European Space Agency

WP 3000
Doppler Stack Processing

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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RATIONALE

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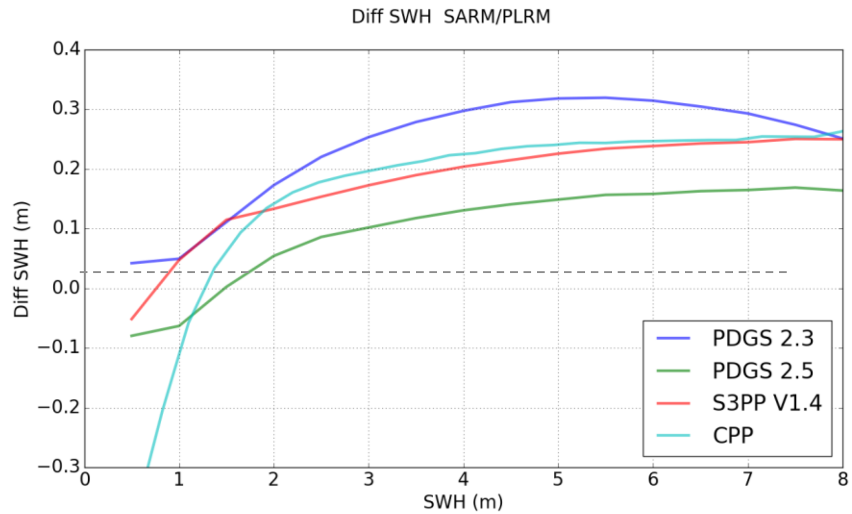
    - **By correcting SWH bias between LRM and SARM but more importantly their dependency with wave height**



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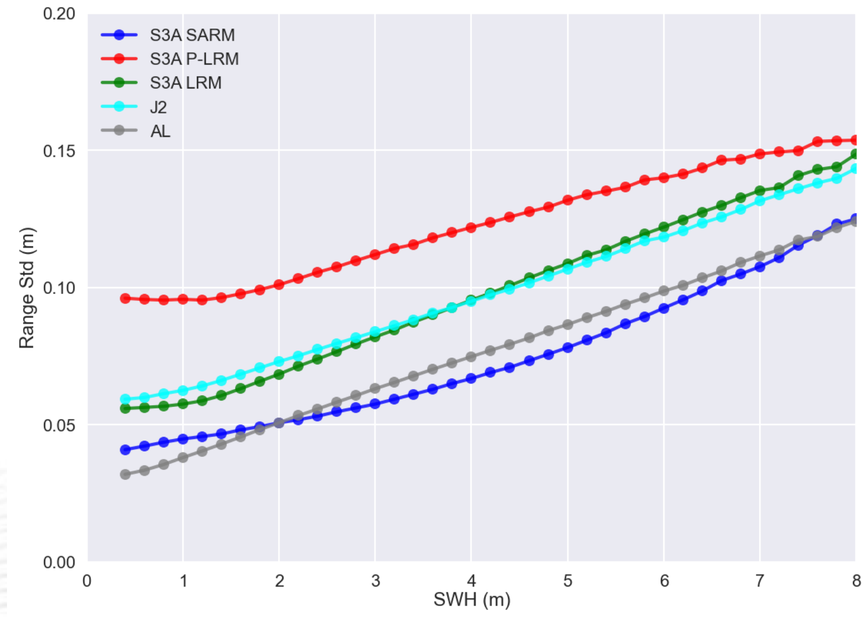
  - The noise reduction performance
    - **Noise level lowered by 40% wrt LRM**
    - **But noise reduction is not as high as expected (lower than $\sqrt{N}$)**



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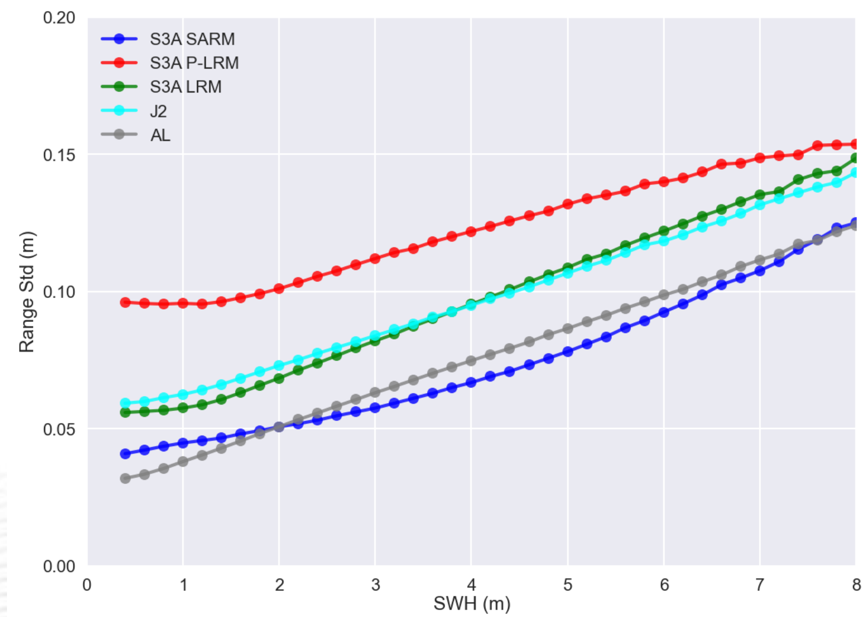
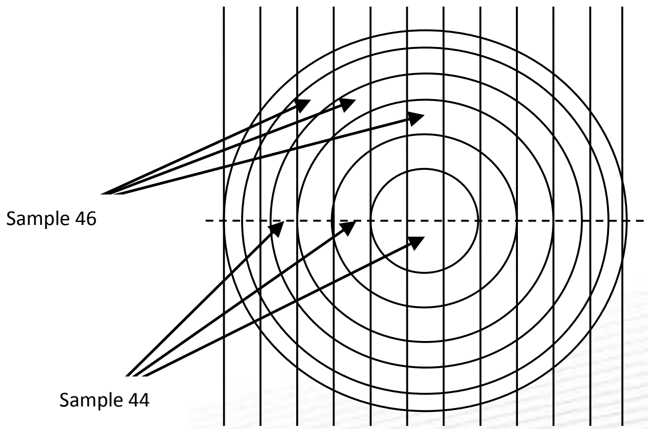
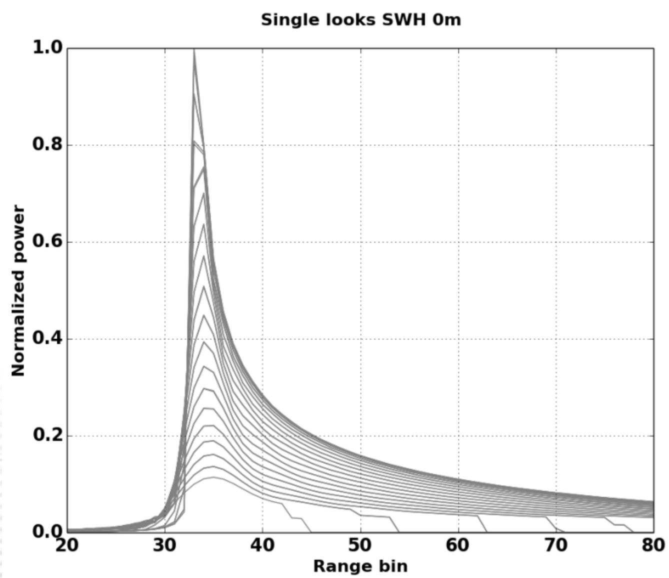


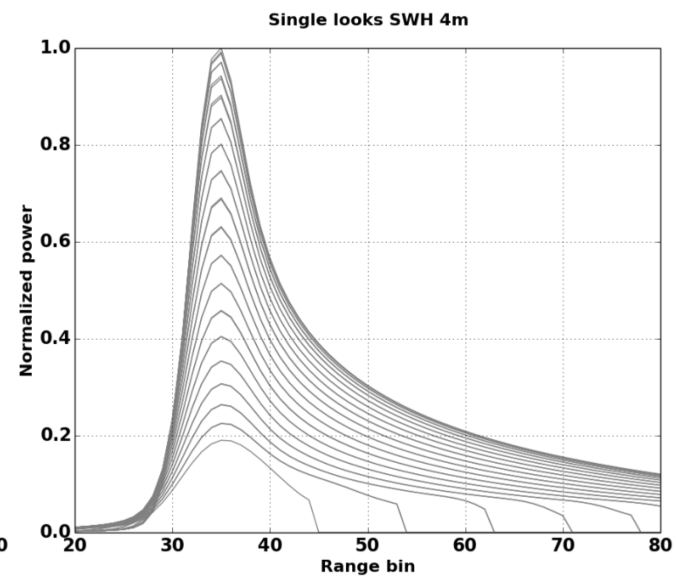
- **New processing algorithms are currently being developed to utilize the information in SAR-mode signal to its highest potential (improving noise reduction performance, resolution, ..)**

SARM NOISE ISSUE

- **Reduction of the noise level not as high as expected (and lower than √*N*) *[Amarouche, meeting SAR, NOC, 2013]***
  - High inhomogeneity between Doppler beams (stack)
    - Different amplitude values from look to look due to antenna gain
    - Different mean shapes in range due to inaccurate migration corrections







SARM NOISE ISSUE

- **Equivalent (or effective) Number of Looks (ENL)**
  - Indicates the degree of averaging in the multilook echo
  - Good indicator of the speckle noise level

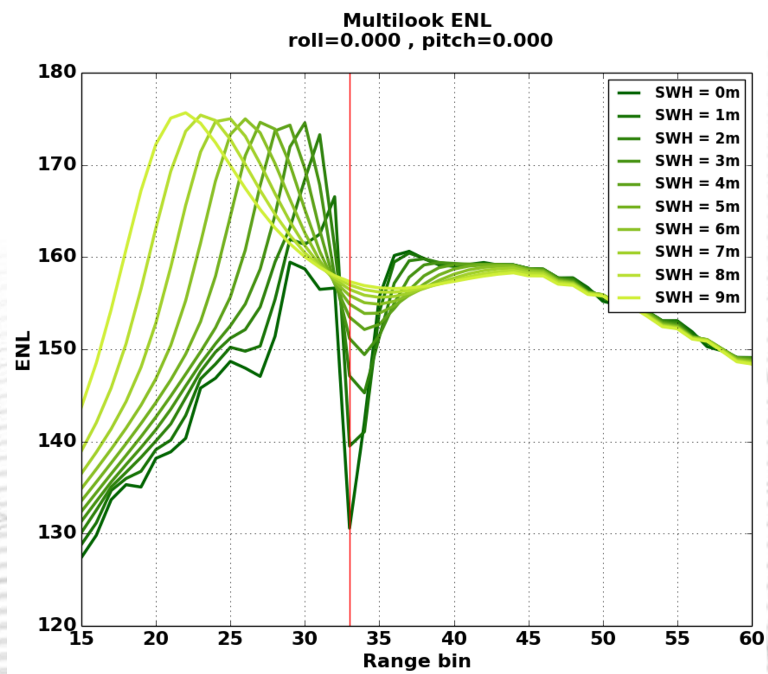
$$ENL = \left(\frac{a}{\sqrt{v}}\right)^2 = \frac{N}{1 + \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\alpha_i}{a}\right)^2} = kN$$

Number of looks

mean power variations within stacked beams

  - High speckle reduction for samples whose look-to-look discrepancies are low
  - Low speckle reduction for large variation of echo amplitude
  - Lowest values in the leading edge for low swh

  ➔ increased noise level while retracking Doppler echoes at low wave height



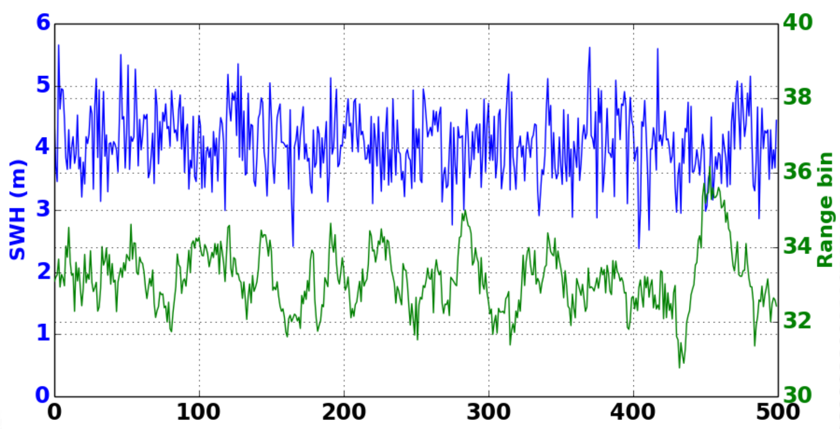
ENL for multilook echoes is lower than *N* and varies in range bins

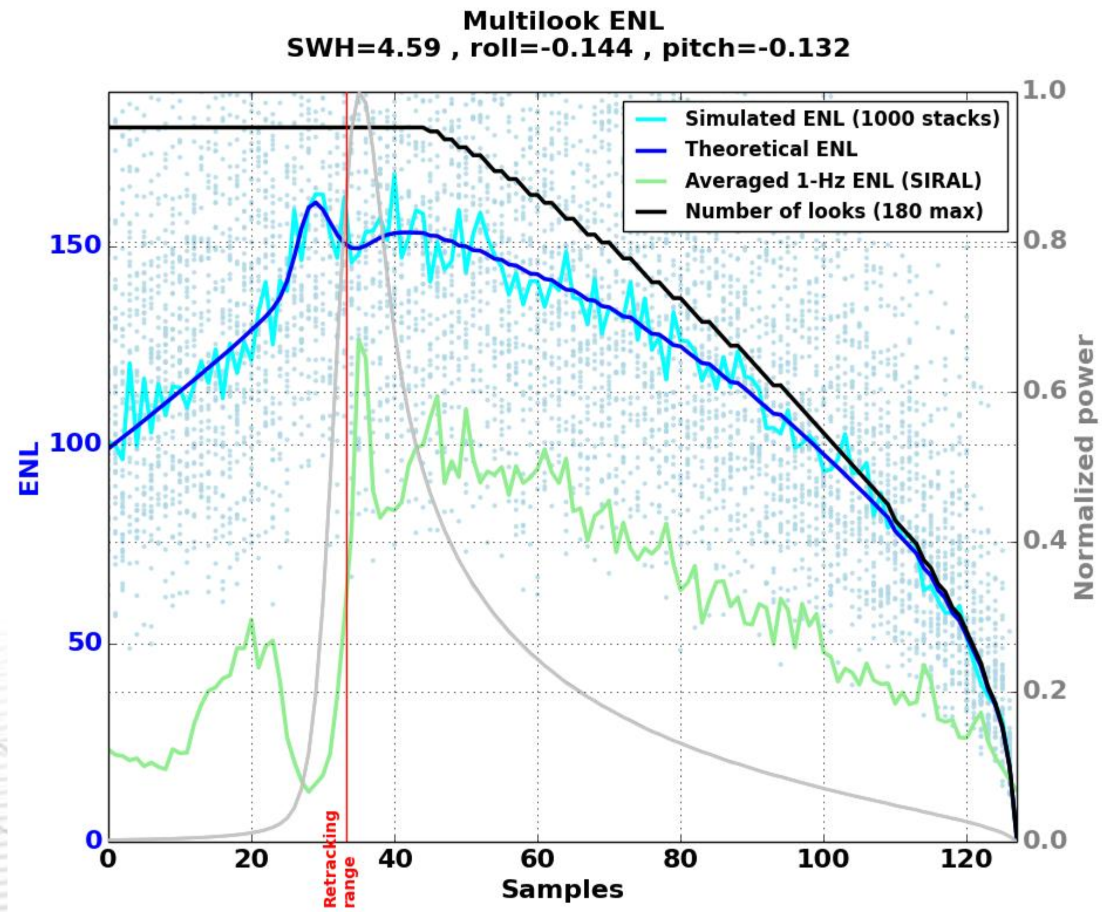
SARM NOISE ISSUE

- **ENL** computed with **real data** (over 500 consecutive 20-Hz data) is **even lower**

  mostly due to the difficulty to gather data of homogeneous sea state and similar orbit parameters

<u>In the Agulhas SAR-mode area</u>



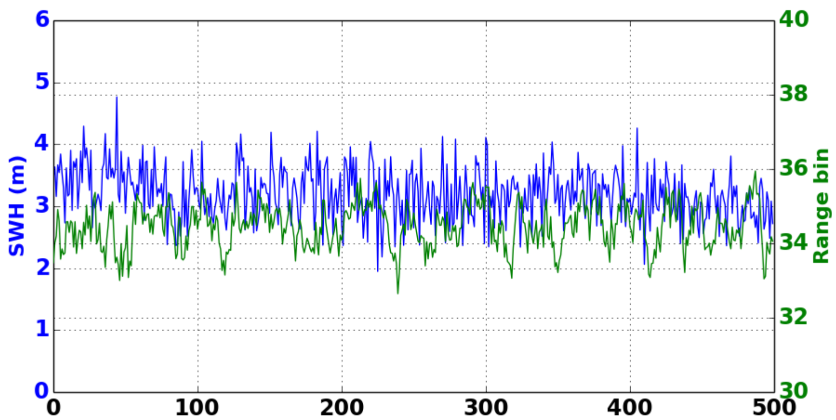


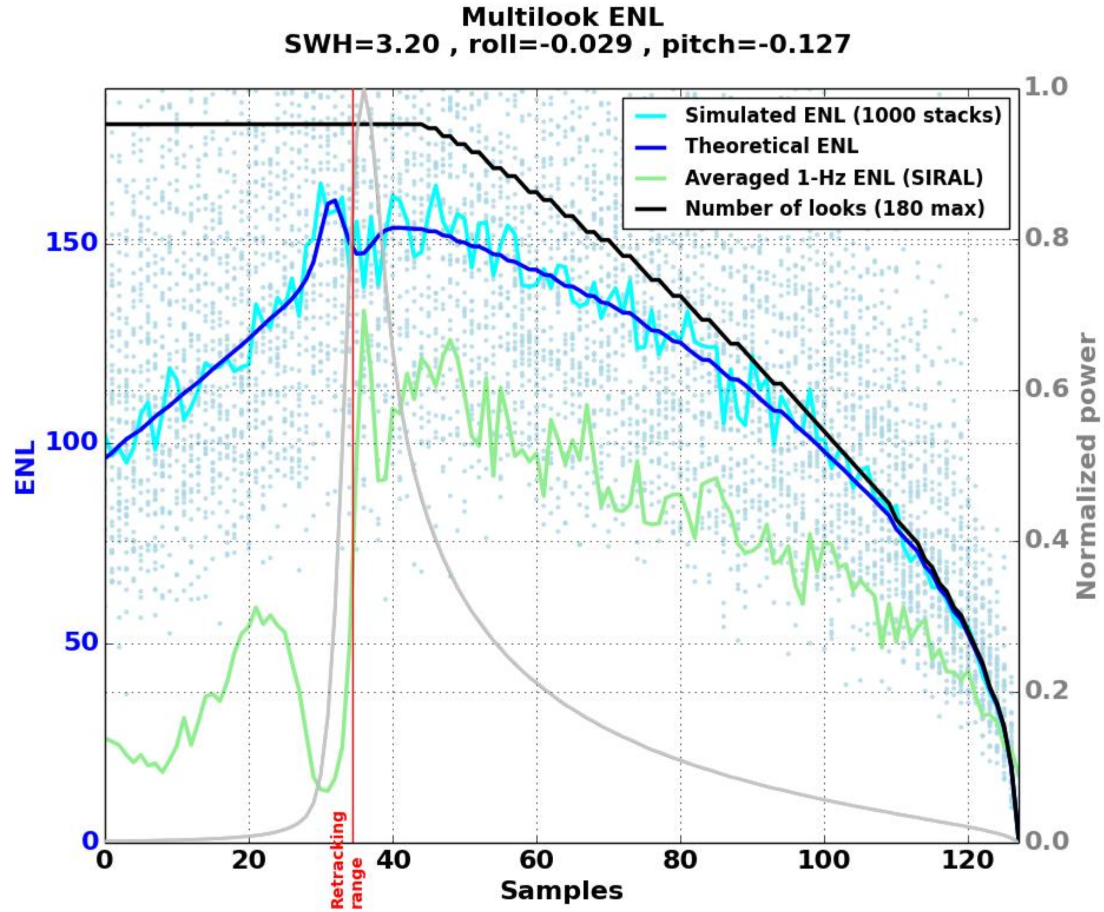
SARM NOISE ISSUE

In the Pacific SAR-mode area

- **ENL** computed with **real data** (over 500 consecutive 20-Hz data) is **even lower**

  A better homogeneity in sea state and orbit parameters improve the computed ENL





SARM NOISE ISSUE

- New L1b processing methodologies are currently being developed
  - new stacking methodology [Ray et al., 2014],
  - antenna pattern compensation [Scagliola et al., 2014; Dinardo et al., 2015], stack beam weighting)

  aiming at giving equal weight to all waveforms in the stack

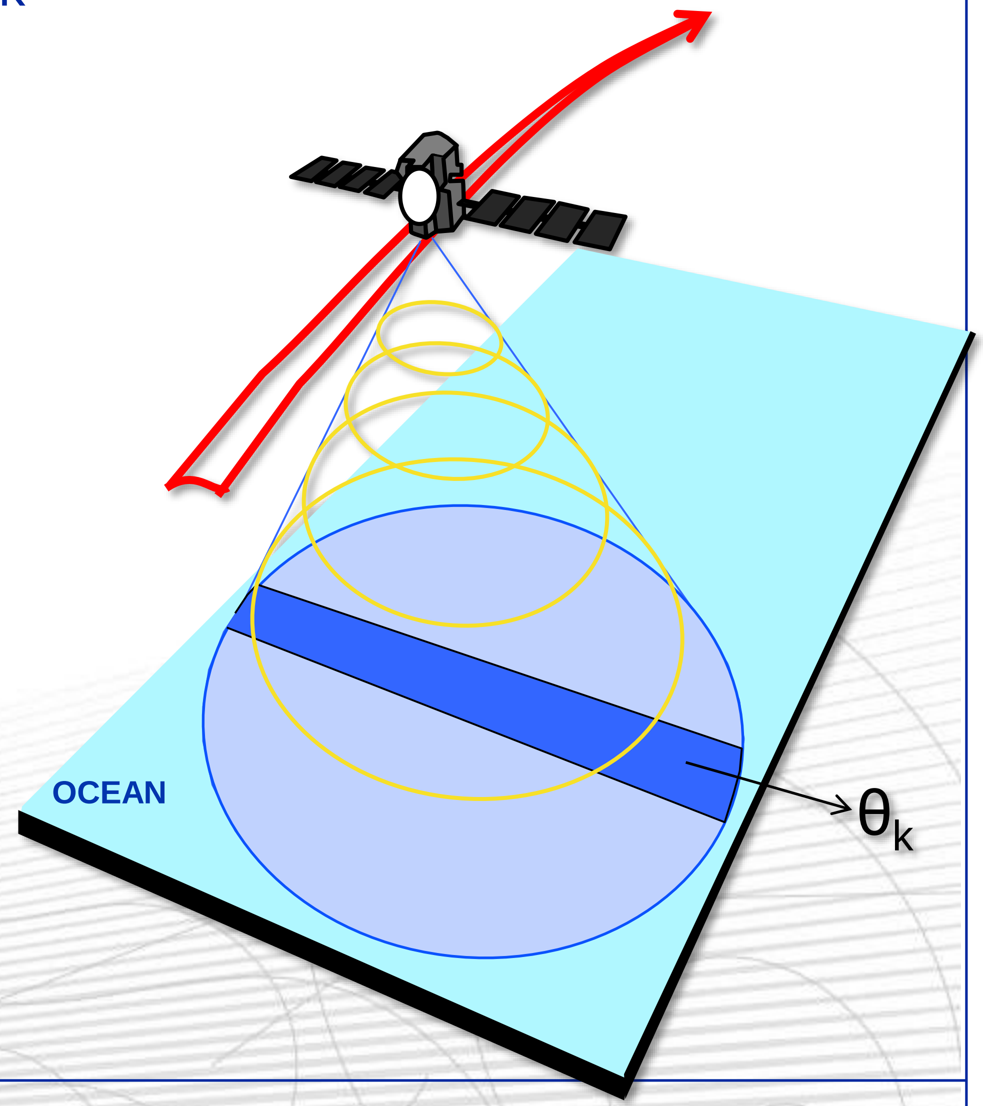
- We propose a new solution: **individual Doppler beams retracker** to optimise the speckle reduction with no beams weighting

- **This alternative SAR processing has been under study**

INDIVIDUAL DOPPLER BEAMS RETRACKER

Moreau et al., OSTST, 2015

- To process each individual look of a stack



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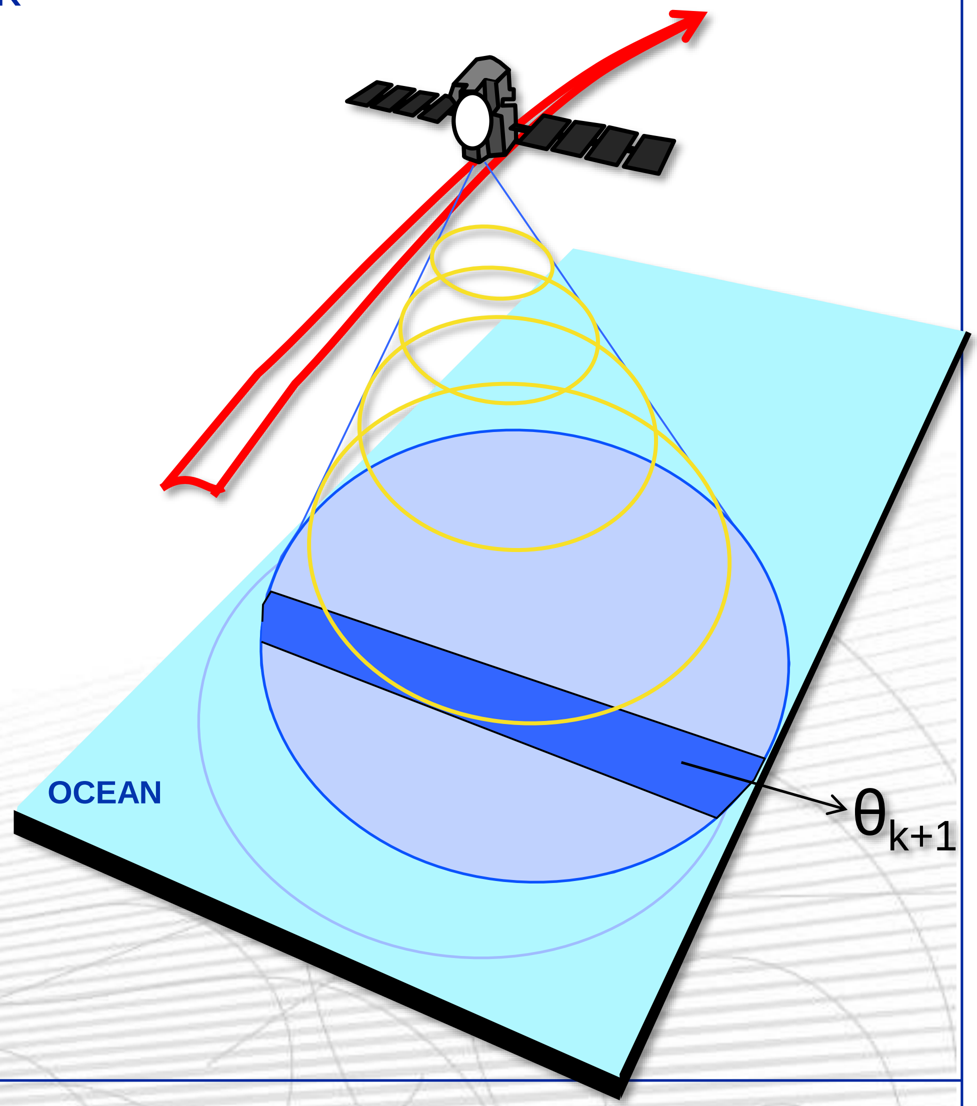

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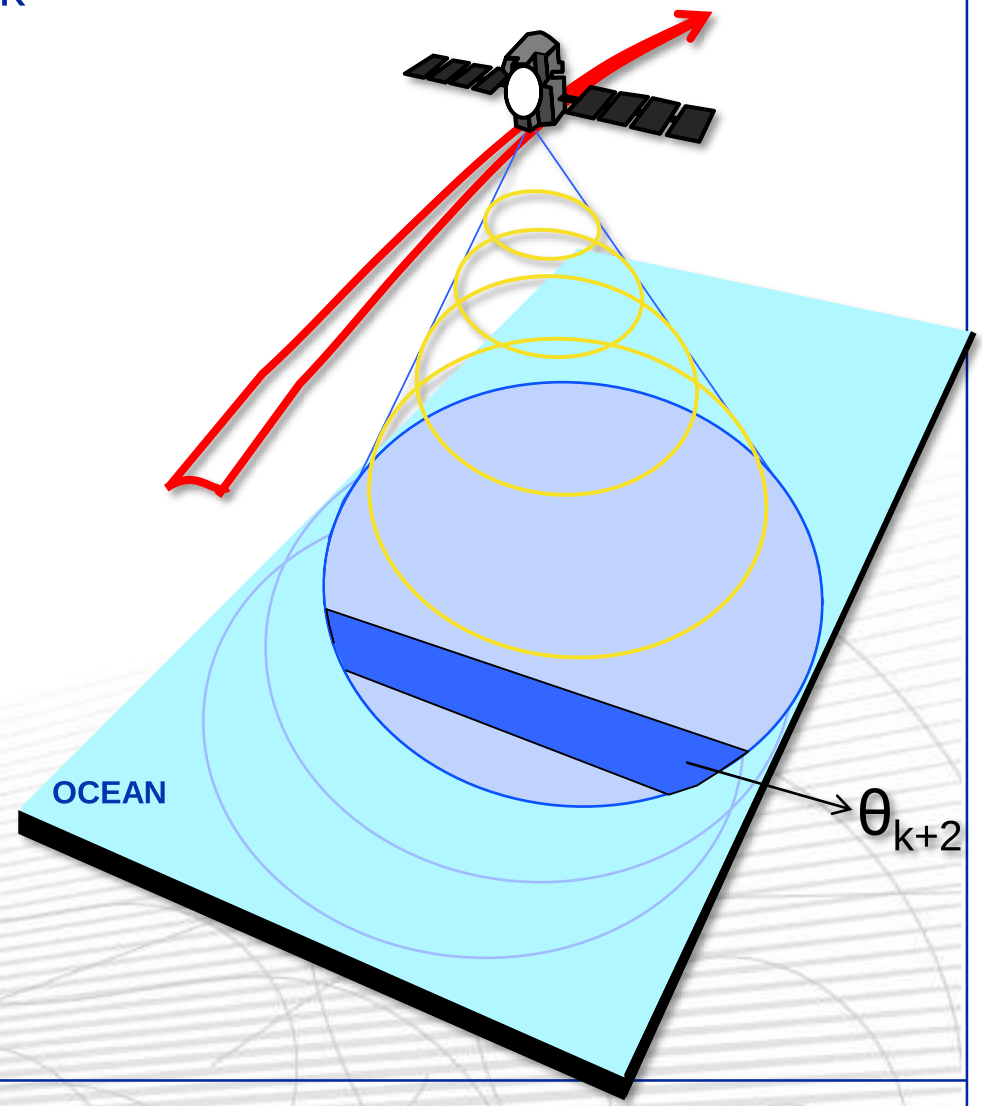

INDIVIDUAL DOPPLER BEAMS RETRACKER

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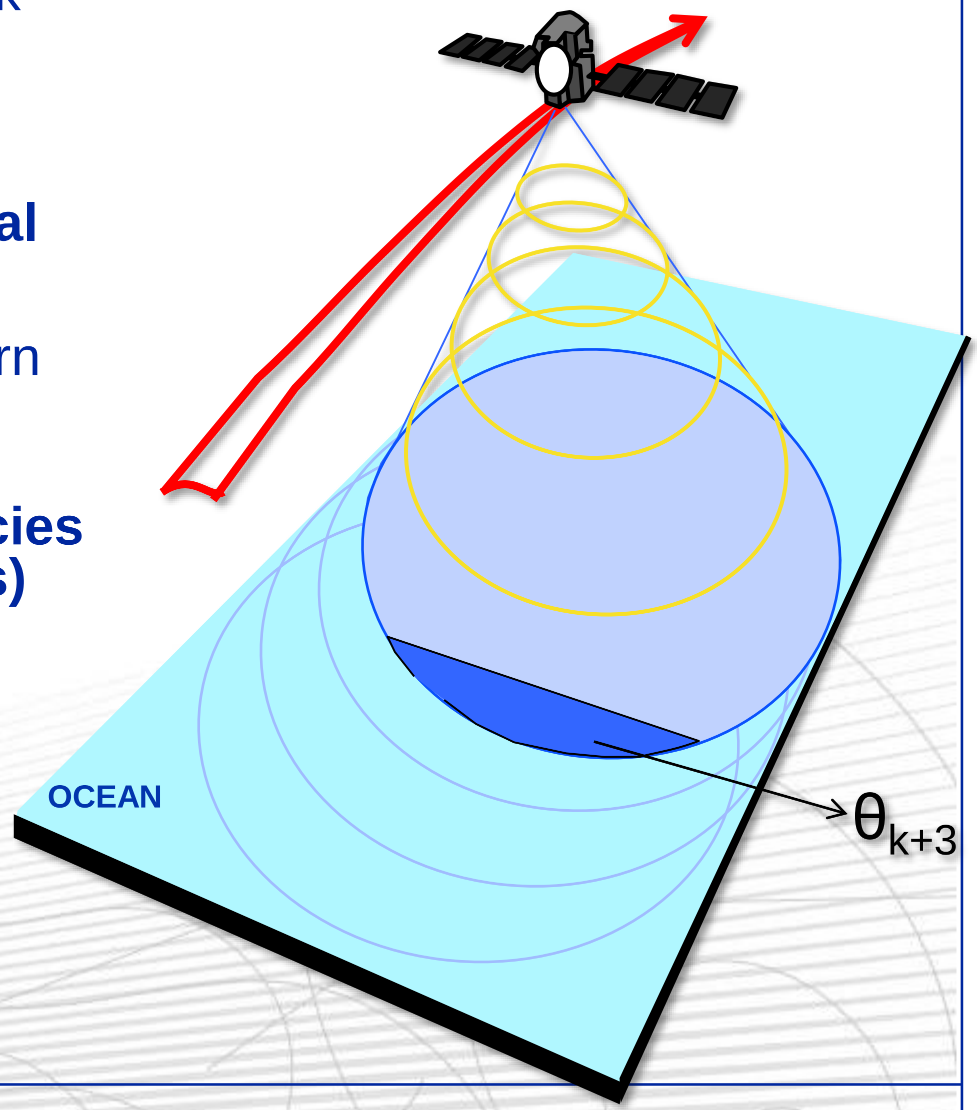
- To process each individual look of a stack
- Then "average" their estimates θ_k

  $\theta = 1/L\ \Sigma(..\ +\theta_k+\theta_{k+1}+\theta_{k+2}+\theta_{k+3}+..)$

  ➔ Making all Doppler beams with equal contribution to the noise reduction

- No beams weighting (e.g., antenna pattern compensation, stack beam weighting)

  ➔ Enabling to assess the model consistency (checking any discrepancies between nadir/off-nadir look estimates)



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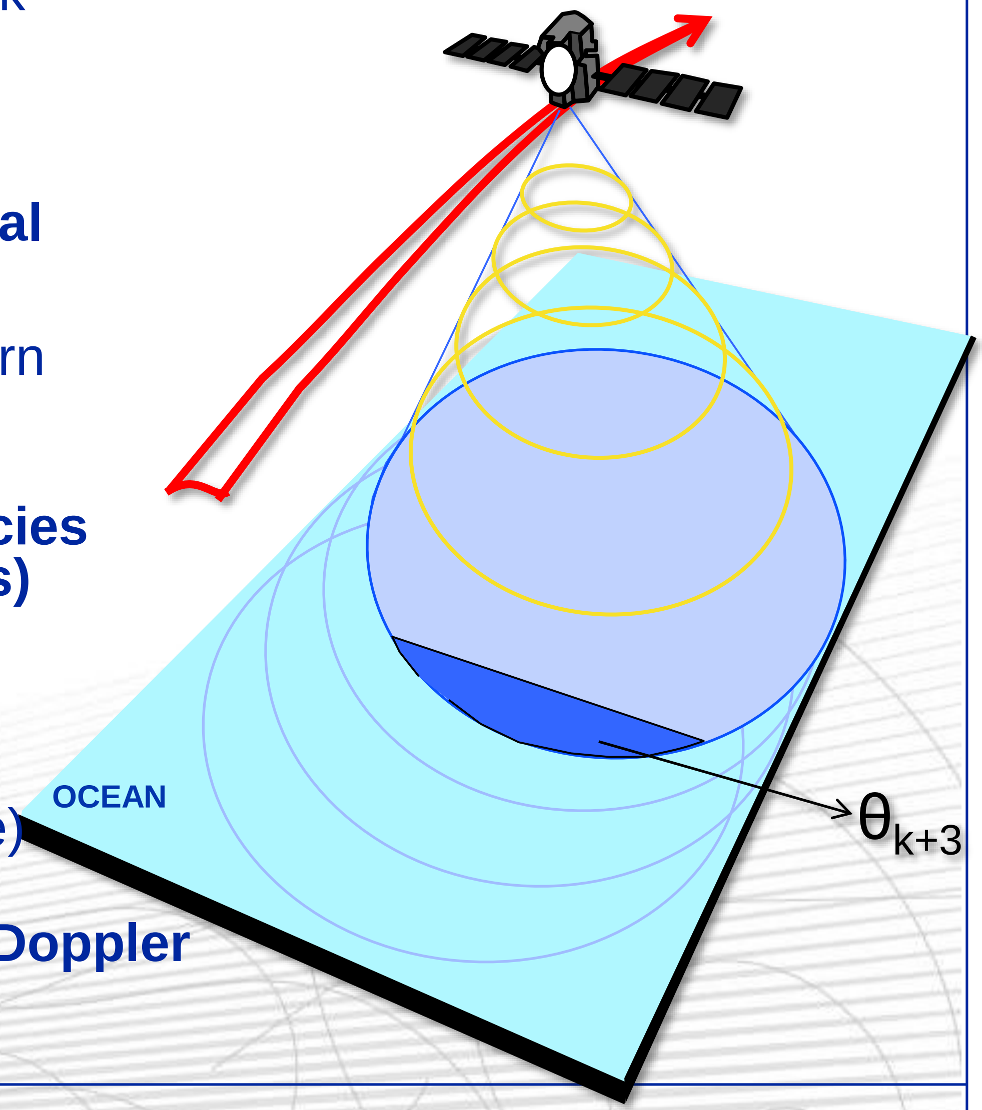
- Beams alignment before multilooking can be disrupted by inaccurate COR2 command (computed on-board) or large variability in surface relief (near shoreline)

  ➔ No compensation for tracker range alignment (slant range migration and Doppler shift correction applied to estimates afterwards) mitigating possible errors



INDIVIDUAL DOPPLER BEAMS RETRACKER

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- No valuable data for tracks perpendicular to the coast line at distance < 2-3km despite its high along-track resolution

  ➔ To edit inconsistent looks still contaminated by land / calm sea (or disrupted by possible on-board tracking error)

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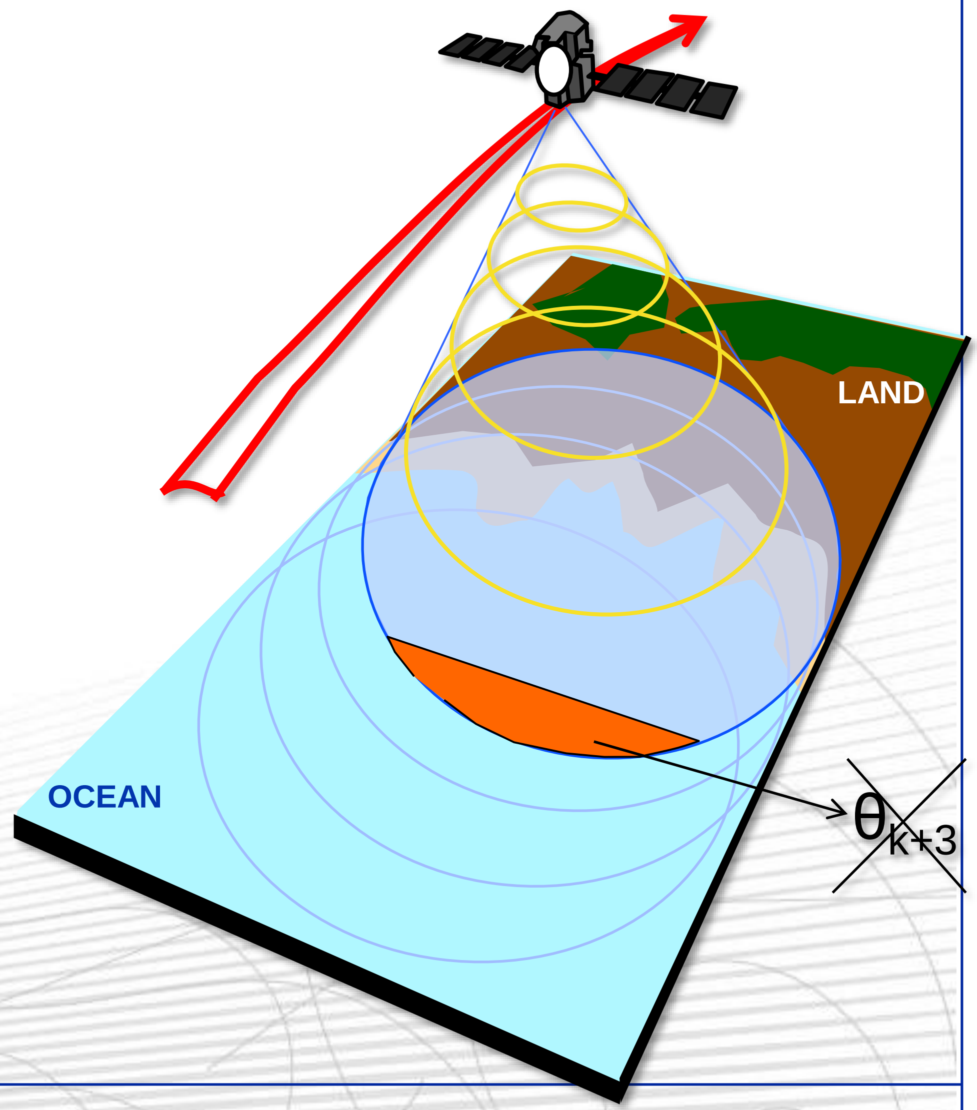

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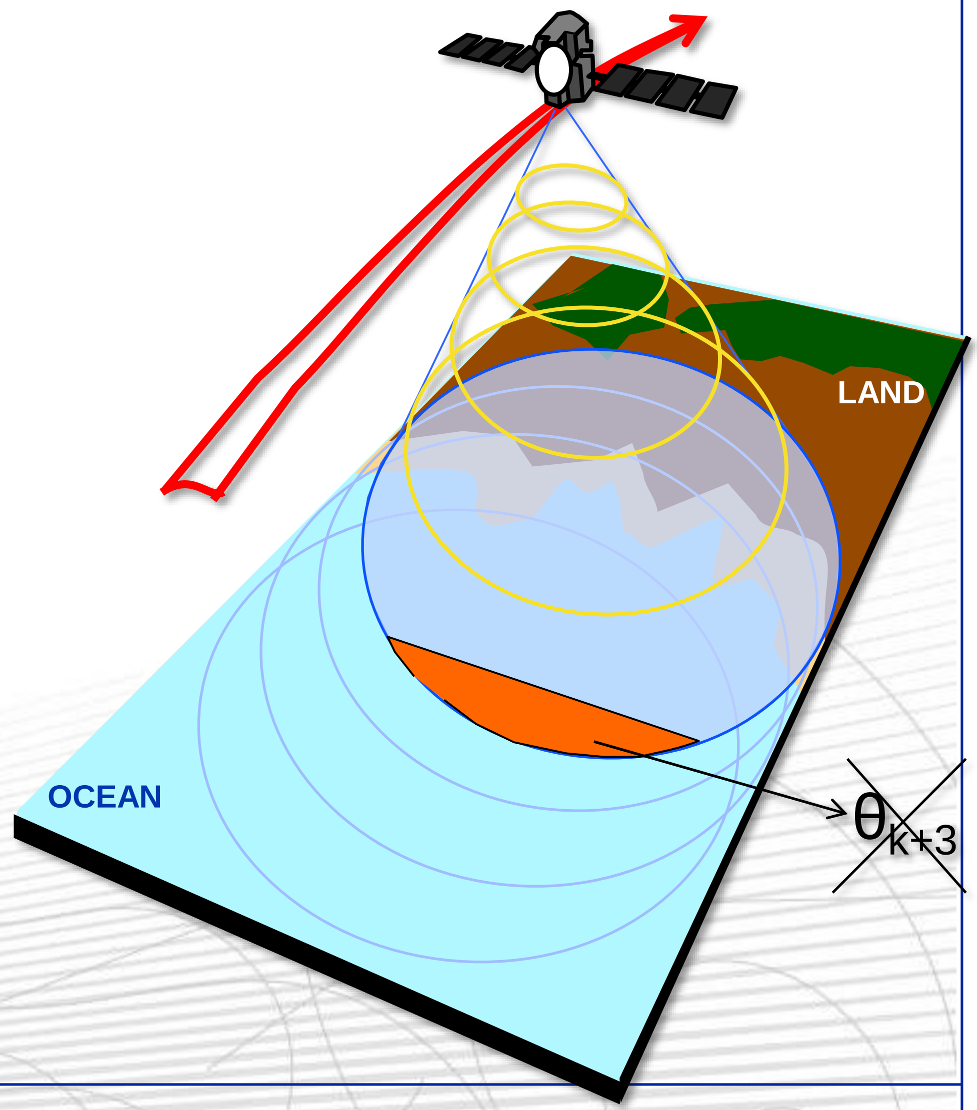
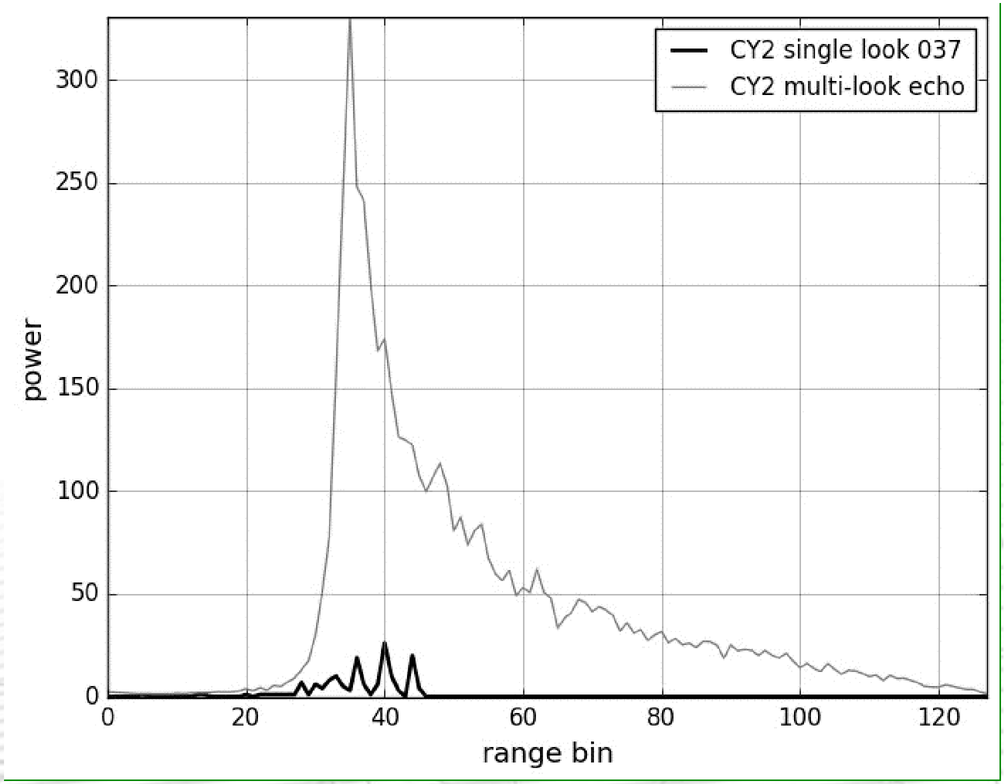
(the term θ_{k+3} is crossed out)

- The parameter estimates that are unwanted (for non-homogeneous surfaces) may be removed from the average



INDIVIDUAL DOPPLER BEAMS RETRACKER

- Need to use non-conventional methods of estimation to fit the model to individual look echoes due to their very high speckle noise

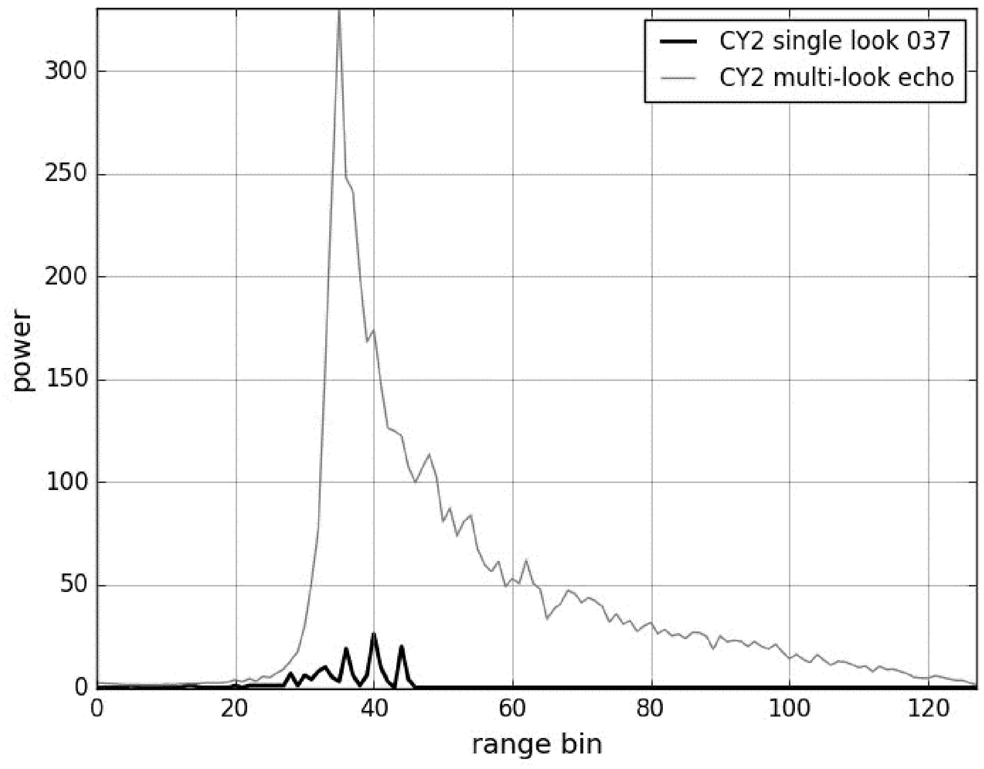


INDIVIDUAL DOPPLER BEAMS RETRACKER

- Need to use non-conventional methods of estimation to fit the model to individual look echoes due to their very high speckle noise

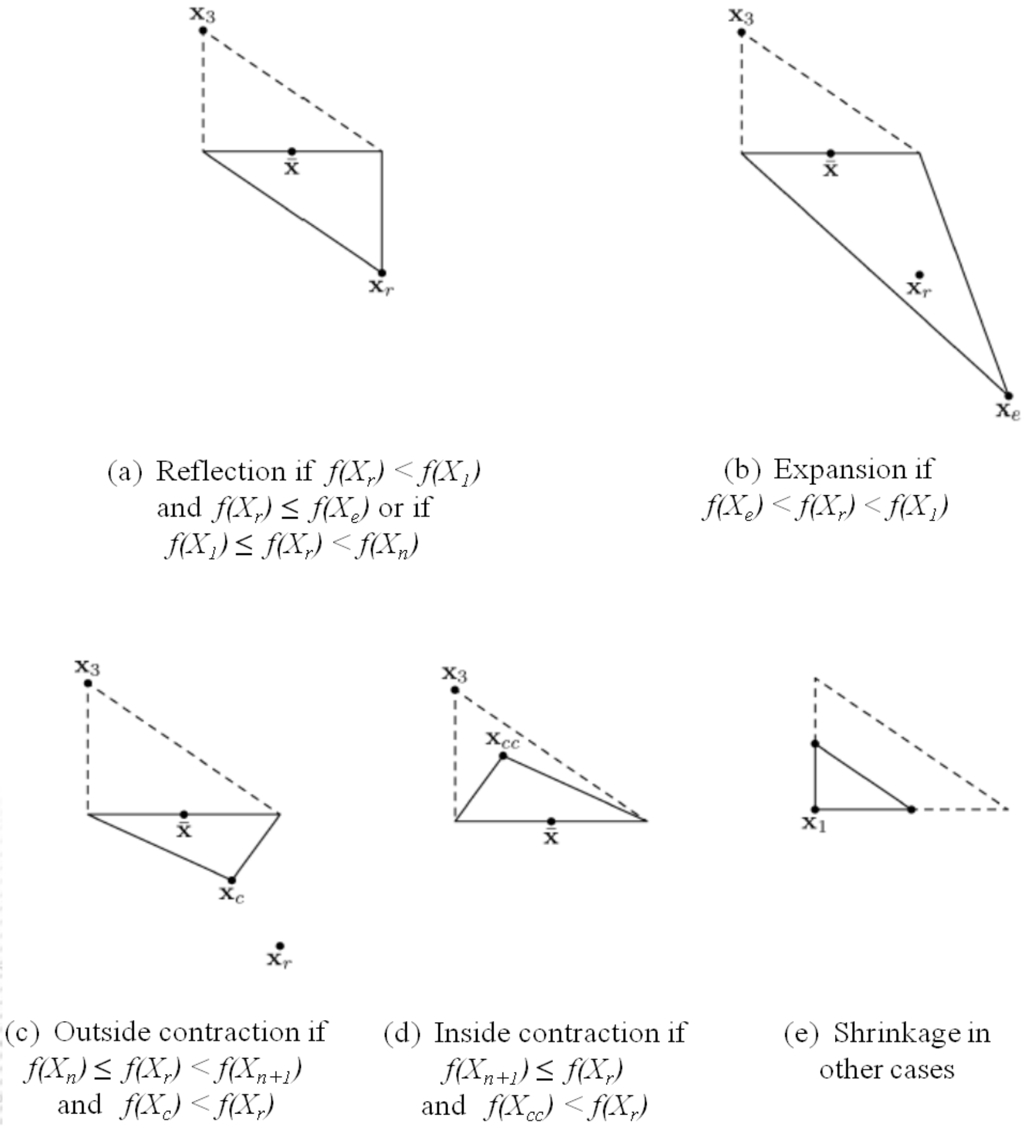
- One approach of this problem is to use the **maximum likelihood** (ML) method of estimation (with no derivative of the cost function) that allows to account for the altimeter signal statistical properties (the noise property) in the waveform parameter estimation

- **The Nelder–Mead (NM) simplex algorithm based on this principle is analyzed in comparison with conventional approach (MLE)**



INDIVIDUAL DOPPLER BEAMS RETRACKER

- The Nelder-Mead (NM) optimization method reshapes a simplex for minimizing the objective function (manifested by expansions or successive contractions of the simplex according to the local topology)
- NM uses the exact maximum likelihood (ML) criterion for the convergence with no approximation or derivates of it
- NM accounts for the exact noise statistic (considering the number of decorrelated pulses) whereas classical approaches do not
- But NM requires higher number of iterations



(a) Reflection if $f(X_r) < f(X_1)$ and $f(X_r) \leq f(X_e)$ or if $f(X_1) \leq f(X_r) < f(X_n)$

(b) Expansion if $f(X_e) < f(X_r) < f(X_1)$

(c) Outside contraction if $f(X_n) \leq f(X_r) < f(X_{n+1})$ and $f(X_c) < f(X_r)$

(d) Inside contraction if $f(X_{n+1}) \leq f(X_r)$ and $f(X_{cc}) < f(X_r)$

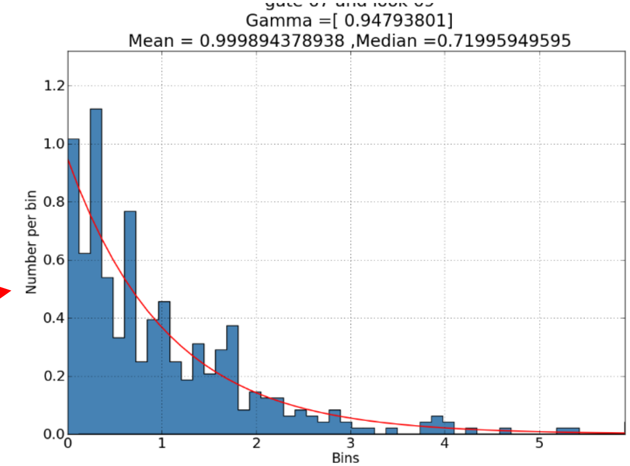
(e) Shrinkage in other cases

NOISE STATISTICS IN DOPPLER BEAMS

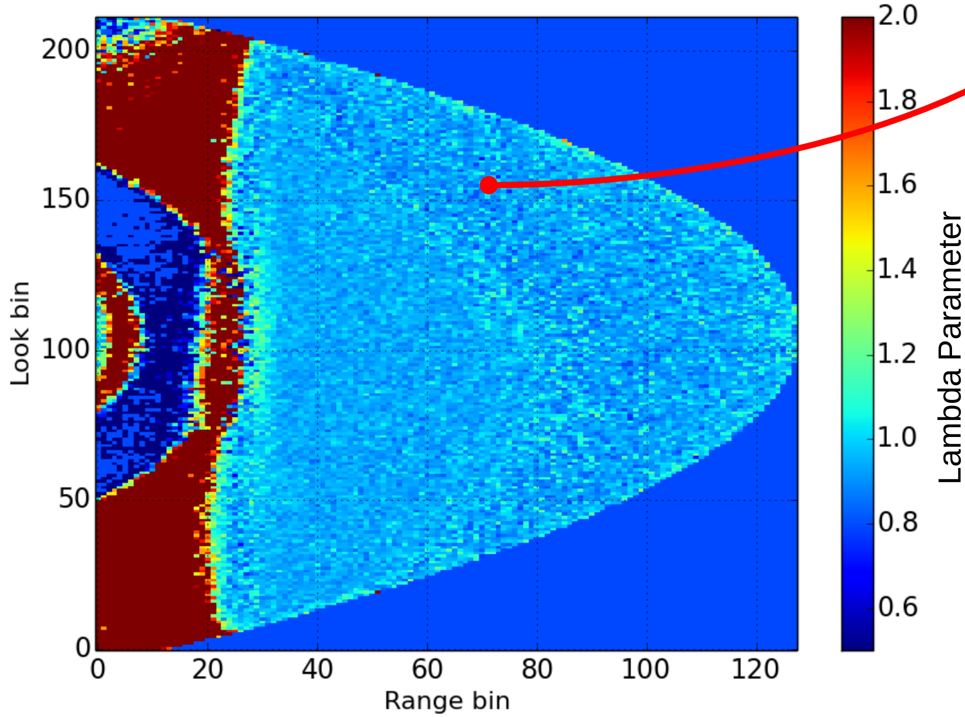
- Speckle noise law has been characterized with SIRAL data (from CPP v14) showing expected exponential distribution

$$f(x; /) = / e^{- / x} \quad \text{with } \lambda=1$$

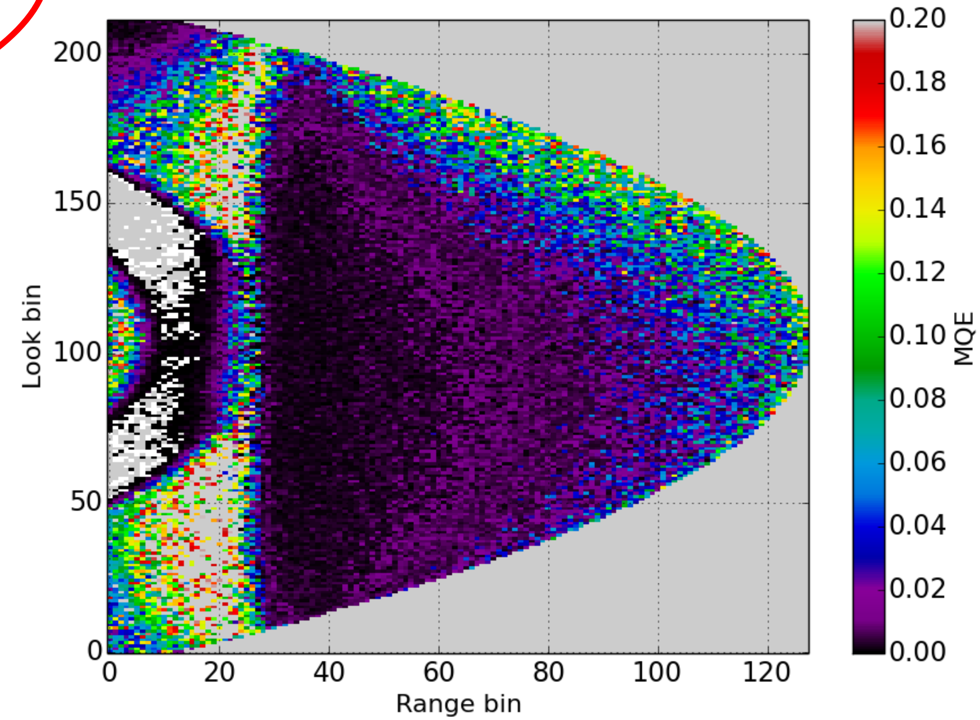
➔ **Same speckle characteristics after Doppler processing as for individual conventional altimetry pulses**



Lambda Parameter for 500 stacks



Mean quadratic Error for 500 stacks

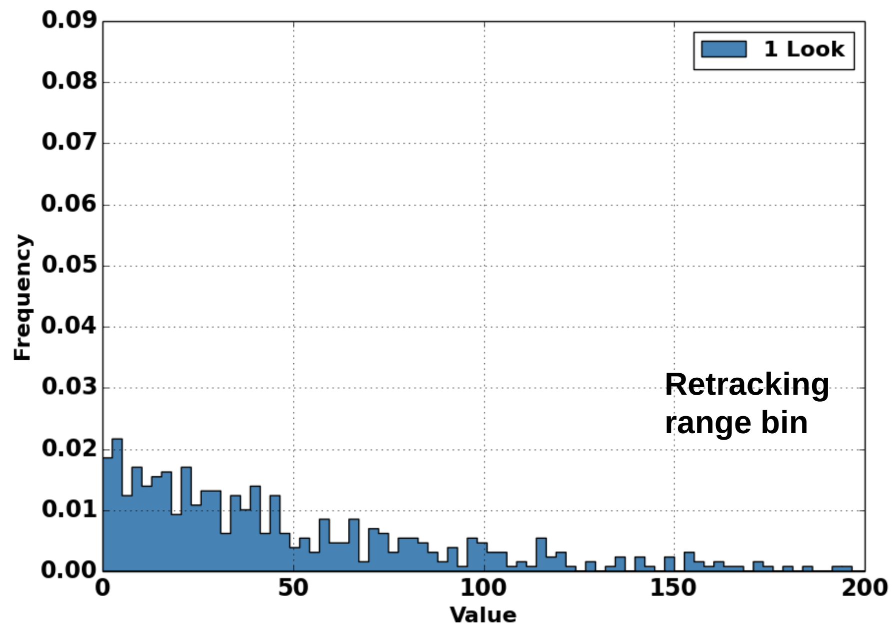


NOISE STATISTICS IN DOPPLER BEAMS

- **Single-look**
  - Probability distribution function has an exponential distribution

$$f(x; /) = / e^{- / x}$$

  - Mean value of the speckle amplitude = standard deviation



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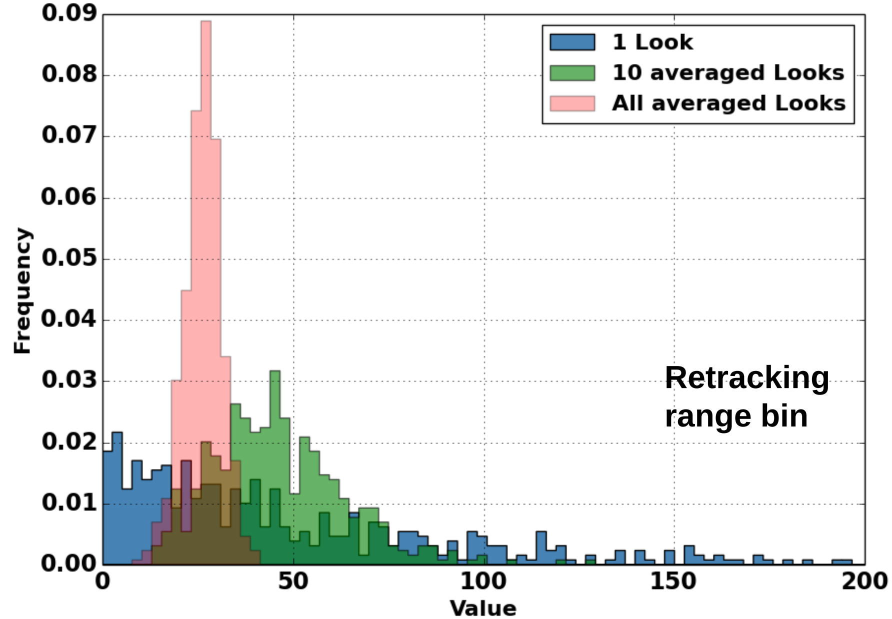


- **Multi-looking**
  - Incoherent addition of independent looks of the same scene (to reduce the speckle noise and data compress)
  - For N-looks, the speckle amplitude has a gamma distribution

$$f(x;N;\lambda)=\frac{\lambda}{\Gamma(N)}e^{-\lambda x}x^{N-1}$$

  - If N-looks have same intensity and shape: **Mean value/standard deviation = √N** (as for conventional altimetry)

INDIVIDUAL DOPPLER BEAMS RETRACKER

- **Speckle *x* is a multiplicative noise of exponential distribution**

  Power return echo $y_t = S_t \mathrm{x}$ (with S_t the model)

- The density of an exponential law:

$$f(x) = e^{-x} I_{\Re^+} \text{, giving} \quad f(y_t) = e^{-\frac{y_t}{S_t}} \frac{1}{S_t} I_{\Re^+}$$

- The log-likelihood function estimator algorithm

$$Ln(f(y_1,..,y_k)) = Ln\left(\prod_{t=1}^{K} f(y_t)\right) = Cste - \sum_{t=1}^{K} \frac{y_t}{S_t} - \sum_{t=1}^{K} Ln(S_t)$$

- To optimize the likelihood function, **two approaches**:
  1. calculate the derivatives of the log wrt parameters and set it to zero (to find the maximum of the log-likelihood)

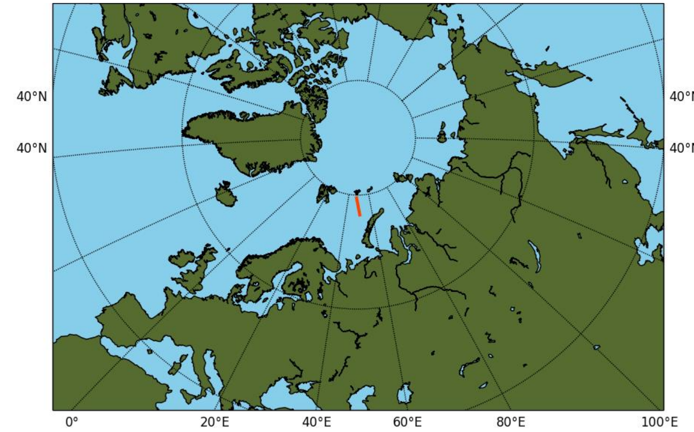
$$\frac{\partial Ln(f(y_1,..,y_k))}{\partial \theta_m} = 0 \quad \rightarrow \quad \sum_{t=1}^{K} \frac{\partial S_t}{\partial \theta_m}\left[\frac{y_t - S_t}{S_t^2}\right] = 0$$

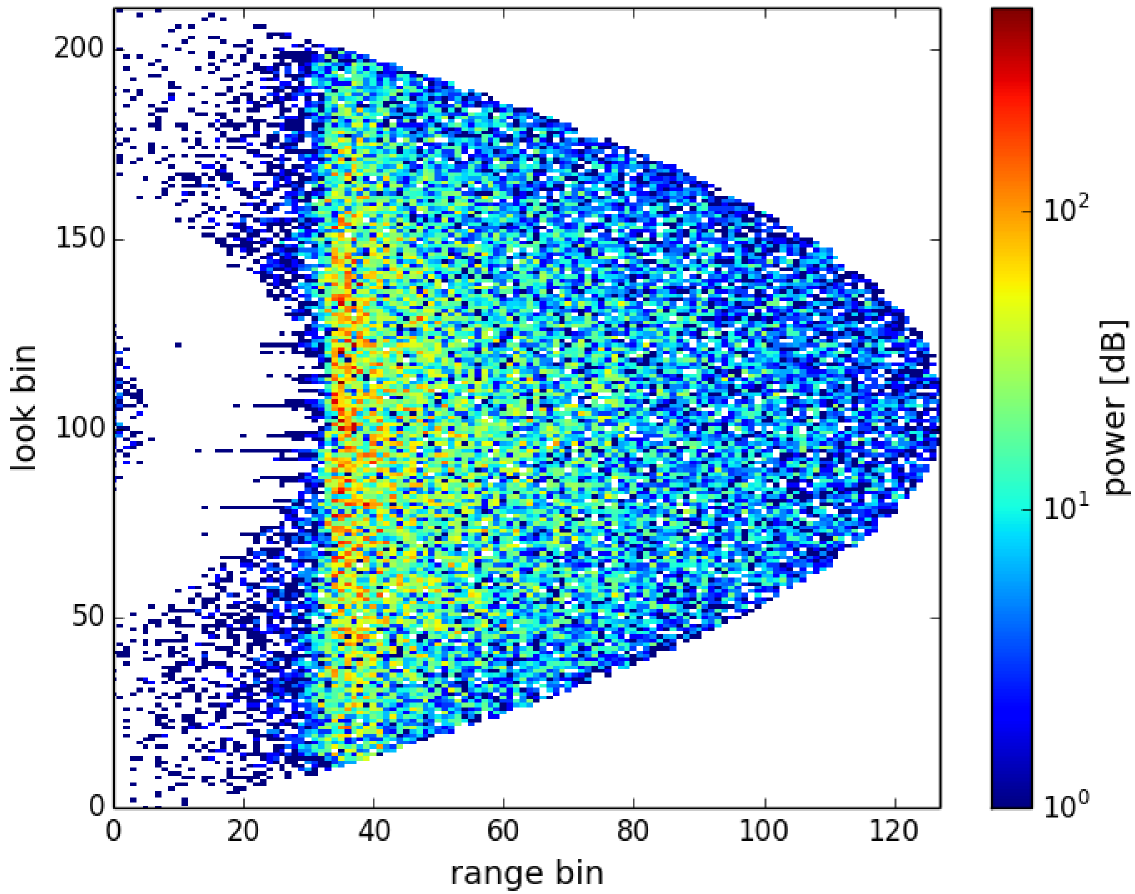
  Same criteria as for the conventional Newton-Raphson algorithm (MLE) to solve the system and infer geophysical parameters

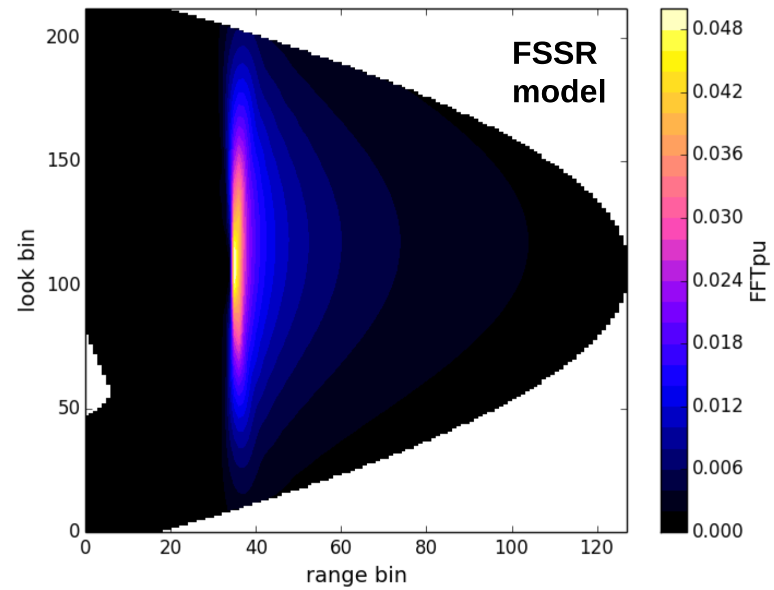
  2. minimize the log-likelihood function using the simplex approach (with no gradients)

INDIVIDUAL DOPPLER BEAMS RETRACKER

- Case study: Low sea state in Arctic ocean







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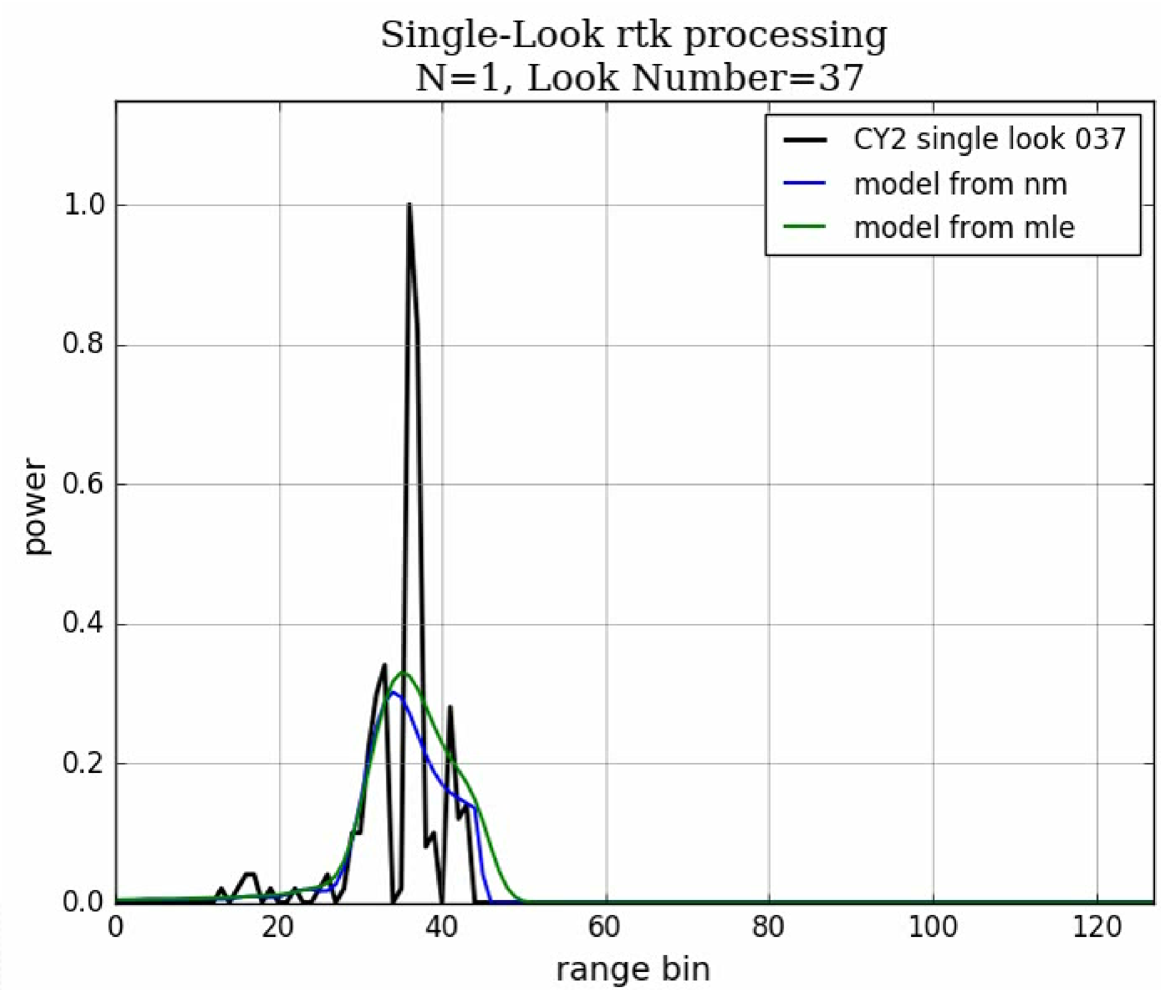
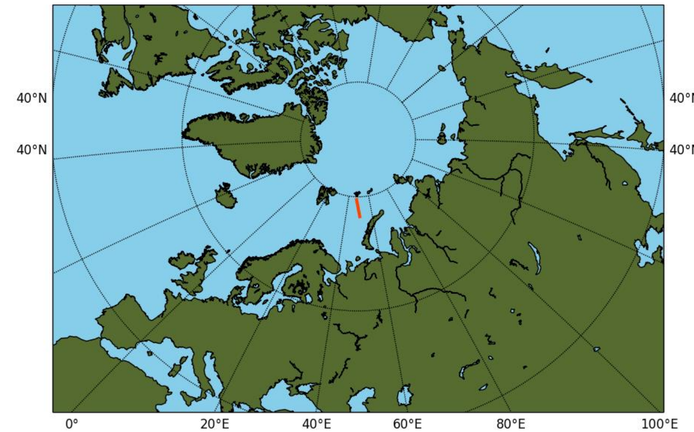
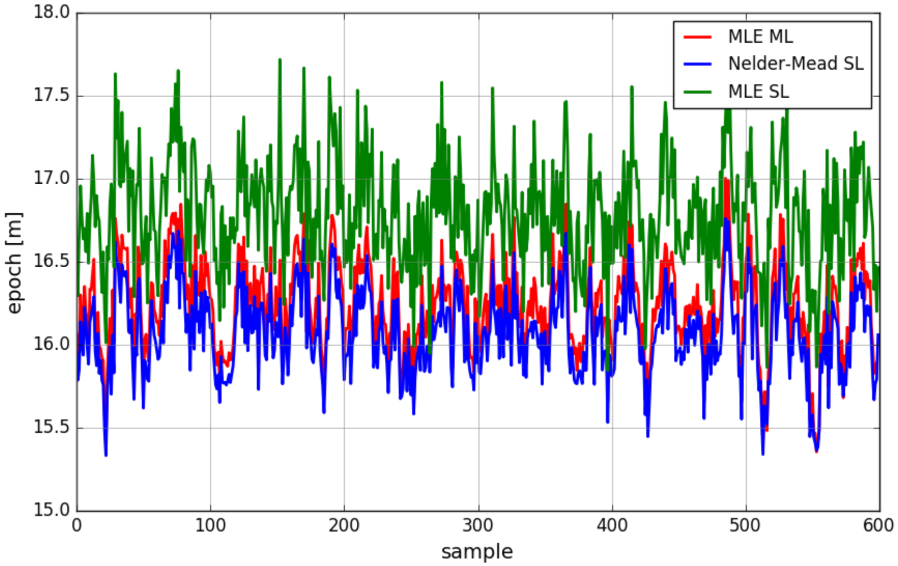
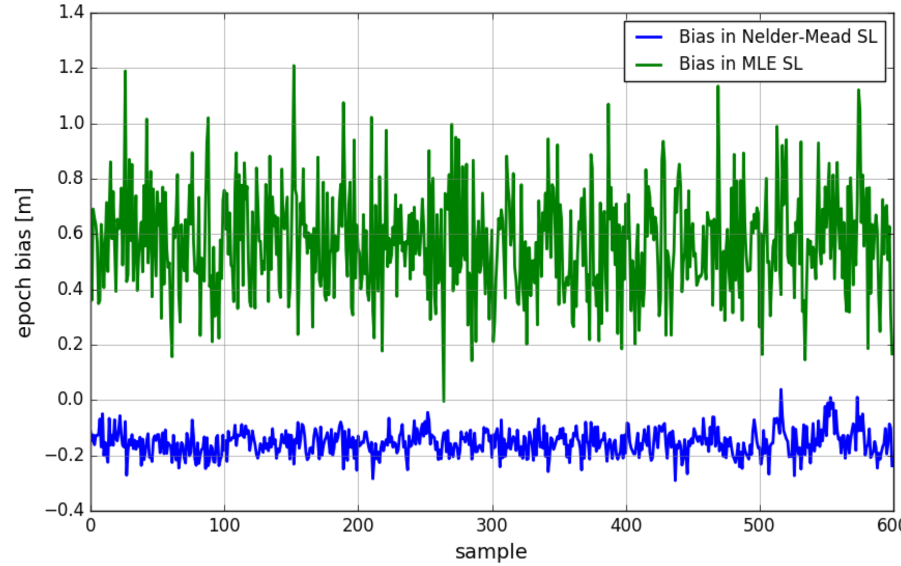


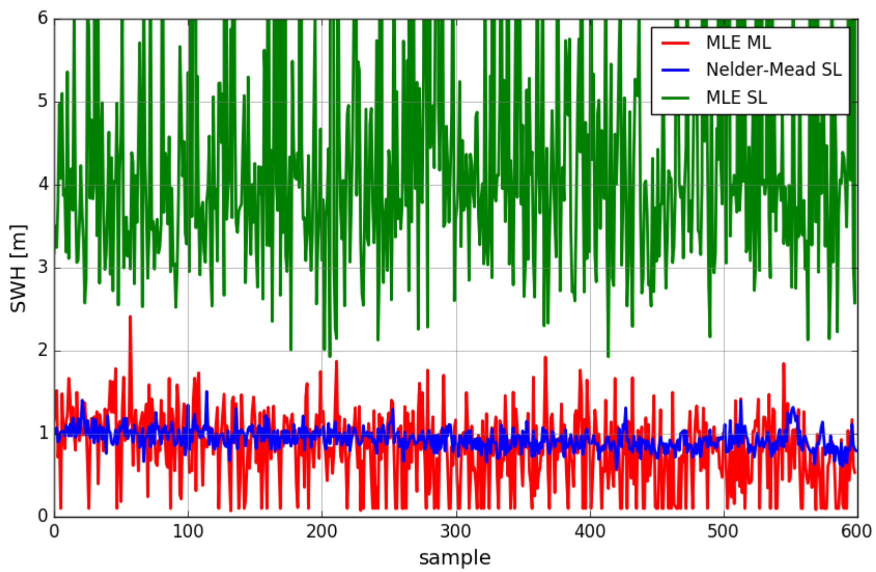


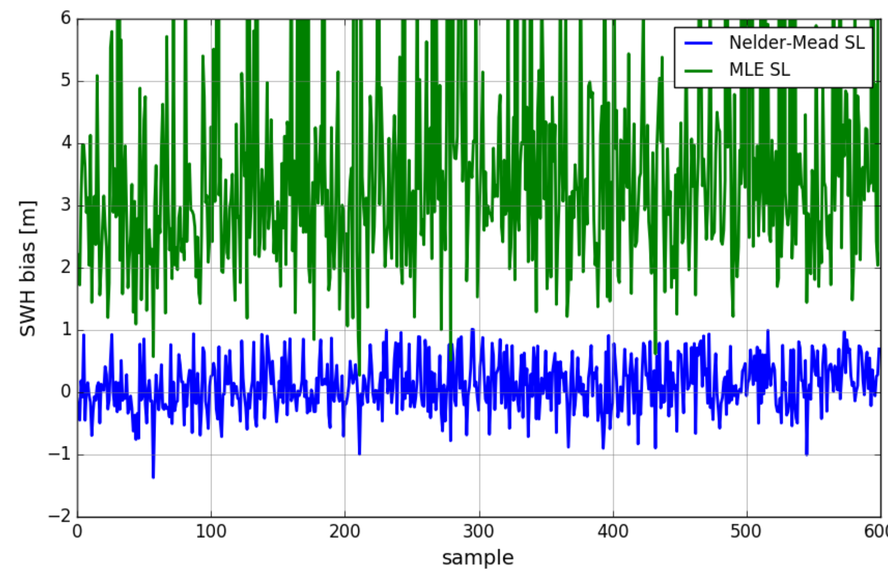
- NM models are tightly clustered around the same leading-edge position
- MLE models are a bit scattered from look to look

INDIVIDUAL DOPPLER BEAMS RETRACKER



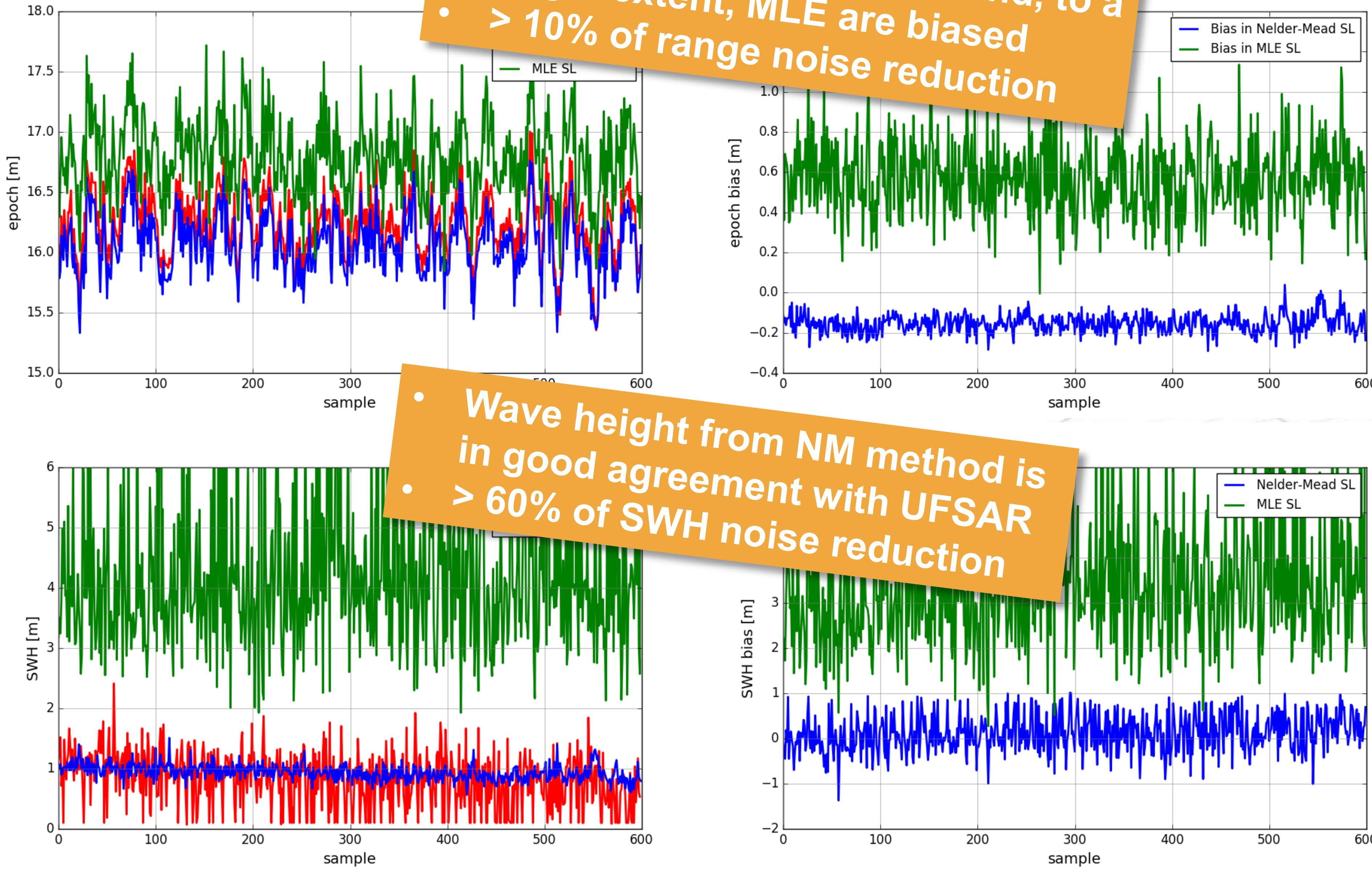






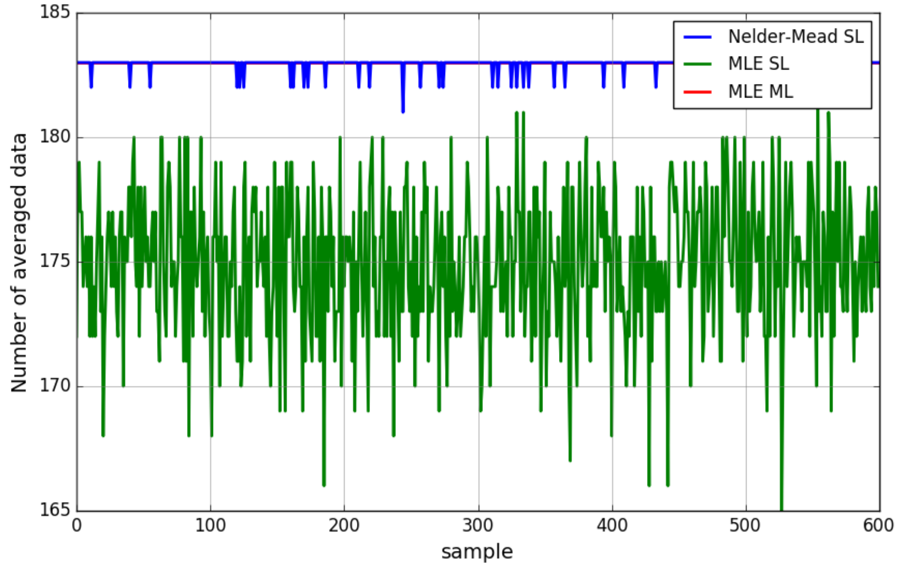
INDIVIDUAL DOPPLER BEAMS RETRACKER

- Ranges from NM method and, to a larger extent, MLE are biased
- > 10% of range noise reduction

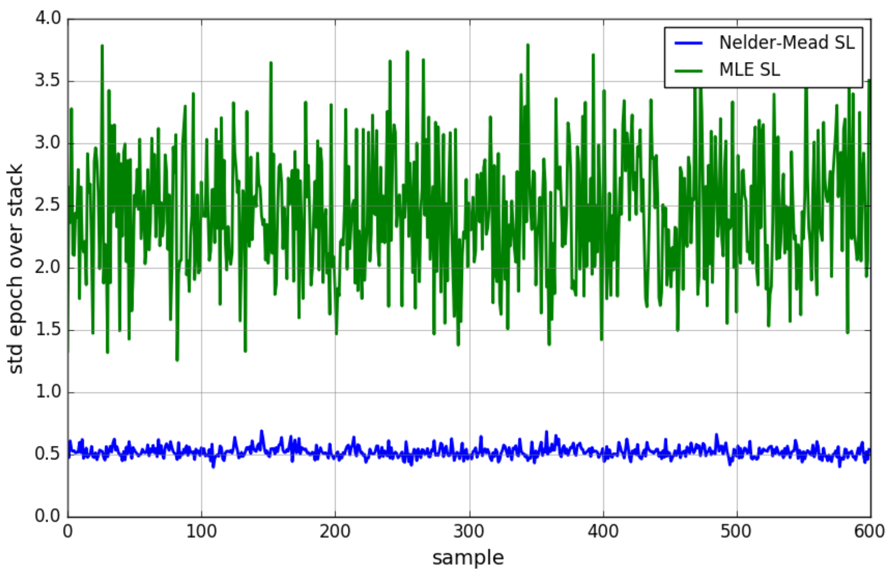


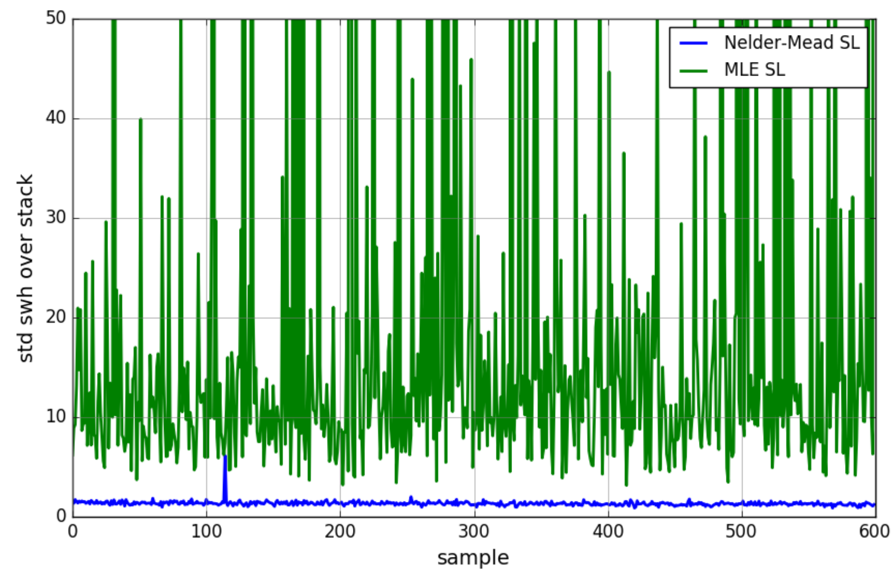
- Wave height from NM method is in good agreement with UFSAR
- > 60% of SWH noise reduction

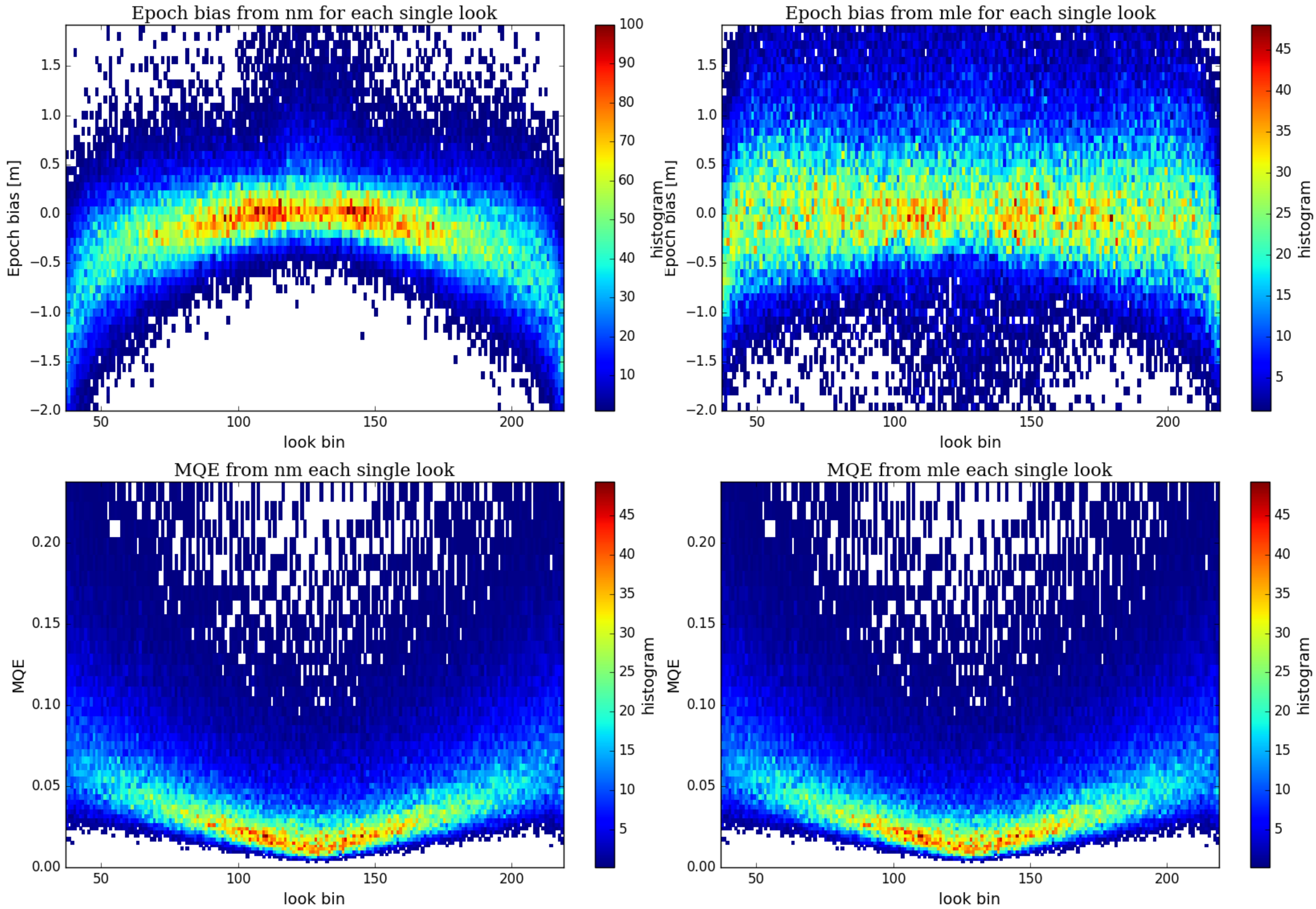
INDIVIDUAL DOPPLER BEAMS RETRACKER



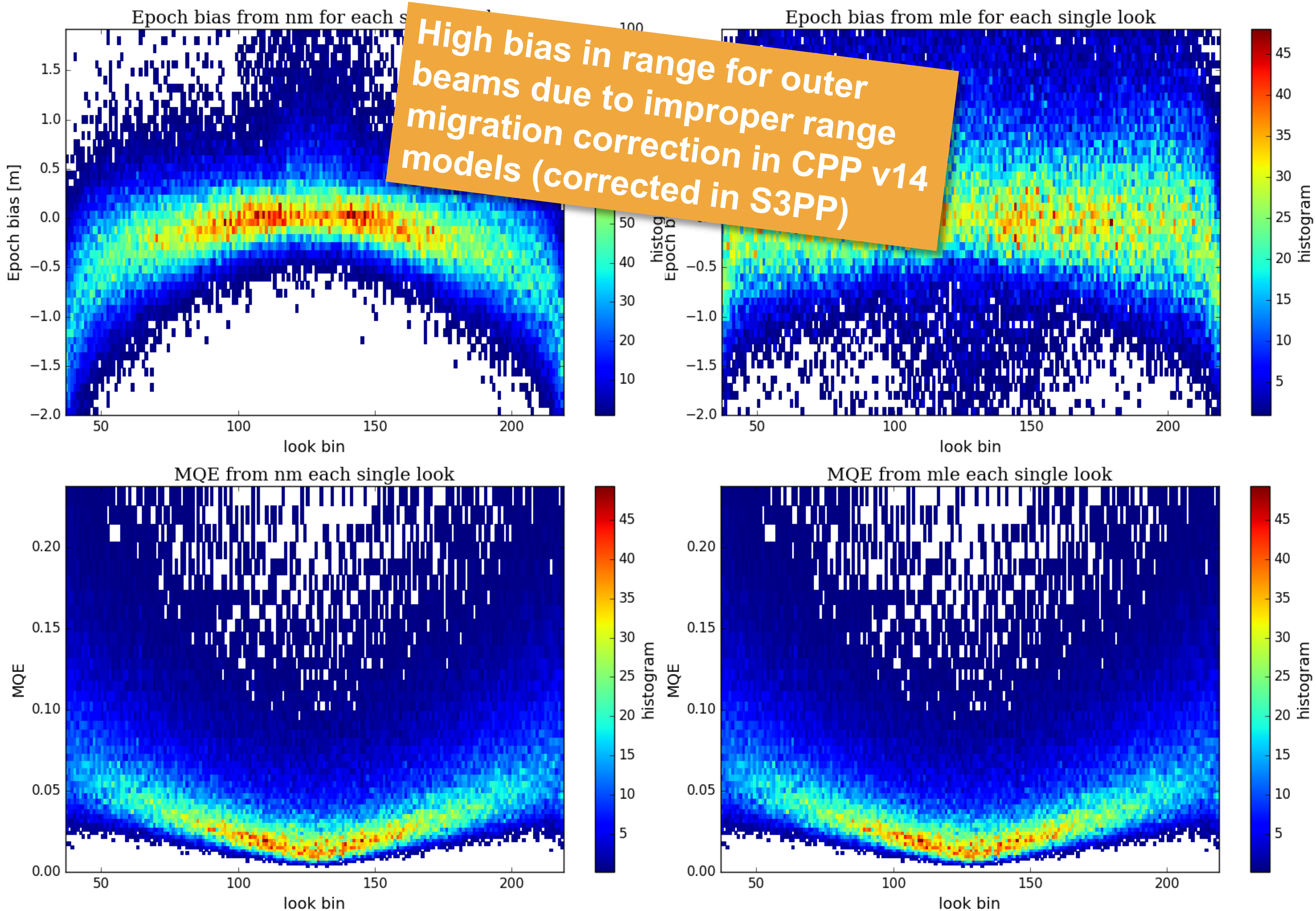
- Higher number of estimates used for NM
- Much lower variance of epoch and SWH estimates in stack







Epoch bias from nm for each single look
Epoch bias from mle for each single look
MQE from nm each single look
MQE from mle each single look
Epoch bias [m]
MQE
look bin
histogram


High bias in range for outer beams due to improper range migration correction in CPP v14 models (corrected in S3PP)
Epoch bias from mle for each single look
Epoch bias [m]
look bin
histogram
MQE from nm each single look
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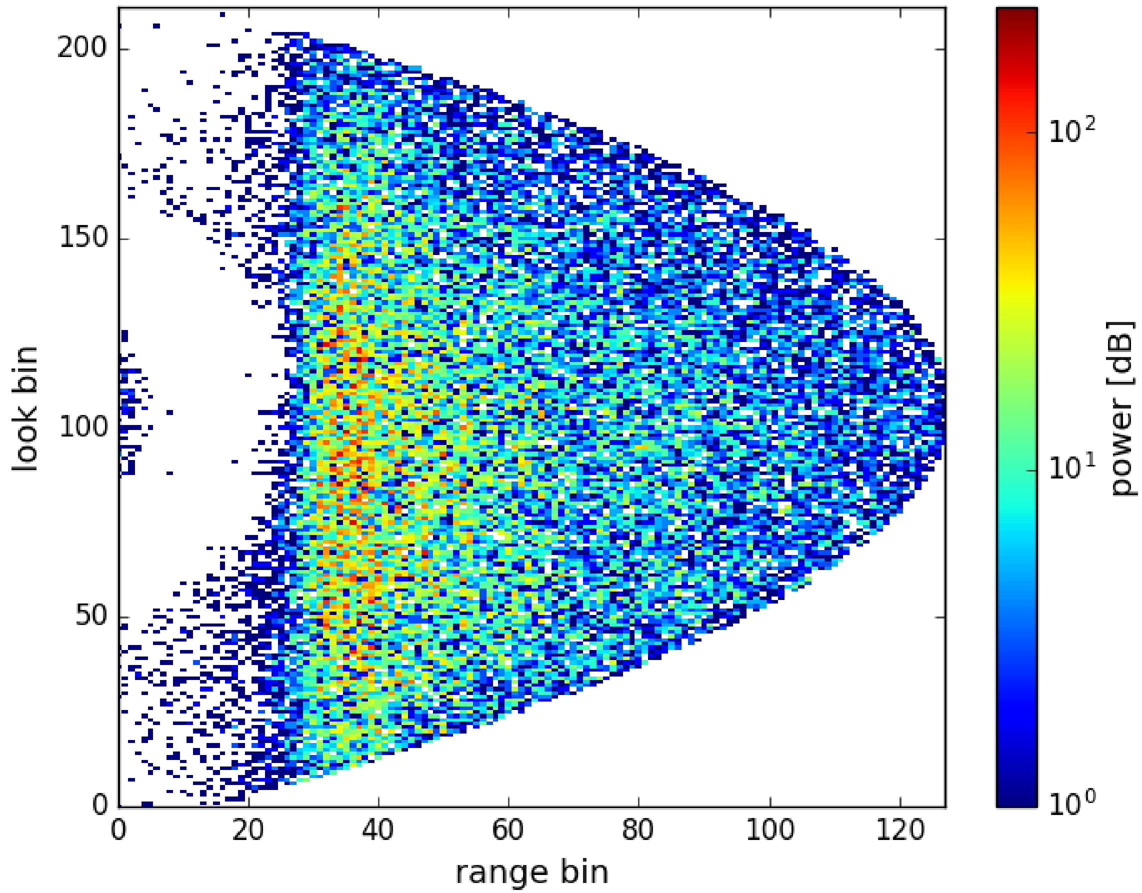
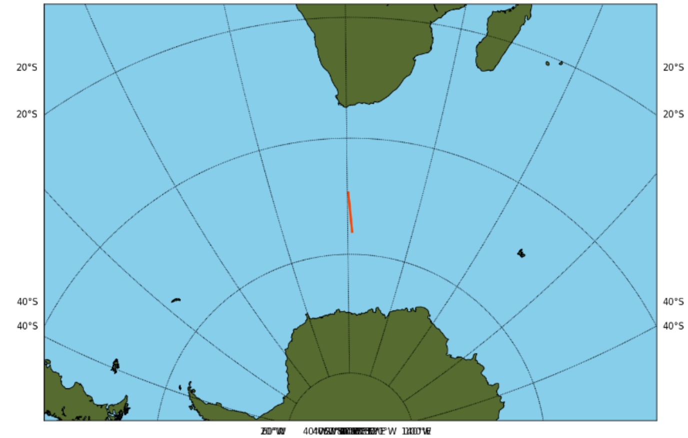
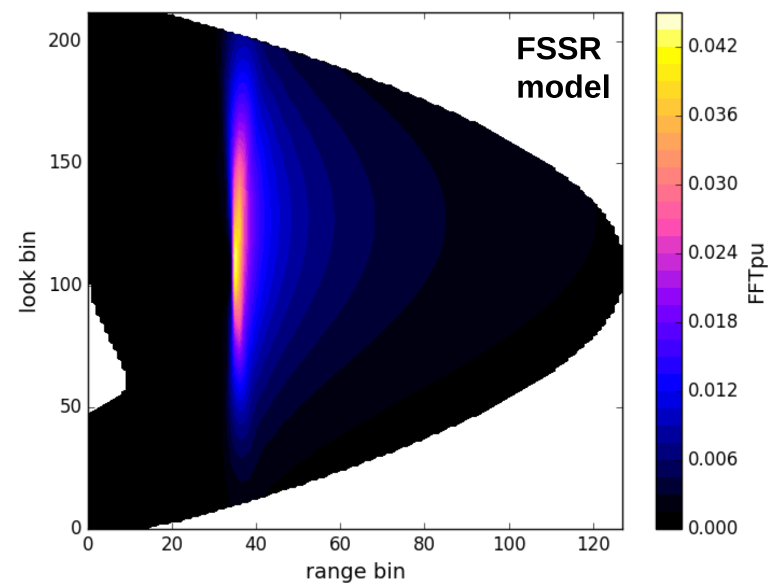
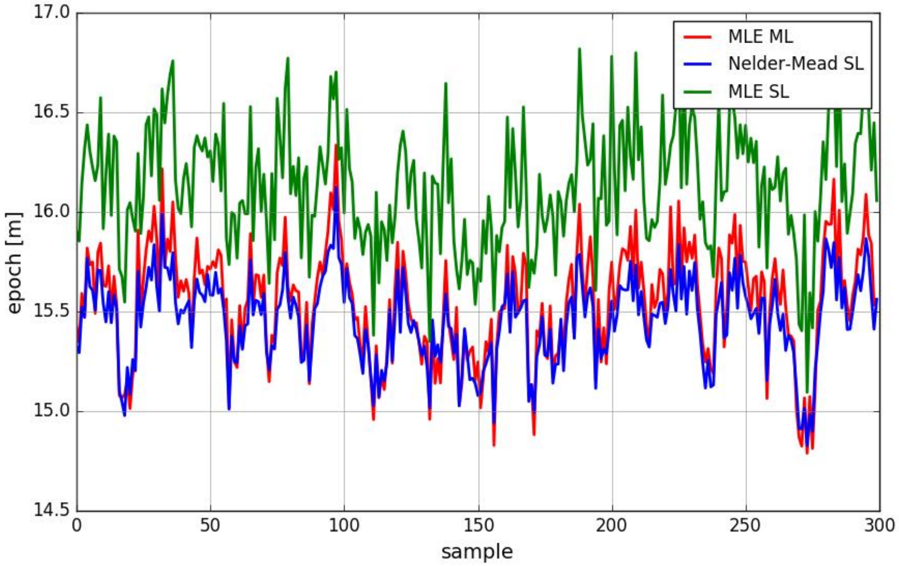
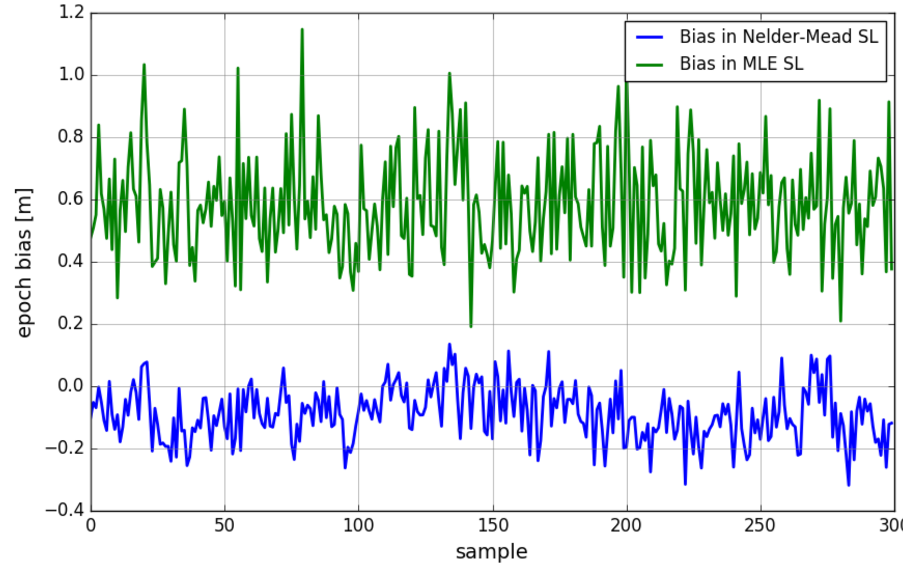


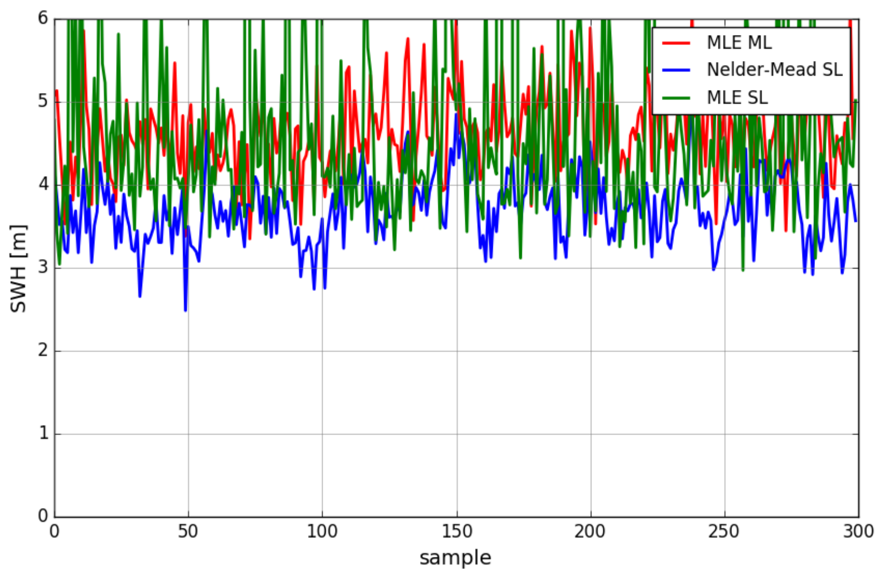


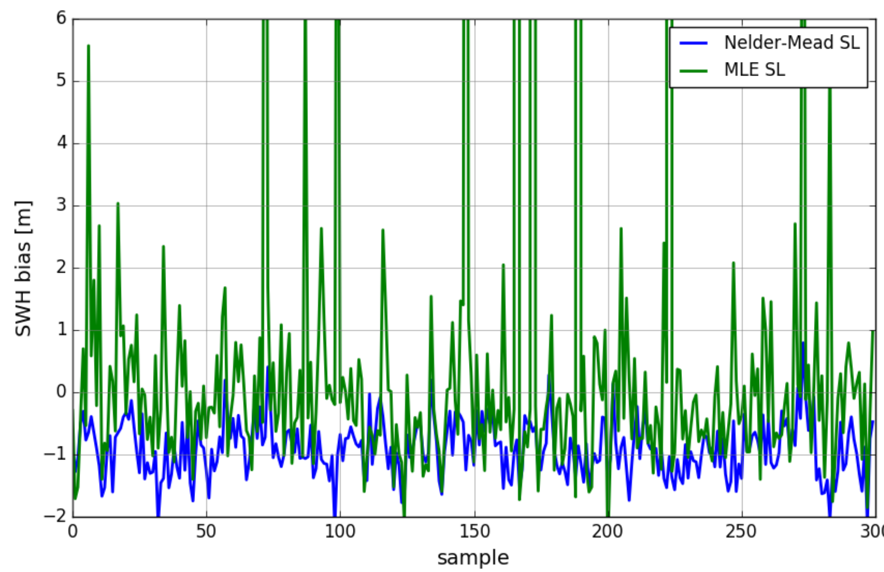


INDIVIDUAL DOPPLER BEAMS RETRACKER

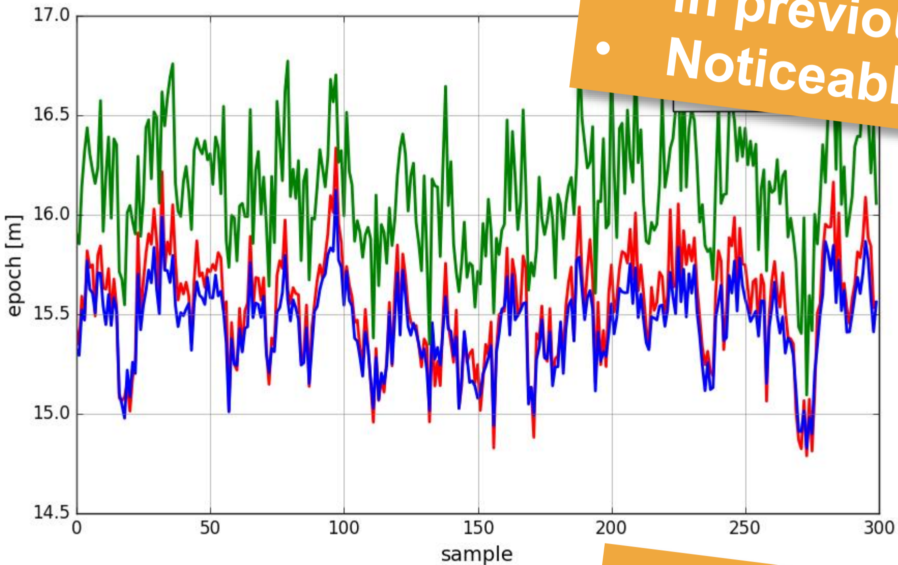


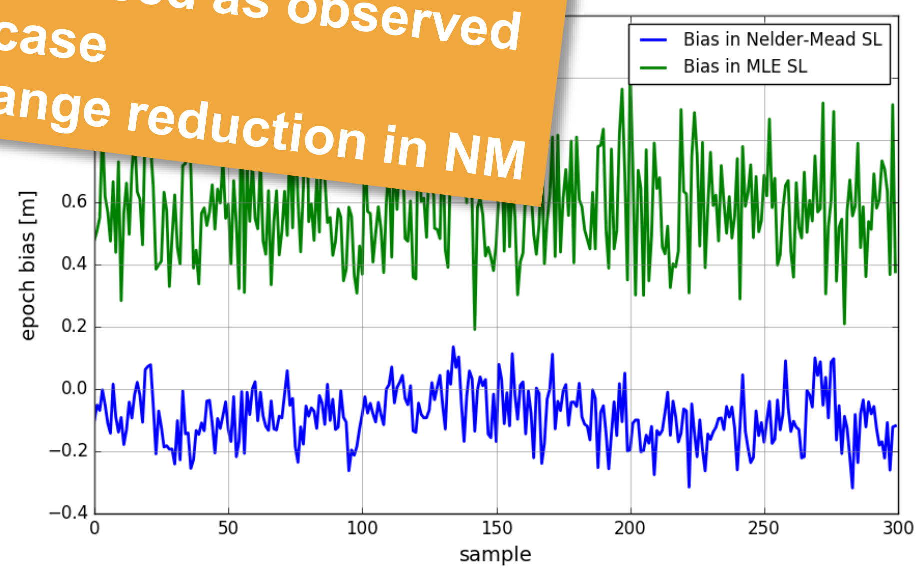




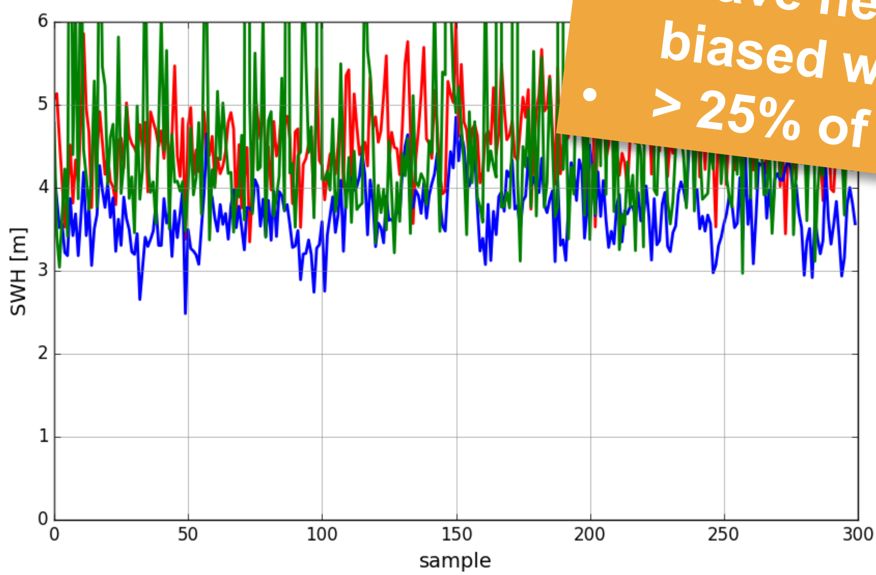


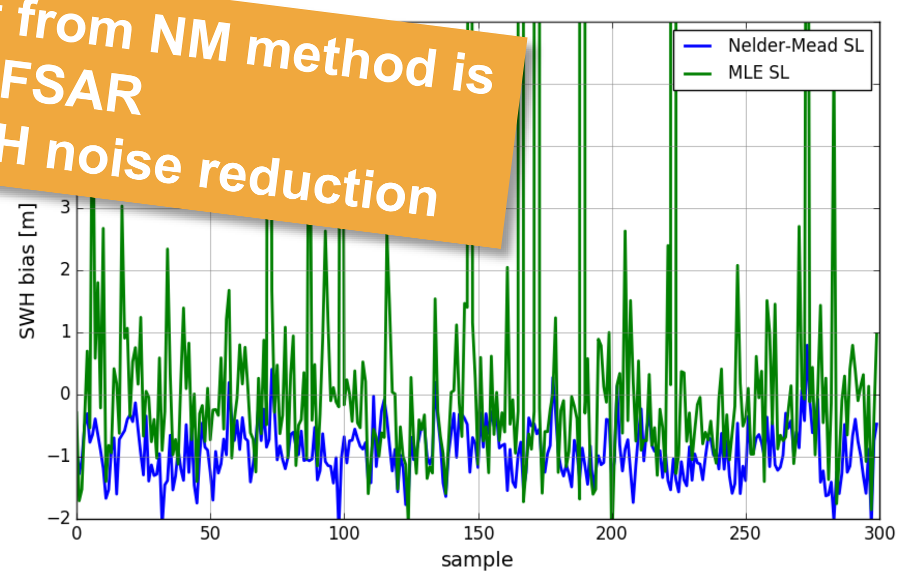
INDIVI… PPLER BEAMS RETRACKER





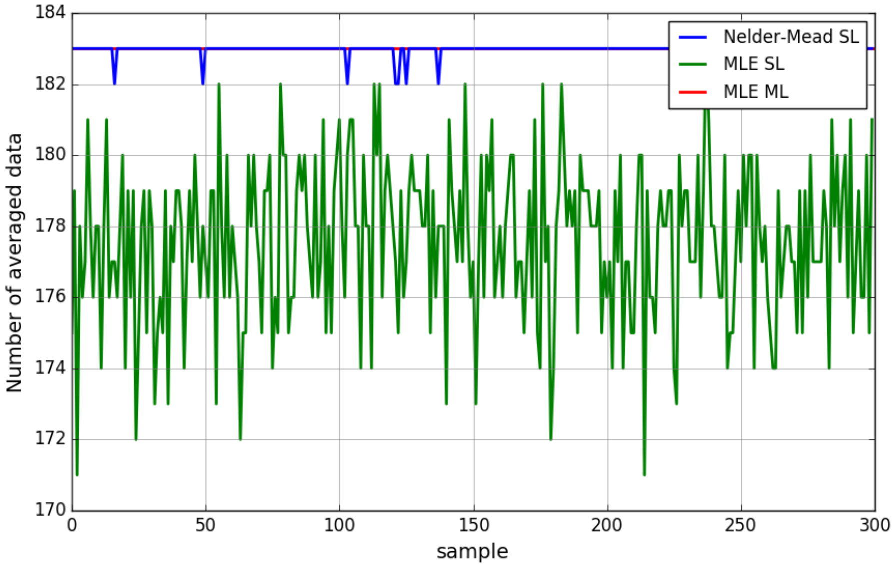
- Ranges from NM and MLE methods are biased as observed in previous case
- Noticeable range reduction in NM



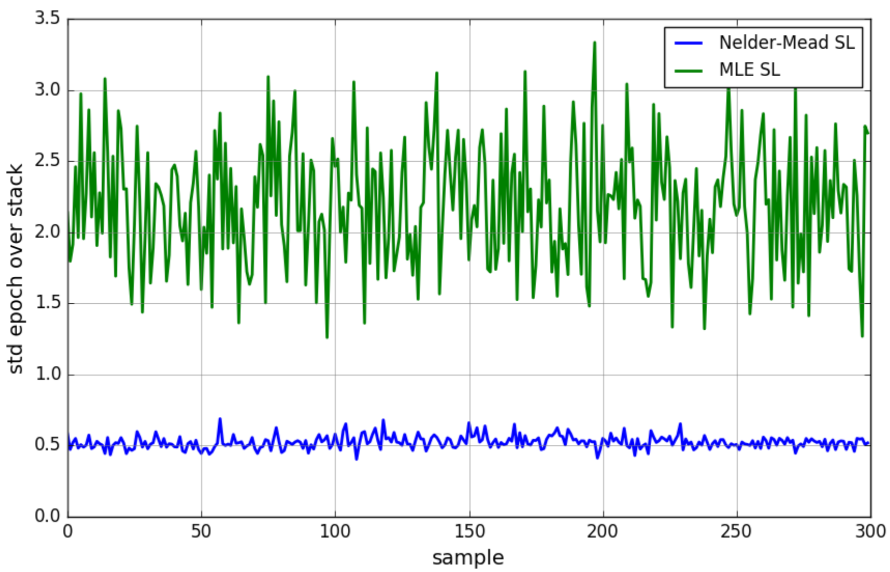


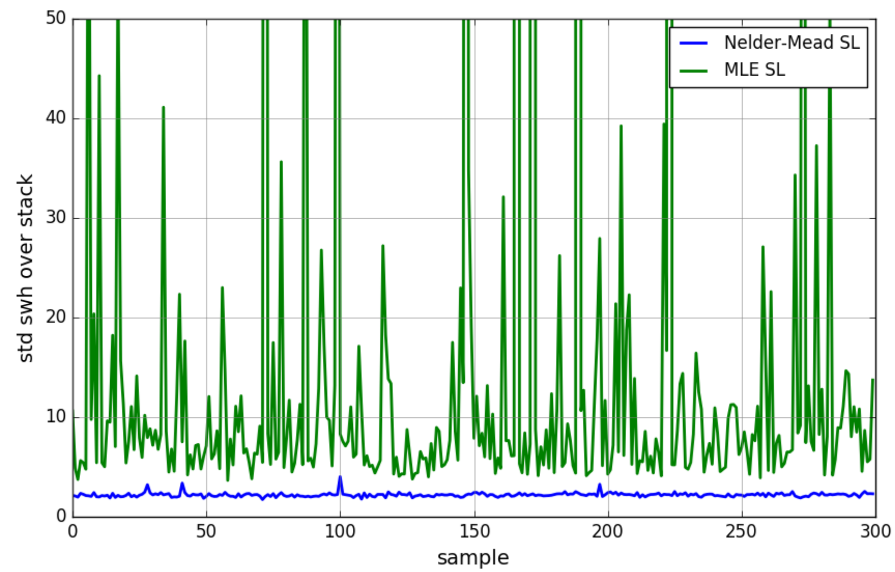
- Wave height from NM method is biased wrt UFSAR
- > 25% of SWH noise reduction

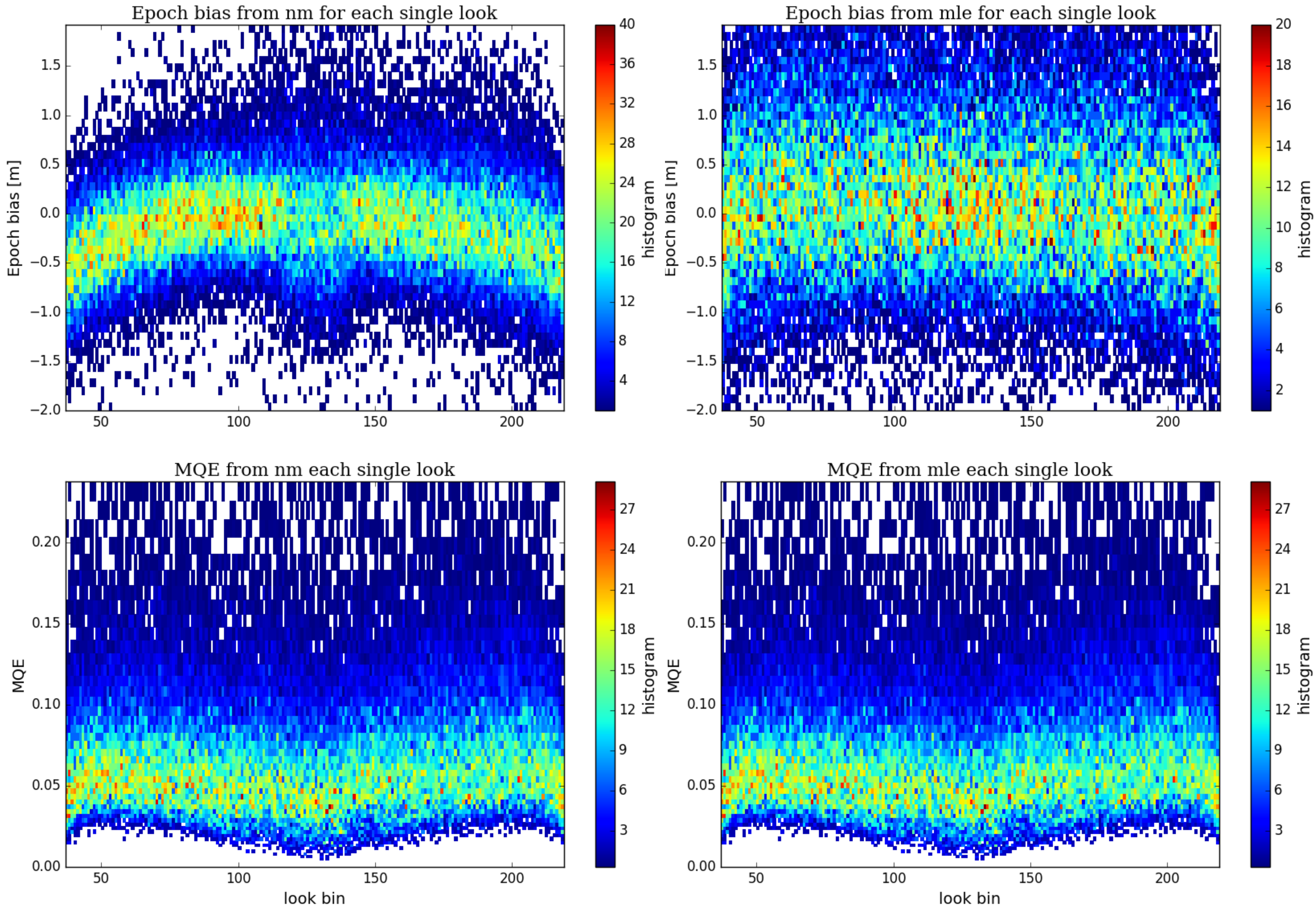
INDIVIDUAL DOPPLER BEAMS RETRACKER



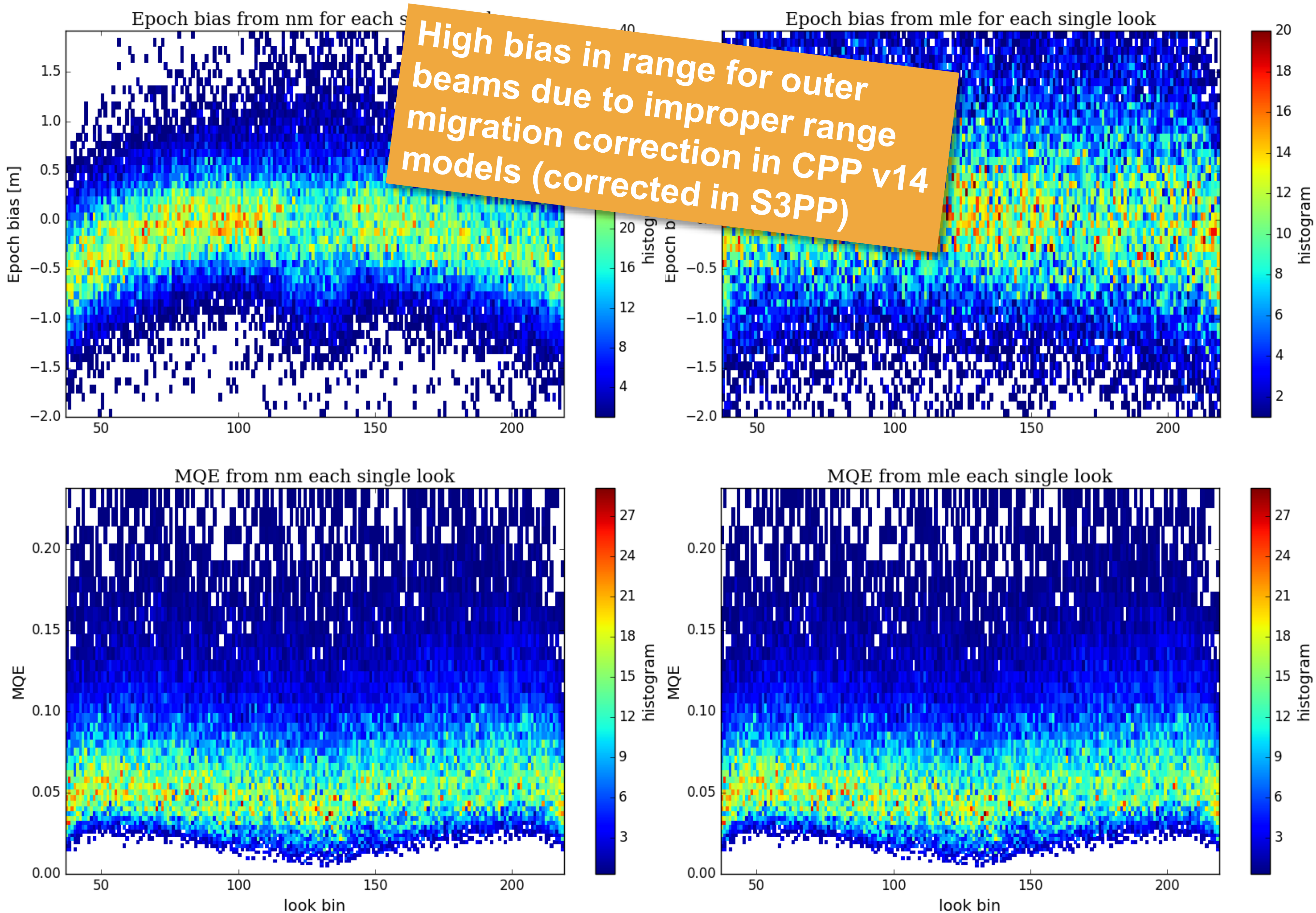
- Higher number of estimates used for NM
- Much lower variance of epoch and SWH estimates in stack





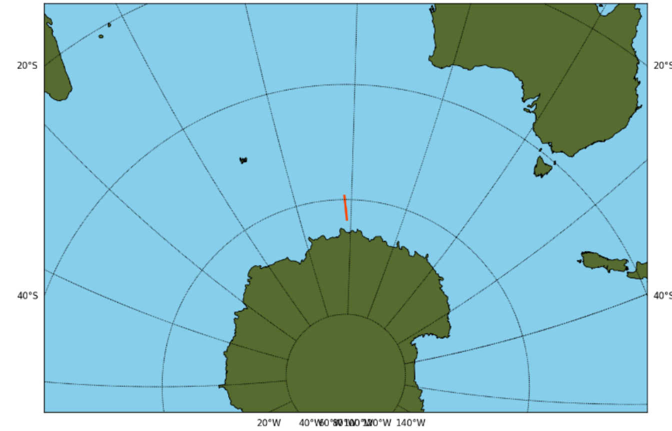


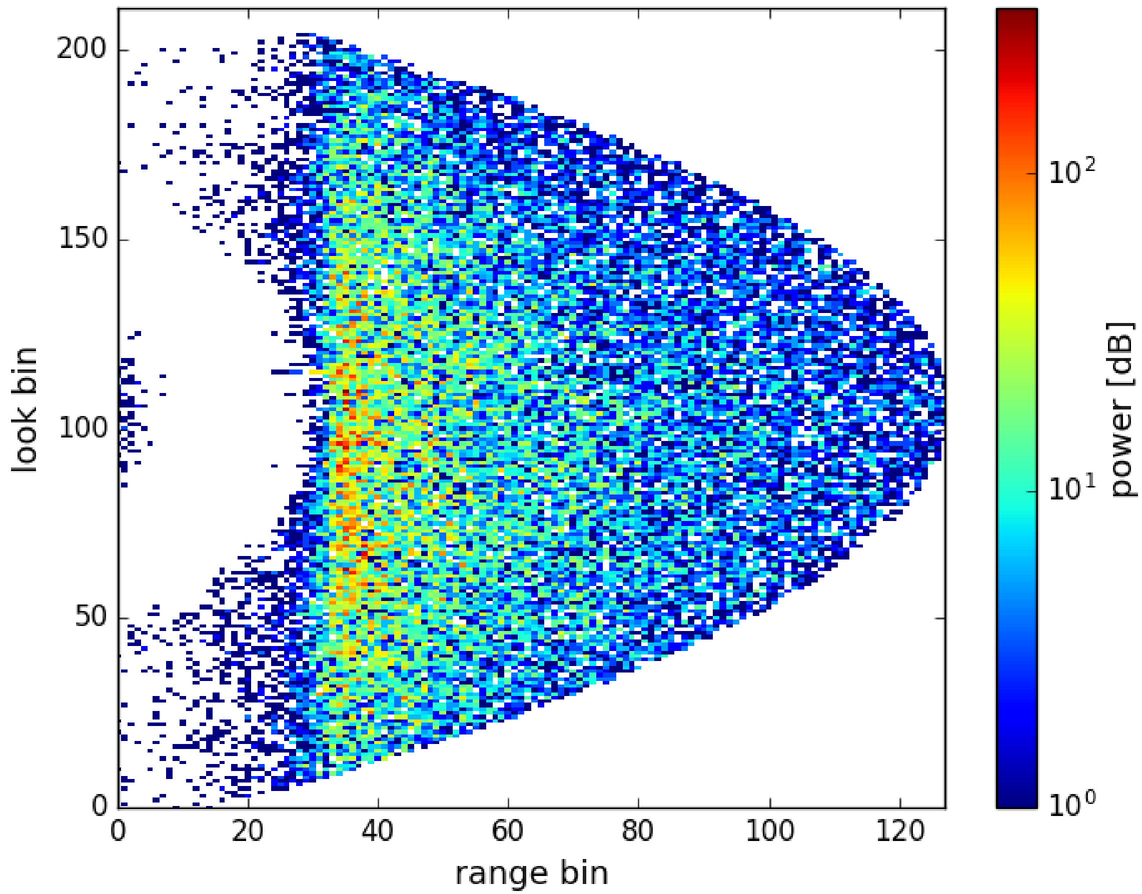
Epoch bias from nm for each single look
Epoch bias from mle for each single look
MQE from nm each single look
MQE from mle each single look
Epoch bias [m]
MQE
look bin
histogram

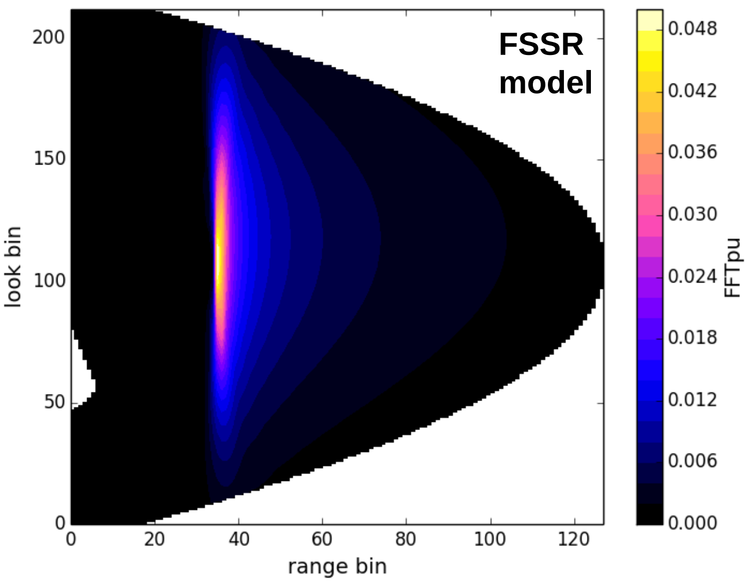

High bias in range for outer beams due to improper range migration correction in CPP v14 models (corrected in S3PP)
Epoch bias from mle for each single look
Epoch bias [m]
MQE from nm each single look
MQE from mle each single look
MQE
look bin
histogram

INDIVIDUAL DOPPLER BEAMS RETRACKER

- Case study: High sea state in Pacific



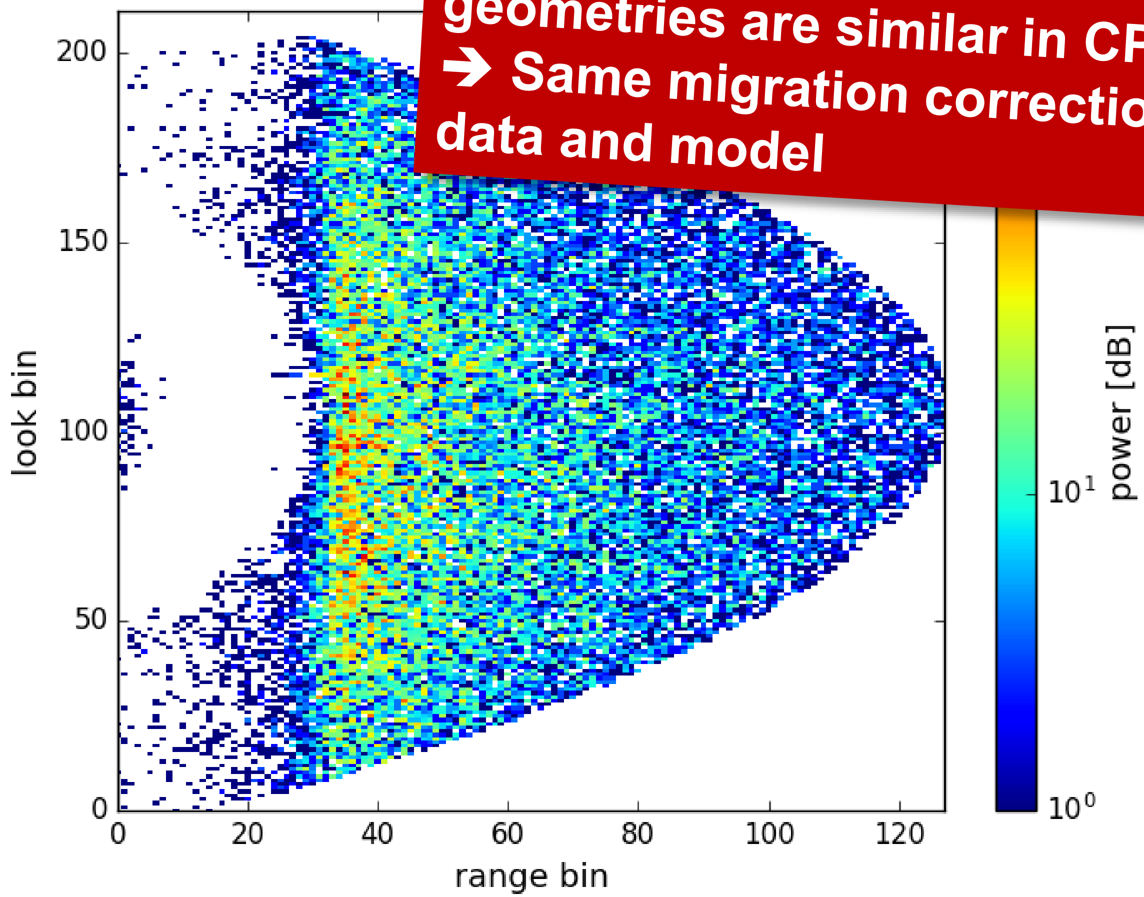


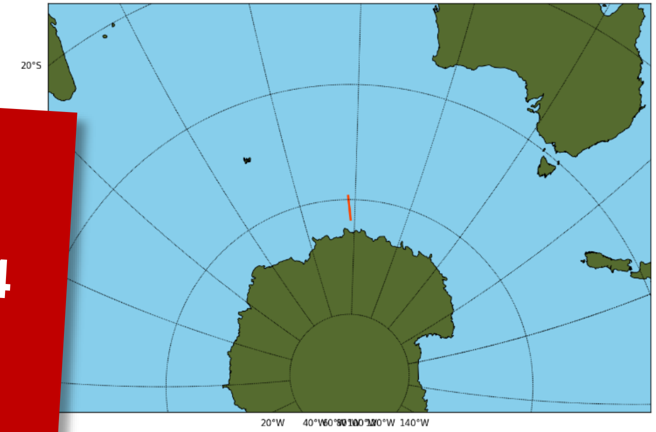


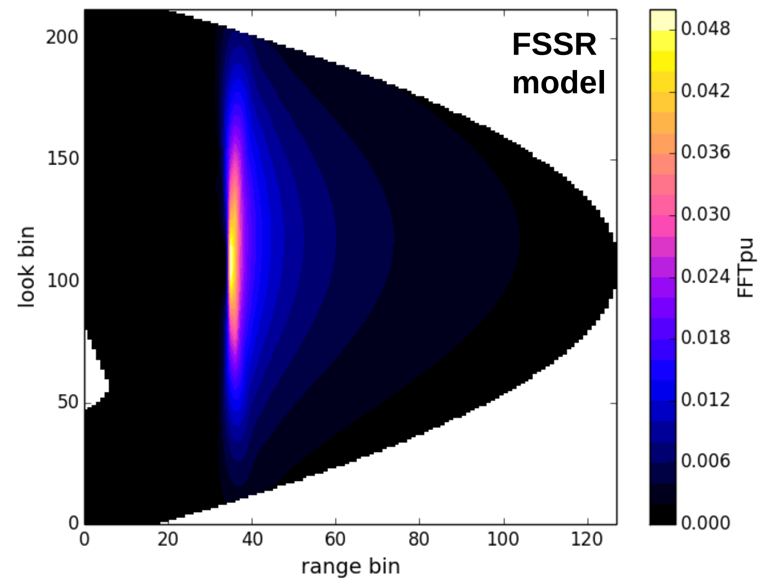
INDIVIDUAL DOPPLER BEAMS RETRACKER

- Case study: H

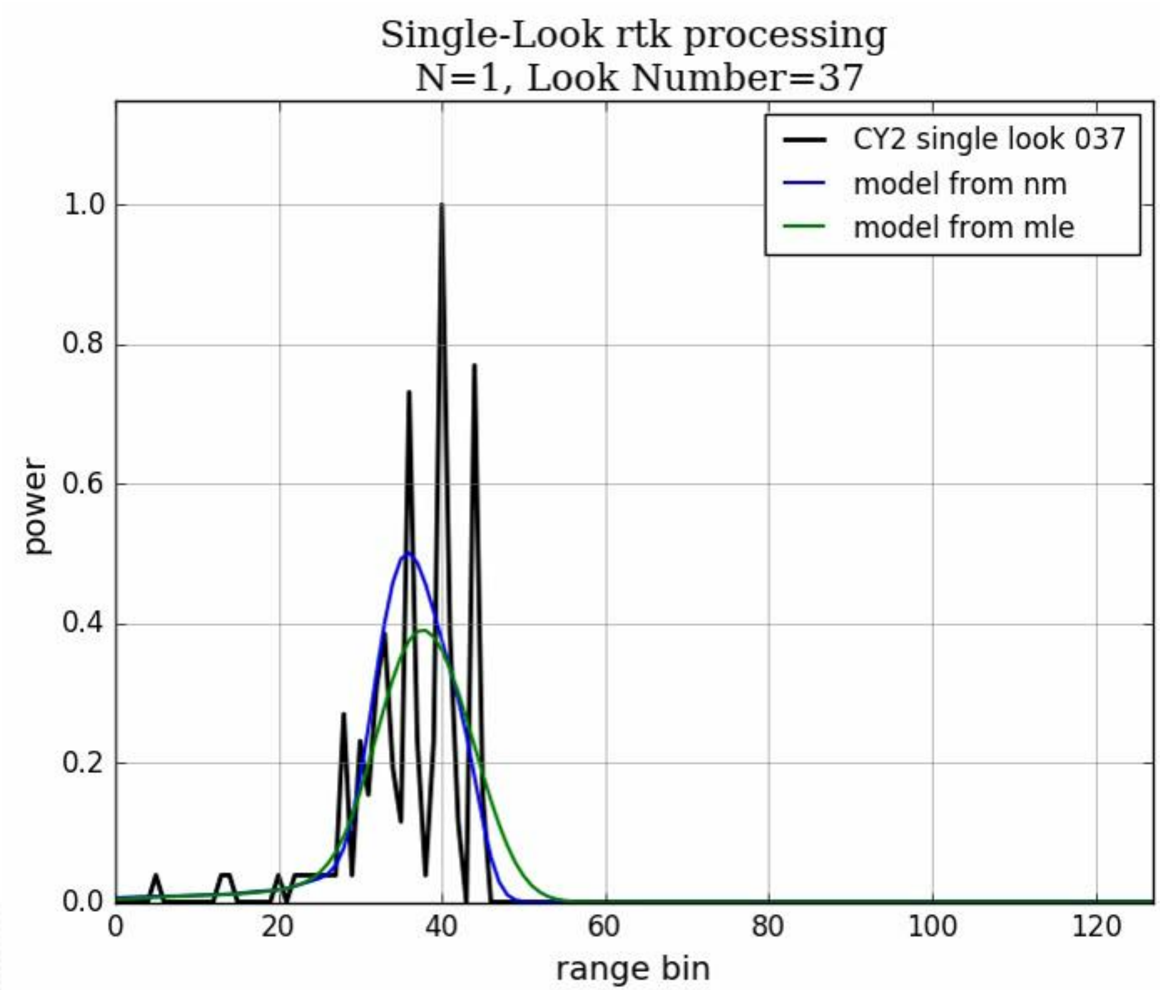
For this segment (at particular orbit altitude): DDM and stack geometries are similar in CPP v14
➔ Same migration correction in data and model

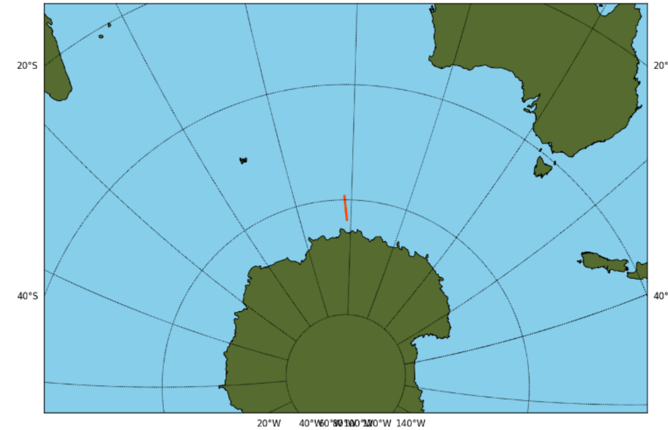






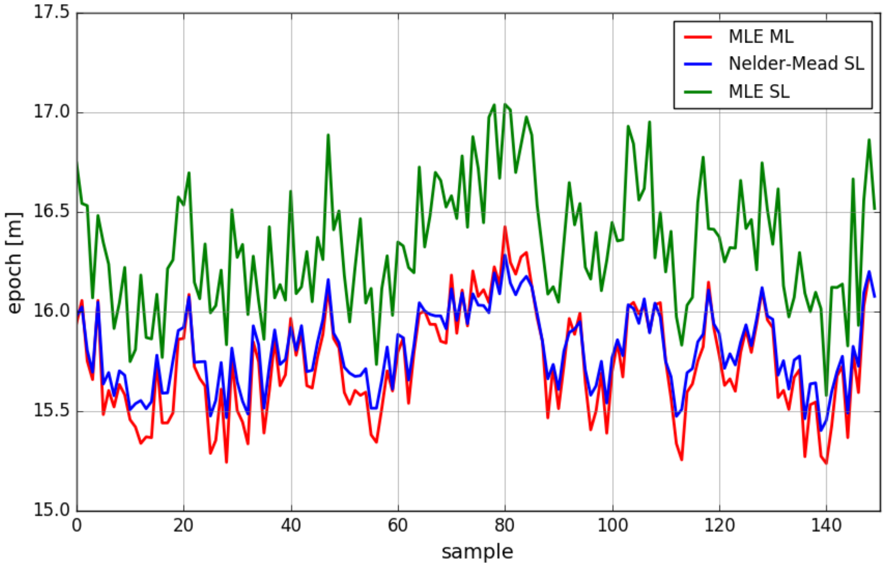
- Case study: High sea state in Pacific

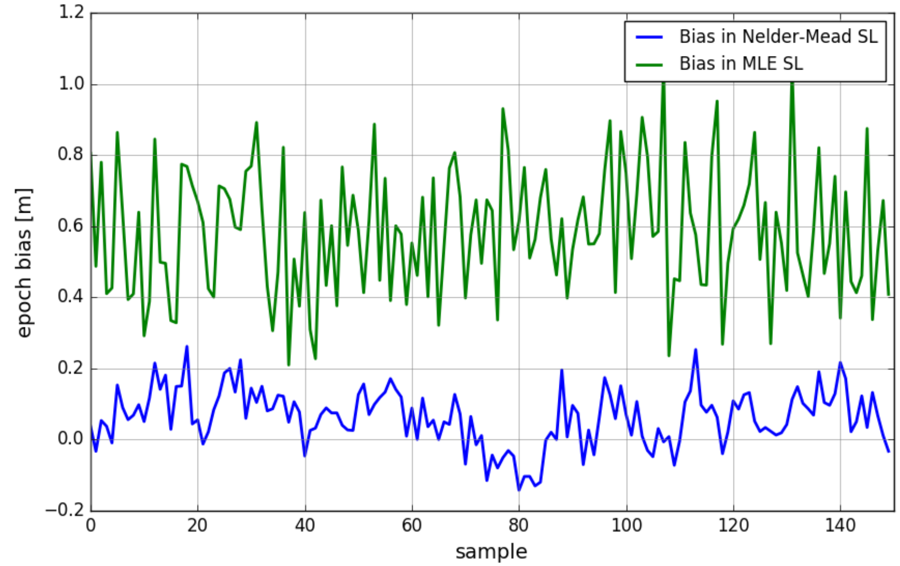


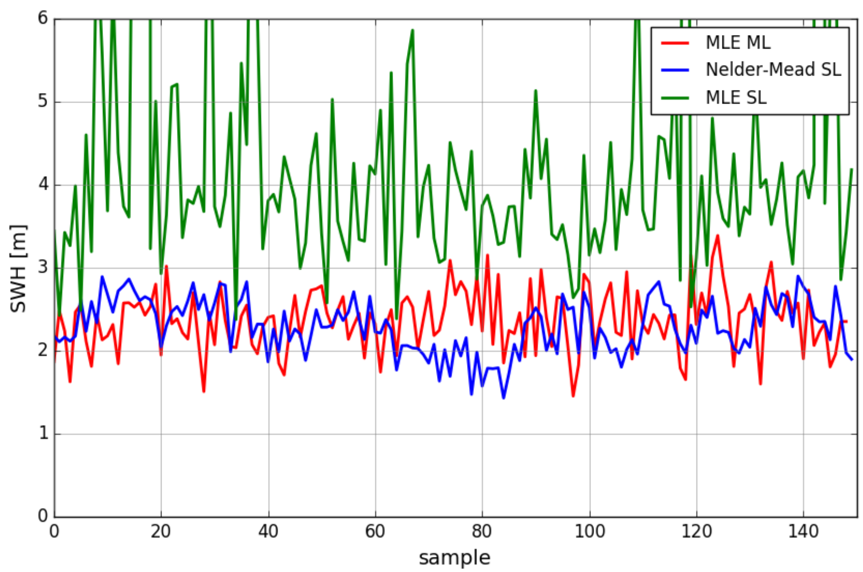


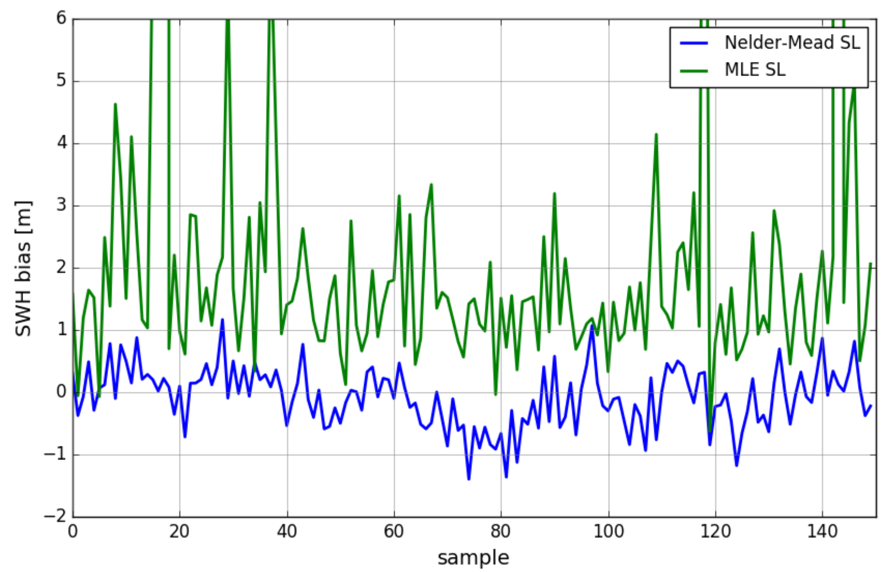
- NM models are tightly clustered around the same leading-edge position
- MLE models are a bit scattered from look to look

INDIVIDUAL DOPPLER BEAMS RETRACKER



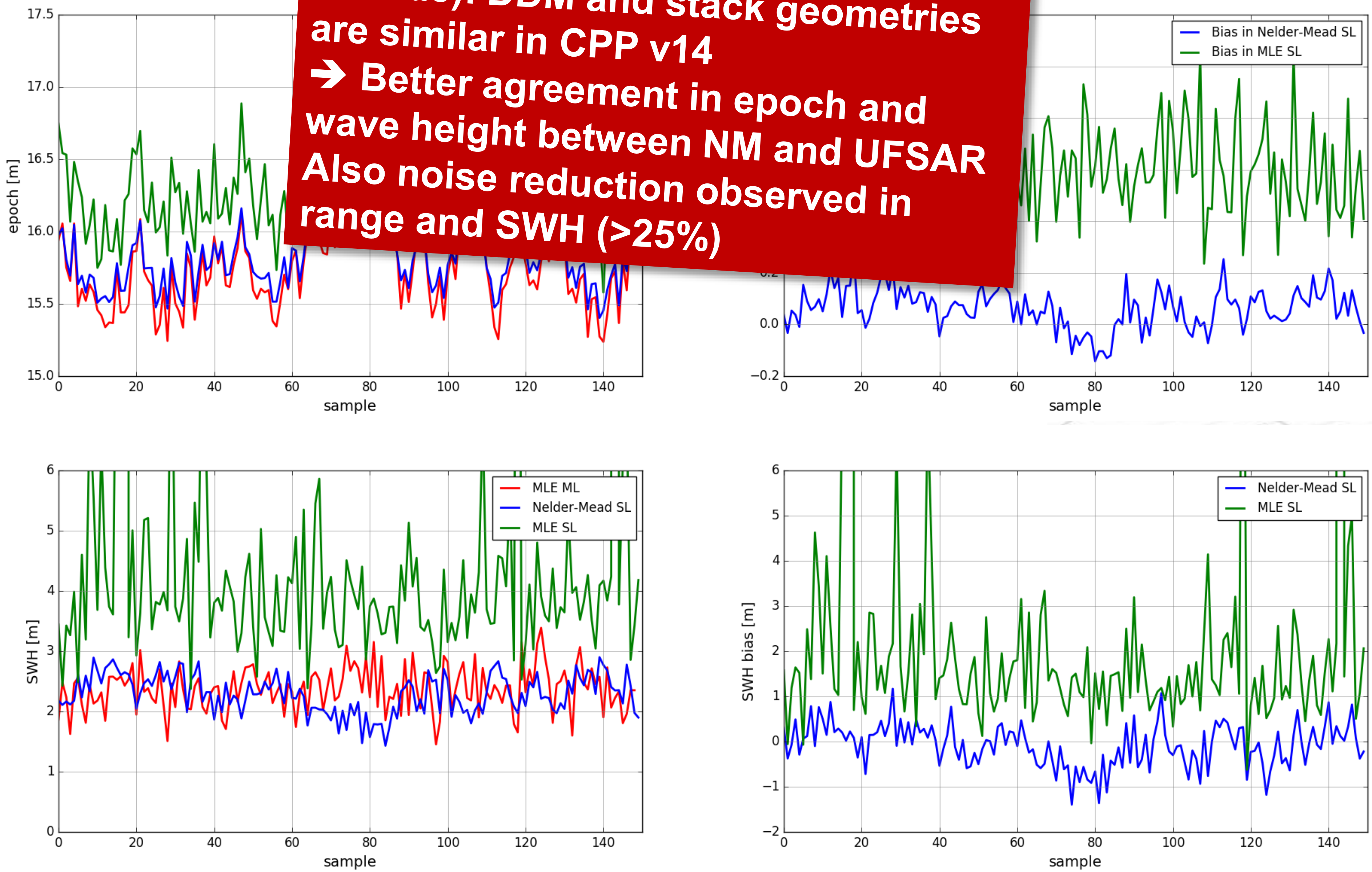




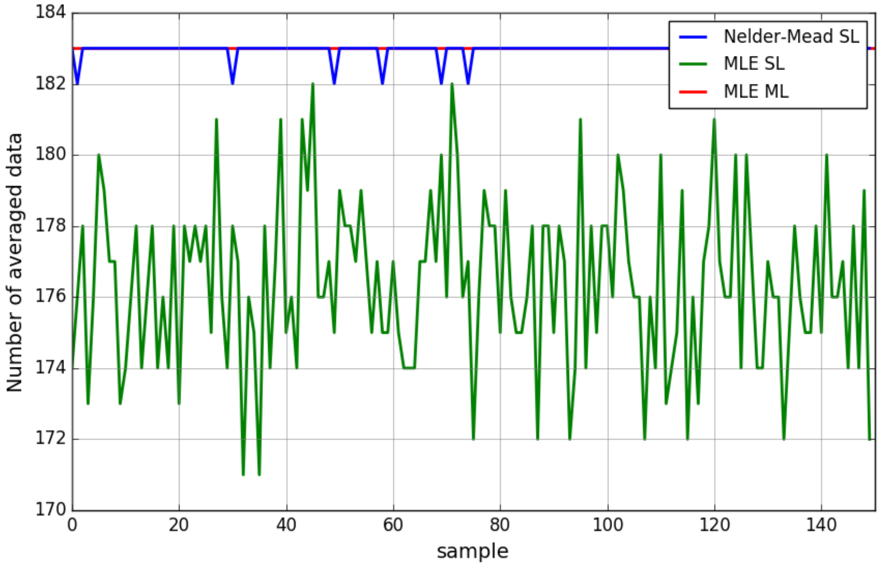


INDIVIDUAL DOPPLER BEAMS RETRACKER

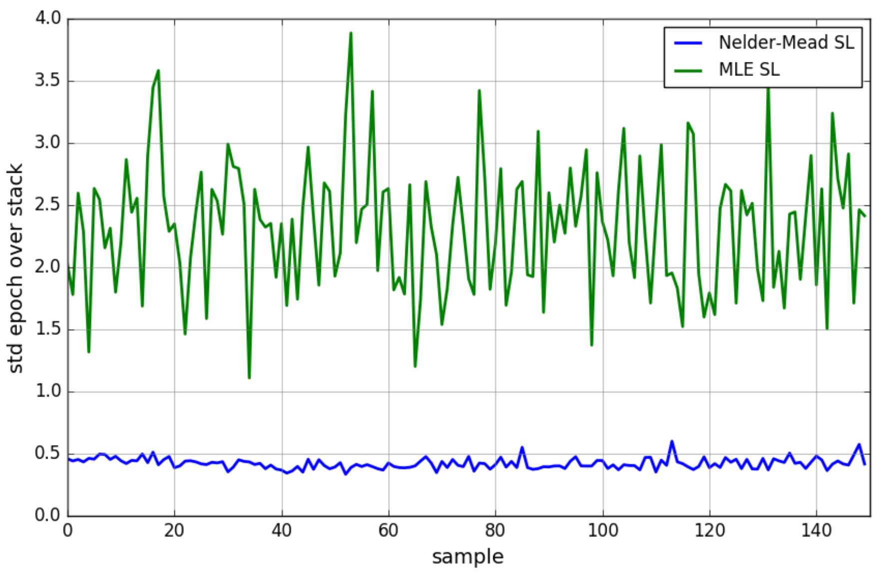
For this segment (at particular orbit altitude): DDM and stack geometries are similar in CPP v14
➔ Better agreement in epoch and wave height between NM and UFSAR
Also noise reduction observed in range and SWH (>25%)

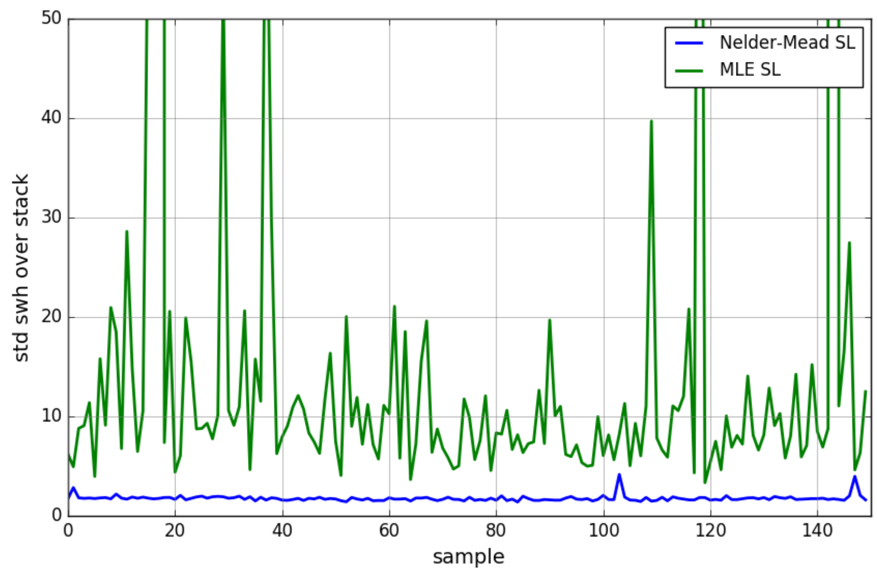


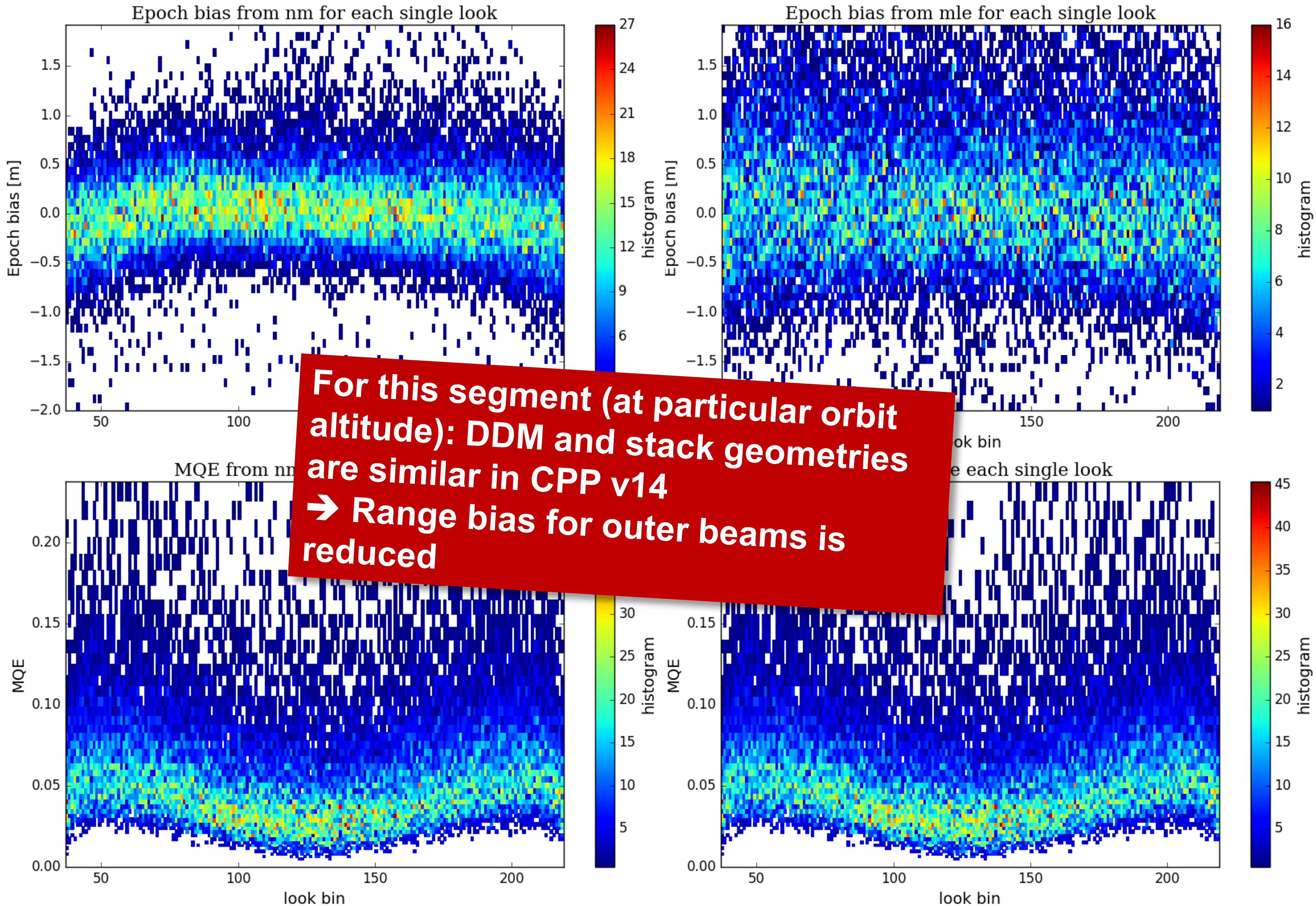
INDIVIDUAL DOPPLER BEAMS RETRACKER



- Higher number of estimates used for NM
- Much lower variance of epoch and SWH estimates in stack






Epoch bias from nm for each single look
Epoch bias [m]
histogram
Epoch bias from mle for each single look
Epoch bias [m]
histogram
look bin
MQE from nm
MQE
histogram
look bin
e each single look
MQE
histogram
look bin
For this segment (at particular orbit altitude): DDM and stack geometries are similar in CPP v14
➔ Range bias for outer beams is reduced

CONCLUSIONS & PERSPECTIVES

- The individual Doppler beams retracker is a new processing approach attempting to better exploit the full capabilities of the altimeter measurements in SAR mode [Amarouche, 2013]
- A NM optimization algorithm was used to better fit the model with highly noisy Doppler beam echoes even though processing time is increased
- It allows to better account for the exact Likelihood criterion and the speckle noise statistics (compared to conventional approaches), also requiring the use of the real impulse responses to infer consistent geophysical parameters
- This method shows very promising results:
  - Detect small structures seen by UFSAR
  - Significantly reduce the noise level of estimates
  - However this study was not able to assess the estimate accuracy with CPP v14 (need to be fully tested with S3PP or S3 IPF-like processing)
  - Also the method may be sensitive to any model errors (impact of the range walk and the vertical orbital wave velocity ?)
- New implementation and analysis need to be done to provide a more complete assessment of this method

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  SAR Altimetry Expert Group Meeting, NOC, Southampton, UK, 26-27 june 2013

- Ray C., Roca M., Martin-Puig C., Garcia A., Escola R., A new multi-look methodology for SAR altimetry, OSTST, Lake Constance, 2014

- Scagliola M., Fornari M., Tagliani N., Di Giacinto A., Speckle reduction on SAR waveforms by along-track antenna pattern compensation on stacks of single look echoes, OSTST, Lake Constance, 2014

- Dinardo S., Scagliola M., Fornari M., Benveniste J., Level-2 assessment of along-track antenna pattern compensation for SAR altimetry, OSTST, Reston, 2015

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