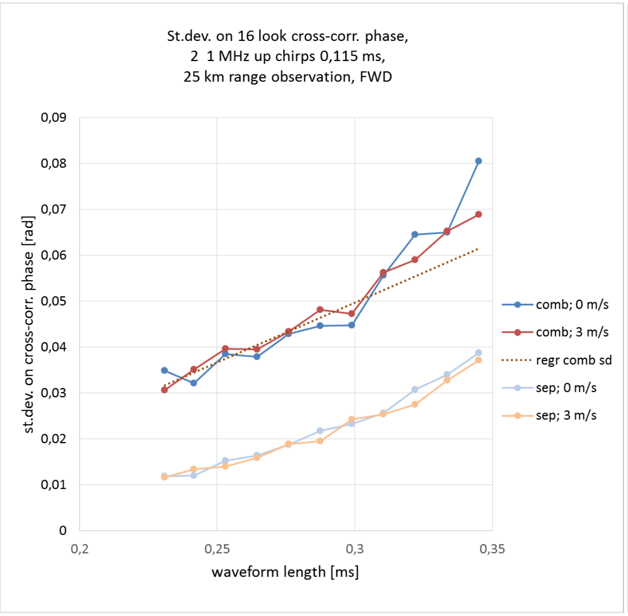


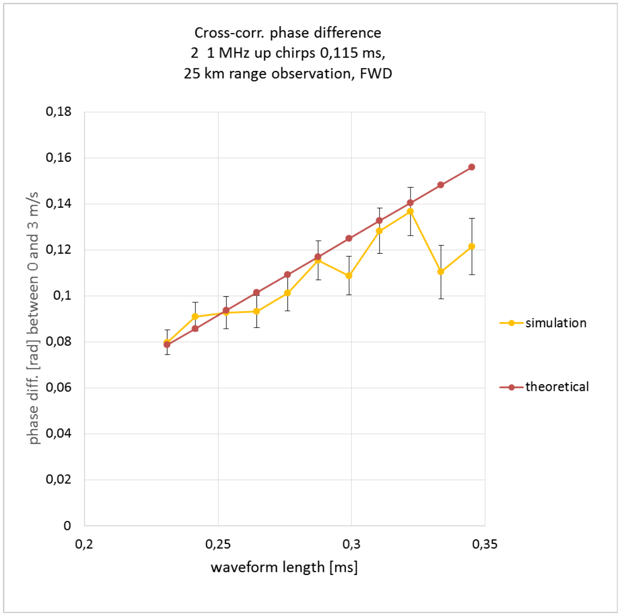




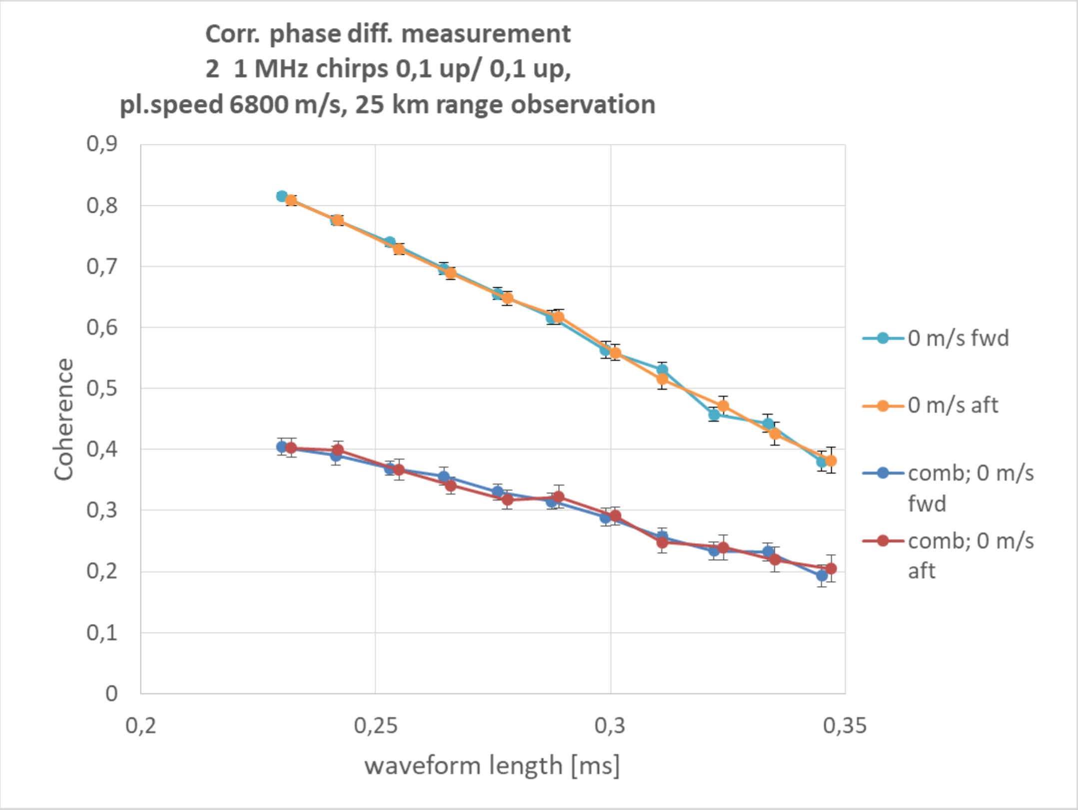
2 pulse pair up chirps 0.115 ms







Coherence for up chirps, FWD and AFT beam



Accuracy for up- and down chirps, 0.115 ms, FWD and AFT beam

measurement time	Precision in m/s for 25 km WVC			
In ms	Up chirp FWD beam	Up chirp AFT beam	Down chirp FWD beam	Down chirp AFT beam
0,231	1,12	1,13	1,39	1,20
0,2415	1,18	1,34	1,33	1,17
0,253	1,28	1,20	1,23	1,14
0,2645	1,24	1,21	1,19	1,23
0,276	1,30	1,14	1,12	1,36
0,2875	1,32	1,20	1,11	1,22
0,299	1,31	1,30	1,28	1,38
0,3105	1,36	1,52	1,19	1,41
0,322	1,39	1,60	1,40	1,50
0,3335	1,69	1,66	1,54	1,64
0,345	1,81	1,80	2,17	2,02

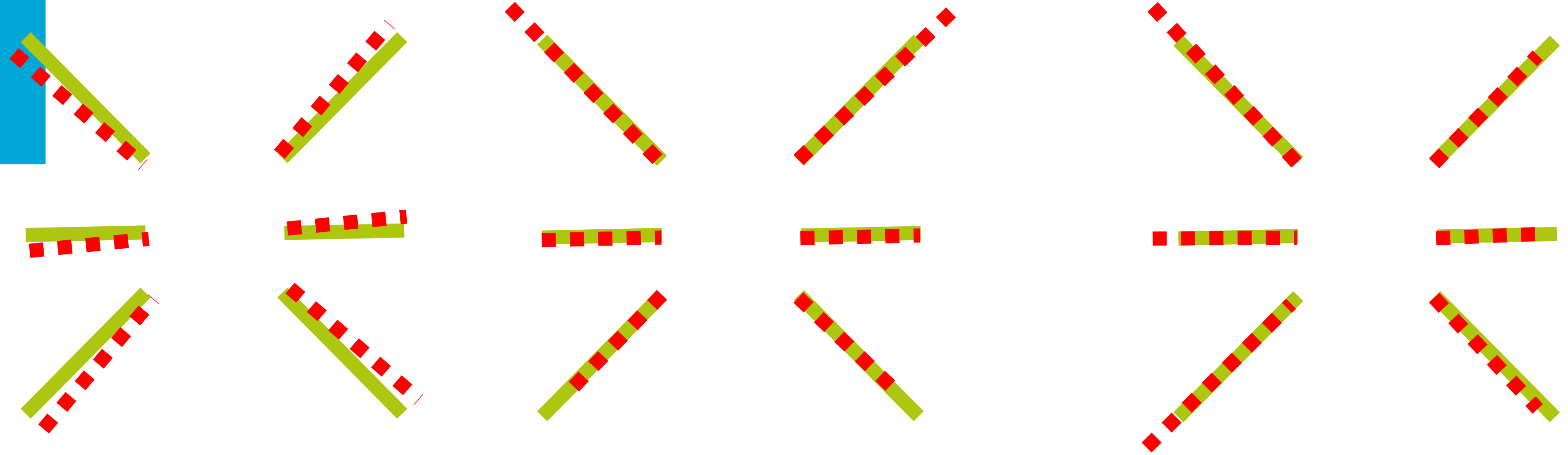
Accuracy for up chirps, FWD beam, 0.134 and 0.161 pulse length

measurement time	Precision in m/s for 25 km WVC		
In ms	0,115 ms pulse length	0,134 ms pulse length	0,161 ms pulse length
0,231	1,12		
0,2415	1,18		
0,253	1,28		
0,2645	1,24		
0,276	1,30	1,26	
0,2875	1,32	1,24	
0,299	1,31	1,27	
0,3105	1,36	1,07	
0,322	1,39	1,20	1,12
0,3335	1,69	1,40	1,13
0,345	1,81	1,44	1,15
0,3565			1,23
0,368			1,67

Optimize energy of SCA transmitter

- Waveform
- Pulse length

Attitude Control?



Yaw = Doppler
- No cone effect

Pitch = Cone
F/A asymmetry
- Also Doppler

Roll = Cone
Left/right asymmetry
- Also Doppler

- SCA wind
- C-DOP -> Doppler expectation

- Attitude corrections are low orbit phase harmonics
- Can use 40*2.000 WVCs per orbit
- Can we estimate 0.2 mrad or 0.01 degrees ? Test with ASCAT!