UAVSAR Polarimetric Calibration

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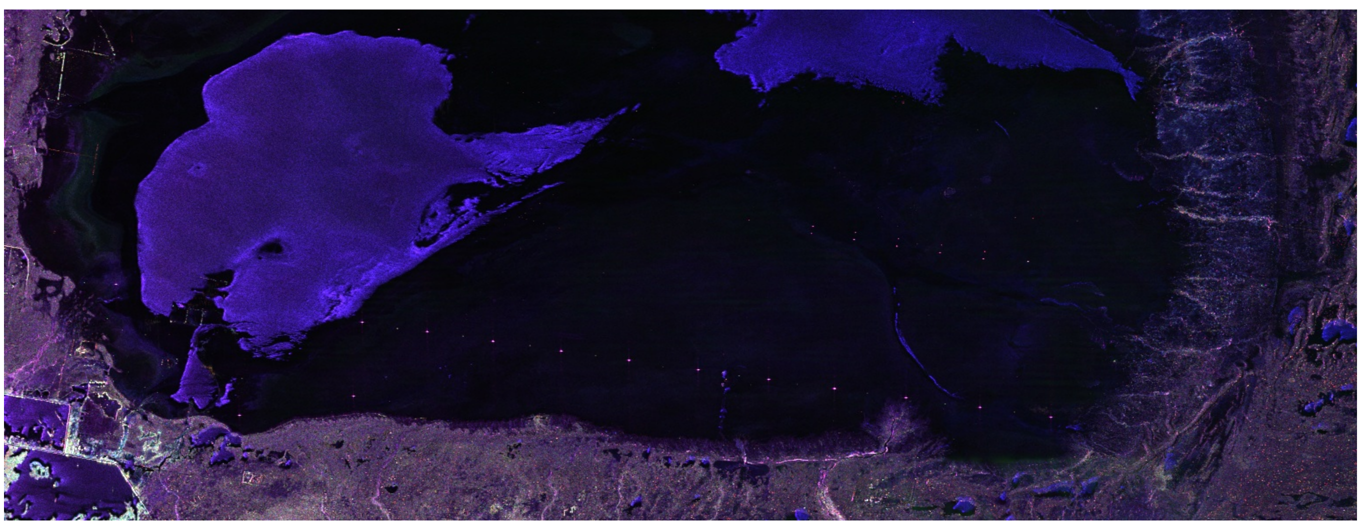
UAVSAR

- UAVSAR is a L-band airborne SAR
- Typically we have a 16 km swath.
- Electronically steer beam to greater than +/- 20 deg in azimuth.
- Designed for repeat-pass InSAR, it uses precision GPS + autopilot to fly within a 10m tube about desired flight path.
- Applications: fault-line monitoring, land subsidence studies, glacier flow, targeted polarimetric studies, …etc.

Radiometric / Phase Calibration

- Antenna pattern correction performed within the processor.
- The radiometric and phase calibration is performed within the processor via pre-computed parameters:
  - Per channel gain bias (HH,HV,VH,VV).
  - HH-VV phase bias linear fit to incidence angle.
  - HV-VH phase bias linear fit to incidence angle.
- We use corner reflectors and compare the estimated σ_0 with the measured σ_0.
  - Corner reflector array in dry lake bed in Rosamond, CA.
  - 23 corner reflectors (side length = 2.4 meters).
  - Position of CR measured very accurately with differential GPS.

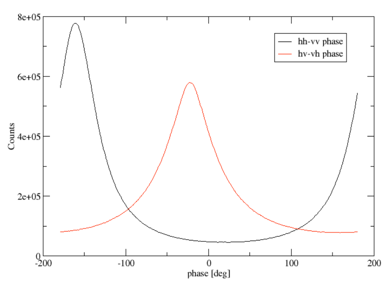


Radiometric / Phase Calibration Estimation

Gather data from multiple flights over array and compare observations to predictions.

- Predicted RCS computed using azimuth and elevation pointing angles + aircraft attitude.
- We over-sample (8x) the signal and compute the peak response for HH and VV channels.
- We compute the relative phase of the HH and VV channels (expect it to be zero).
- We compute the ratio of the HH response to the VV response (expect them to be the same).

Phase Histogram:

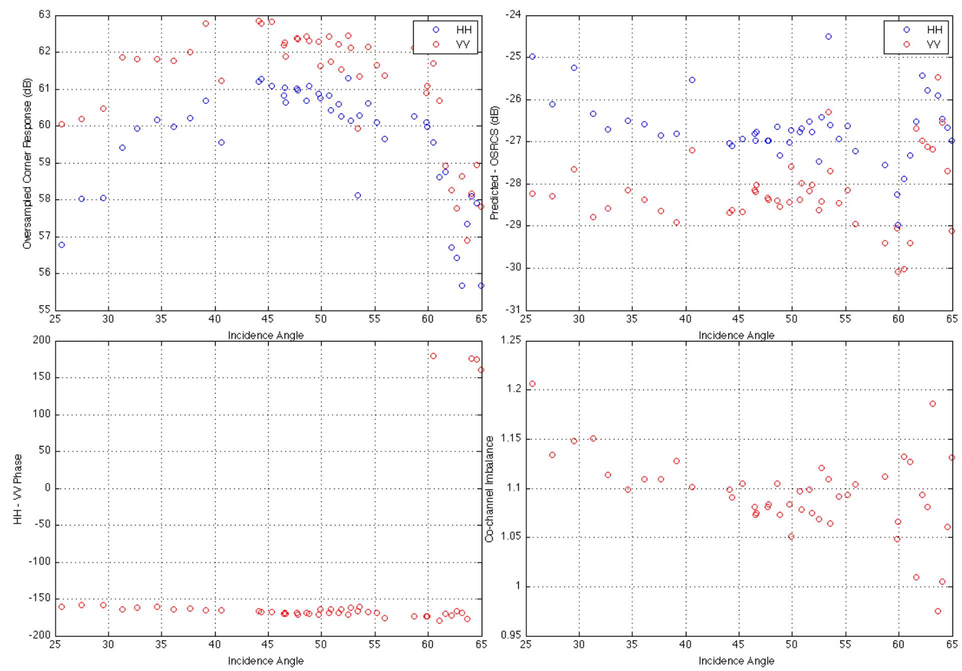


Predicted CR Response:

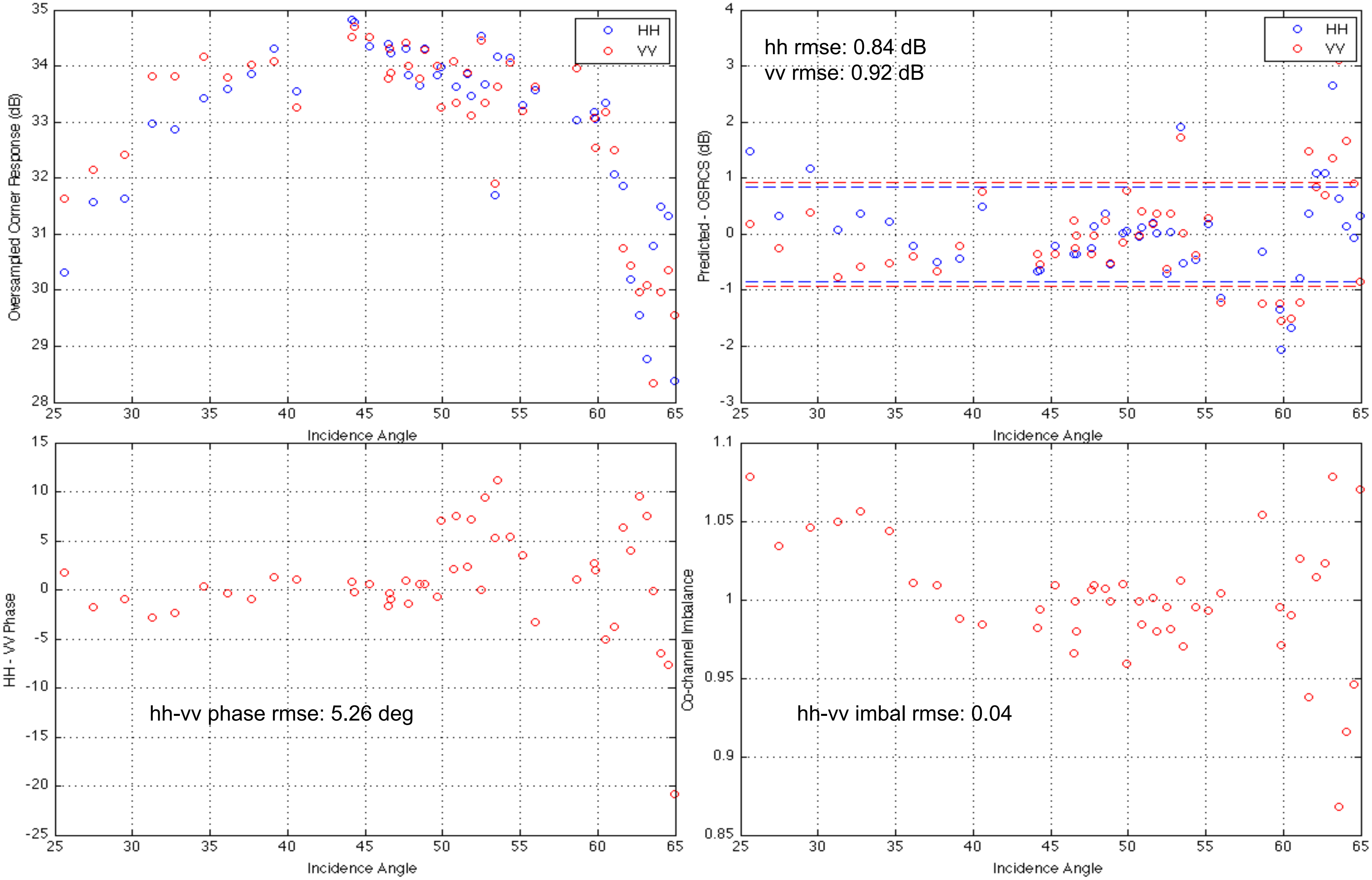
$$\sigma_{cr} = \frac{4\pi l^4}{\lambda^2}\left[\sqrt{3}\hat{\mathbf{p}}\cdot\hat{\mathbf{n}} - \frac{2}{\sqrt{3}\hat{\mathbf{p}}\cdot\hat{\mathbf{n}}}\right]^2$$

$\hat{\mathbf{p}}$:= pointing vector

$\hat{\mathbf{n}}$:= boresight of CR



Evaluation of Calibration



Cross-Talk Calibration (v. 1)

- Cross-talk calibration is performed as as stand-alone process after the processor.
  - We start with a fully general distortion model.
    - k is co-pol channel imbalance; α is the cross-pol channel imbalance.
    - u, v, w, z are the cross-talk parameters.
    - O is observed response; S is calibrated response.
    - Co-pol imbalance and radiometric cal already done => $k=1/\sqrt{\alpha}$; Y=1.
- The first version of the cross-talk calibration used Quegan's method to estimate the cross-talk parameters.
  - Estimated the covariance using a "swath" of pixels; 10 pixels wide in range; extending over the whole image.
  - Filter out pixels with large hh-hv correlation (>0.3) and very bright regions (> -5dB co-pol).
  - Computed the cross-talk parameters for that "swath"; applied a 100 pixel moving window average to cross-talk parameters in range.

Distortion Model:

$$\begin{pmatrix} O_{hh} \\ O_{vh} \\ O_{hv} \\ O_{vv} \end{pmatrix} = Y \begin{pmatrix} 1 & w & v & vw \\ u & 1 & uv & v \\ z & wz & 1 & w \\ uz & z & u & 1 \end{pmatrix} \begin{pmatrix} \alpha & 0 & 0 & 0 \\ 0 & \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} k^2 & 0 & 0 & 0 \\ 0 & k & 0 & 0 \\ 0 & 0 & k & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_{hh} \\ S_{vh} \\ S_{hv} \\ S_{vv} \end{pmatrix} + \begin{pmatrix} N_{hh} \\ N_{vh} \\ N_{hv} \\ N_{vv} \end{pmatrix}$$

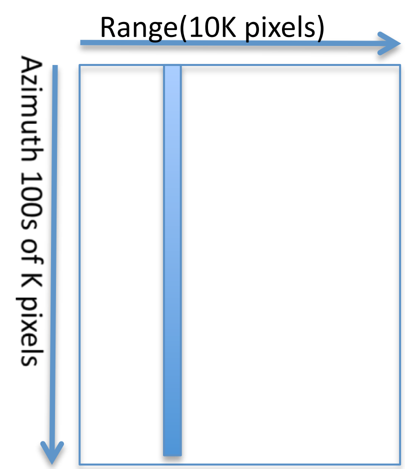
u,v,w,z - Cross - Talk Parameters

k - Co - pol channel imbalance

α - Cross - pol channel imbalance

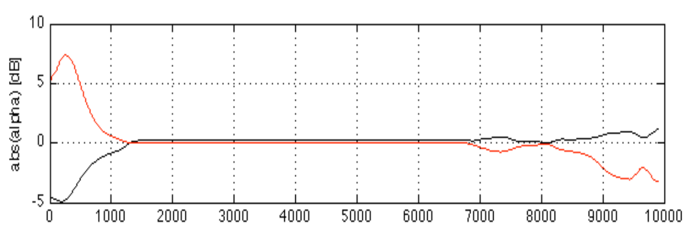
Quegan Model
Covariance matrix:

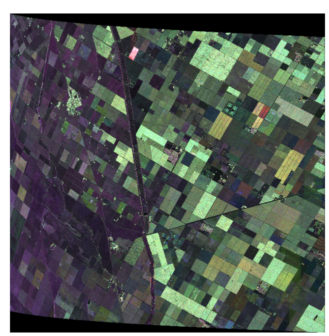
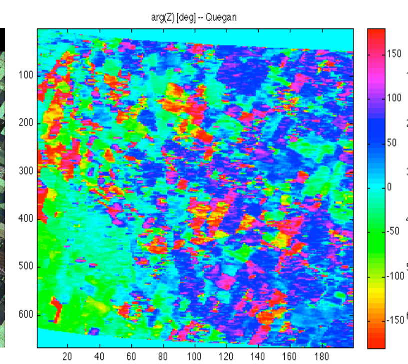
$$\begin{pmatrix} C_{hhhh} & 0 & 0 & C_{hhvv} \\ 0 & \beta & \beta' & 0 \\ 0 & \beta' & \beta & 0 \\ C^{*}_{hhvv} & 0 & 0 & C_{vvvv} \end{pmatrix}$$

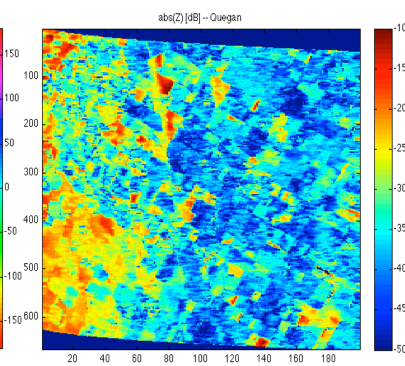


Issues with v. 1

- Cross-talk estimation fails for some data, ocean / island lines in particular.
  - Typically we would see estimates of residual α that were worse than the pre-calibration estimates in some portions of the image. (abs(α) > 6 dB in some places!)
  - This seemed to be due to the large regions of ocean being included in the computation of the covariance matrix. (even though we filter out pixels with significant co-cross correlations).
- Cross-talk removal did not seem to be very successful.
  - Estimates of residual cross-talk were only marginally less than the initial cross-talk estimates.
  - Typically estimate ~ -15 dB before cross-talk calibration and ~ -20 dB after.
- To alleviate the 1st problem we attempted to use a sliding window to compute the covariance.
  - Cross-talk parameters now a function of range and azimuth.
  - However, then we could distinctly see structure in the resulting estimates of the cross-talk parameters.



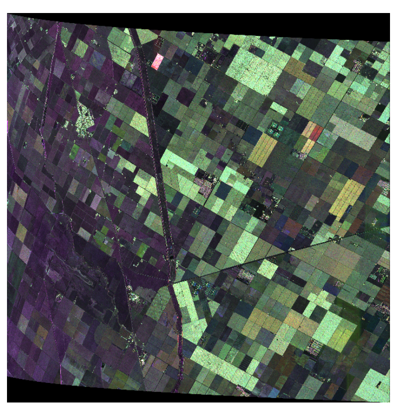


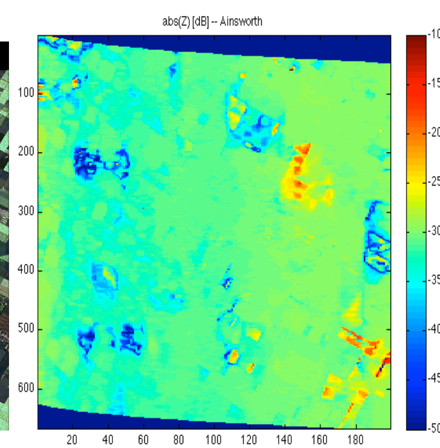
Cross-Talk Calibration (v. 2)

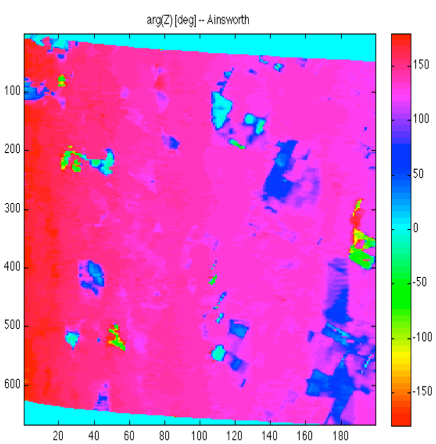
- Motivated by these issues, we explored the Ainsworth method of computing the cross-talk parameters.
  - The major difference is in the model covariance matrix that is assumed.
  - Ainsworth's method explicitly allows for co-cross polar correlations (the A and B terms).
- We compute the covariance (C) matrix in a sliding window.
  - Use Ainsworth et al method to compute (α,u,v,w,z) parameters.
  - Filter out pixels with large hh-hv correlation (>0.5) and very bright regions (> -5dB co-pol).
  - Use a very large window to improve statistics (201*201 > 40,000 pixels in window).
  - Ainsworth's method performs much better than Quegan's method.
    - Much less residual cross-talk after calibration.
    - Less unphysical dependence of cross-talk parameters on target type.
- Estimating cross-talk using a moving window is much more CPU intensive; it takes 5 hours to process 10^5 lines.
  - Made a process-parallel (no MPI, no OpenMP) implementation via domain decomposition.
  - Scales up to IO limitations. (we use 16 concurrent processes, each operating on a chunk of the total image).

Ainsworth Model Covariance matrix:

$$\begin{pmatrix} C_{hhhh} & A^* & A^* & C_{hhvv} \\ A & \beta & \beta' & B \\ A & \beta' & \beta & B \\ C^*_{hhvv} & B^* & B^* & C_{vvvv} \end{pmatrix}$$







Ainsworth Parameter Estimation

- Inputs: C – observed covariance matrix in window
- Outputs: (α,u,v,w,z) the cross-talk parameters.
- Algorithm:
  - Estimate α from C
  - Set (u=0; v=0; w=0; z=0; iter=1;)
  - Do while(iter < 12 && diff < TOL)
    - Construct calibration matrix E from (α,u,v,w,z)
    - Construct C_try:=E C E*ᵀ
    - Estimate (A,B) from C_try
    - Estimate (α',u',v',w',z') from C_try and A, B
    - Update parameters:
      - α = α*α'
      - u=u+u'/√α; v=v+v'/√α
      - w=w+w'√α; z=z+z'√α
    - Diff=max(cabs(u'),cabs(v'),cabs(w'),cabs(z'))
    - Iter=iter+1

Estimation of α, A, B:

$$\alpha = \frac{C_{VHHV}}{|C_{VHHV}|}\sqrt{\frac{|C_{VHVH}|}{|C_{HVHV}|}} \qquad A = \frac{C_{HVHH} + C_{VHHH}}{2} \qquad B = \frac{C_{HVVV} + C_{VHVV}}{2}$$

Calibration Matrix:

$$E = \frac{1}{(uv-1)(vz-1)}\begin{pmatrix} 1 & -w & -v & vw \\ -u/\sqrt{\alpha} & 1/\sqrt{\alpha} & uv/\sqrt{\alpha} & -v/\sqrt{\alpha} \\ -z\sqrt{\alpha} & wz\sqrt{\alpha} & \sqrt{\alpha} & -w\sqrt{\alpha} \\ uz & -z & -u & 1 \end{pmatrix}$$

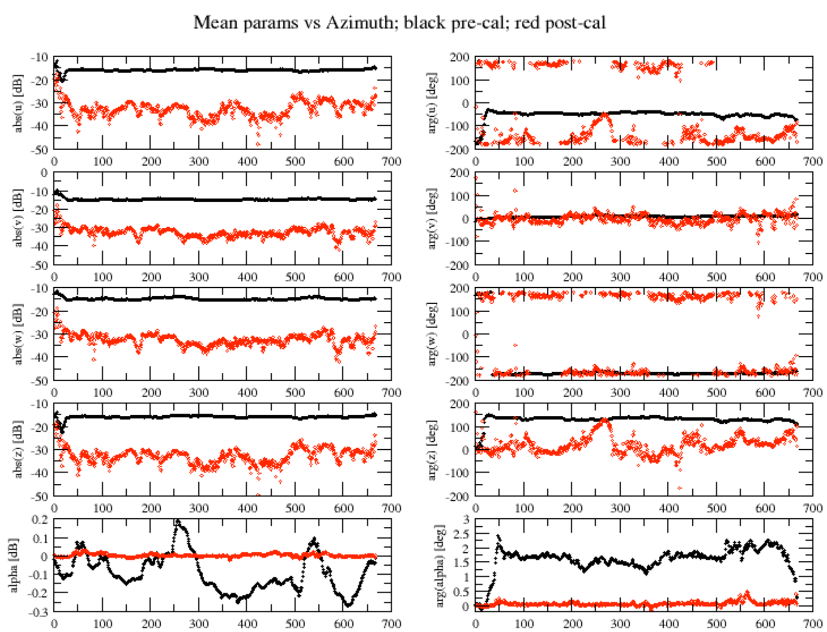
Solve linear system of equations for u, v, w, z:

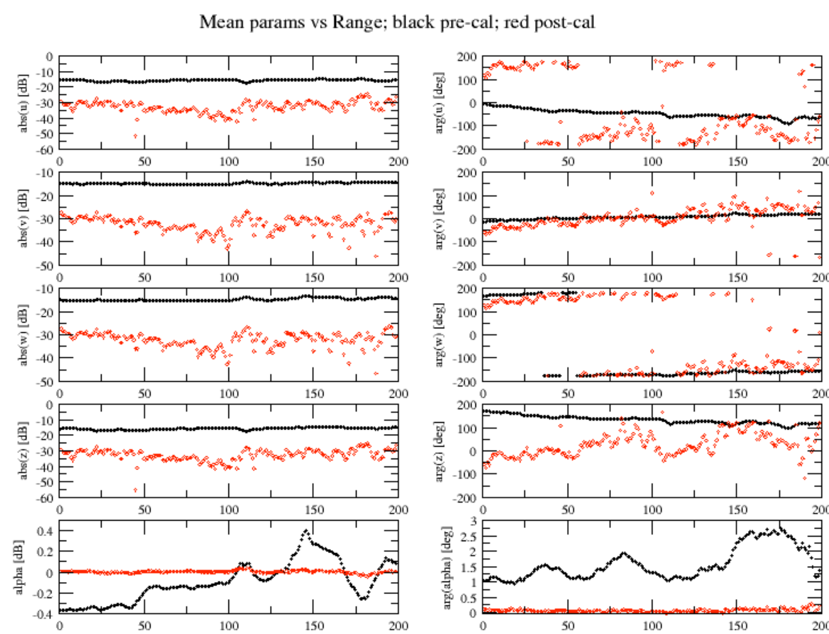
$$\begin{pmatrix} 0 & C_{HVHV} & C_{VVHH} + C_{HVVH} & C_{HHHH} \\ C_{HHHH} & C_{VVHH} + C_{VHHV} & C_{VHVH} & 0 \\ C_{HVHV} & 0 & C_{VVVV} & C_{HHVV} + C_{HVVH} \\ C_{HHVV} + C_{VHHV} & C_{VVVV} & 0 & C_{VHVH} \end{pmatrix}\begin{pmatrix} u \\ v \\ w \\ z \end{pmatrix} = \begin{pmatrix} C_{HVHH} - A \\ C_{VHHH} - A \\ C_{HVVV} - B \\ C_{VHVV} - B \end{pmatrix}$$

Cross-talk Removal Performance Ainsworth (window method)

- Before cross-talk calibration:
  - We typically estimate cross-talk *parameters* on the order of -15 dB.
  - Some variation in the cross-pol channel imbalance is evident.
- After cross-talk calibration:
  - We see cross-talk *parameters* that are -25 to -40 dB depending on target type.
  - α parameter is nearly 1, and has almost no imaginary part.

```
Before xtalk calibration:
Mean Alpha [dB,deg]:    -0.099307    1.696073
    Mean U [dB,deg]:   -16.007141  -48.953918
    Mean V [dB,deg]:   -14.943415    6.774332
    Mean W [dB,deg]:   -14.935524 -171.495956
    Mean Z [dB,deg]:   -15.975571  131.579514

After xtalk calibration:
Mean Alpha [dB,deg]:     0.002567    0.069257
    Mean U [dB,deg]:   -32.918896 -162.805344
    Mean V [dB,deg]:   -32.496246   -0.088953
    Mean W [dB,deg]:   -32.422440 -179.125076
    Mean Z [dB,deg]:   -33.061737   19.846634
```

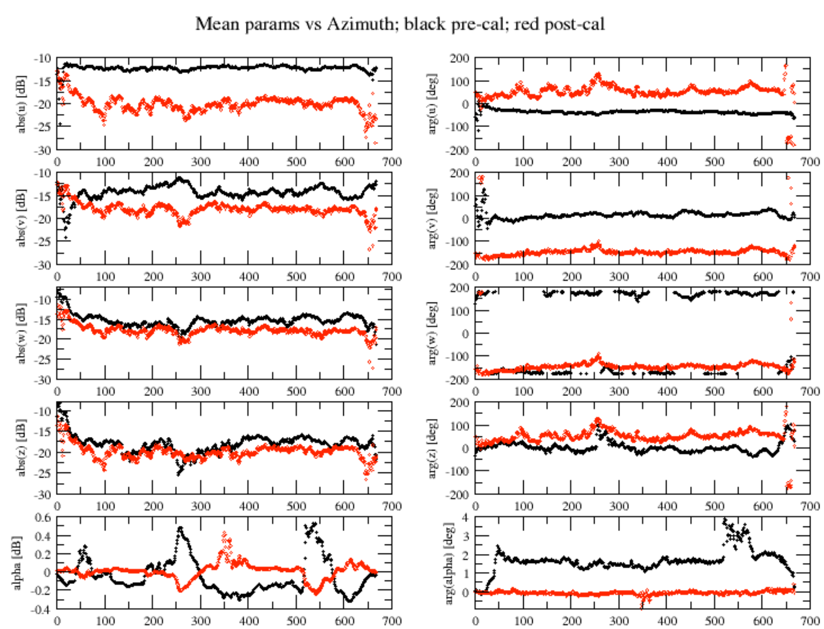


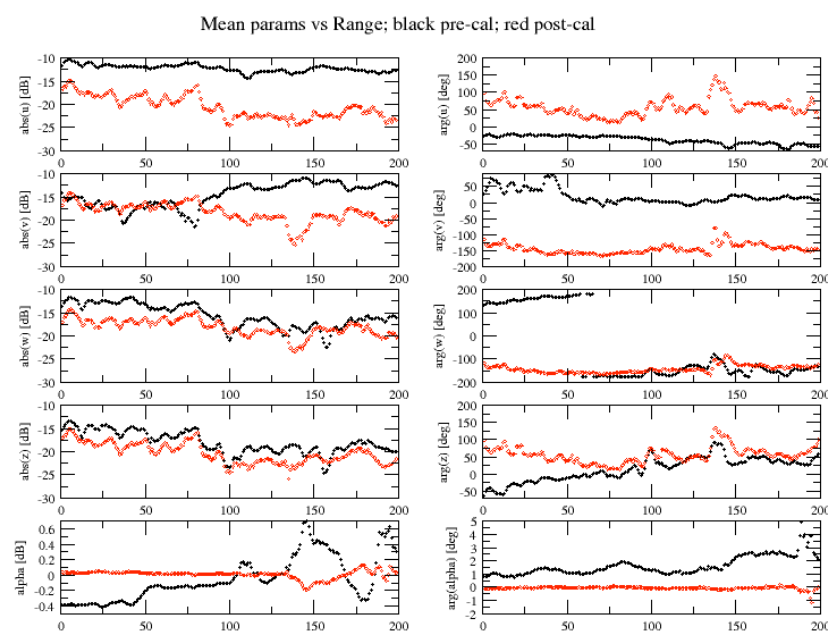


Cross-talk Removal Performance Quegan (window method)

- Before cross-talk calibration:
  - We typically estimate cross-talk *parameters* on the order of -15 dB.
  - Some variation in the cross-pol channel imbalance is evident.
- After cross-talk calibration:
  - Generally estimate residual cross-talk parameters ~ -20 dB
  - α parameter still shows some fluctuations, however the phase is nearly zero.

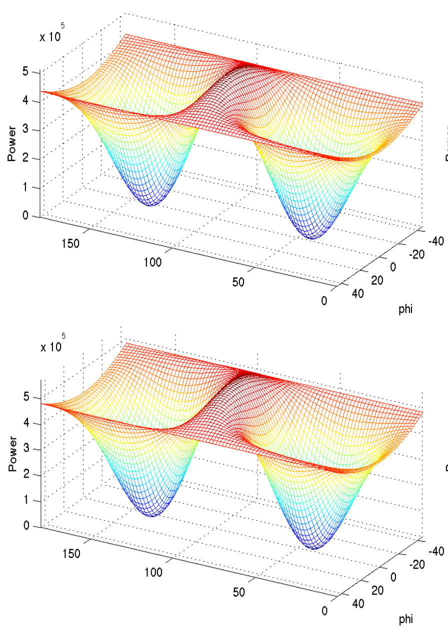
```
Before xtalk calibration:
Mean Alpha [dB,deg]:    -0.045941     1.758549
    Mean U [dB,deg]:   -12.287176   -37.337124
    Mean V [dB,deg]:   -14.176173    13.322126
    Mean W [dB,deg]:   -15.490755   178.854462
    Mean Z [dB,deg]:   -18.194115    -2.522836

After xtalk calibration:
Mean Alpha [dB,deg]:     0.009207    -0.065000
    Mean U [dB,deg]:   -20.248520    52.851189
    Mean V [dB,deg]:   -18.019426  -147.475693
    Mean W [dB,deg]:   -17.890226  -146.620285
    Mean Z [dB,deg]:   -20.114719    52.107059
```



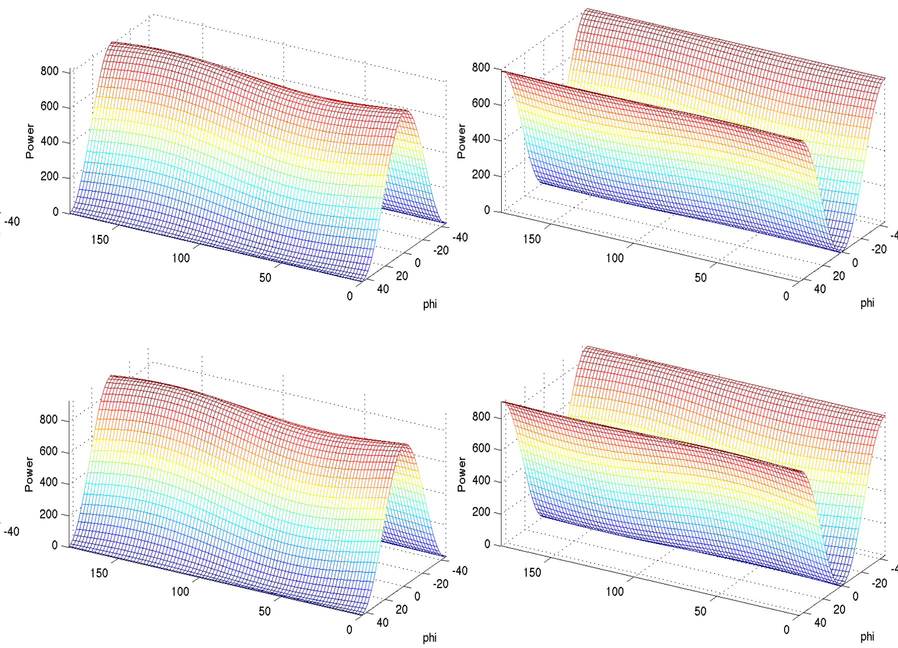


Polarization Signatures

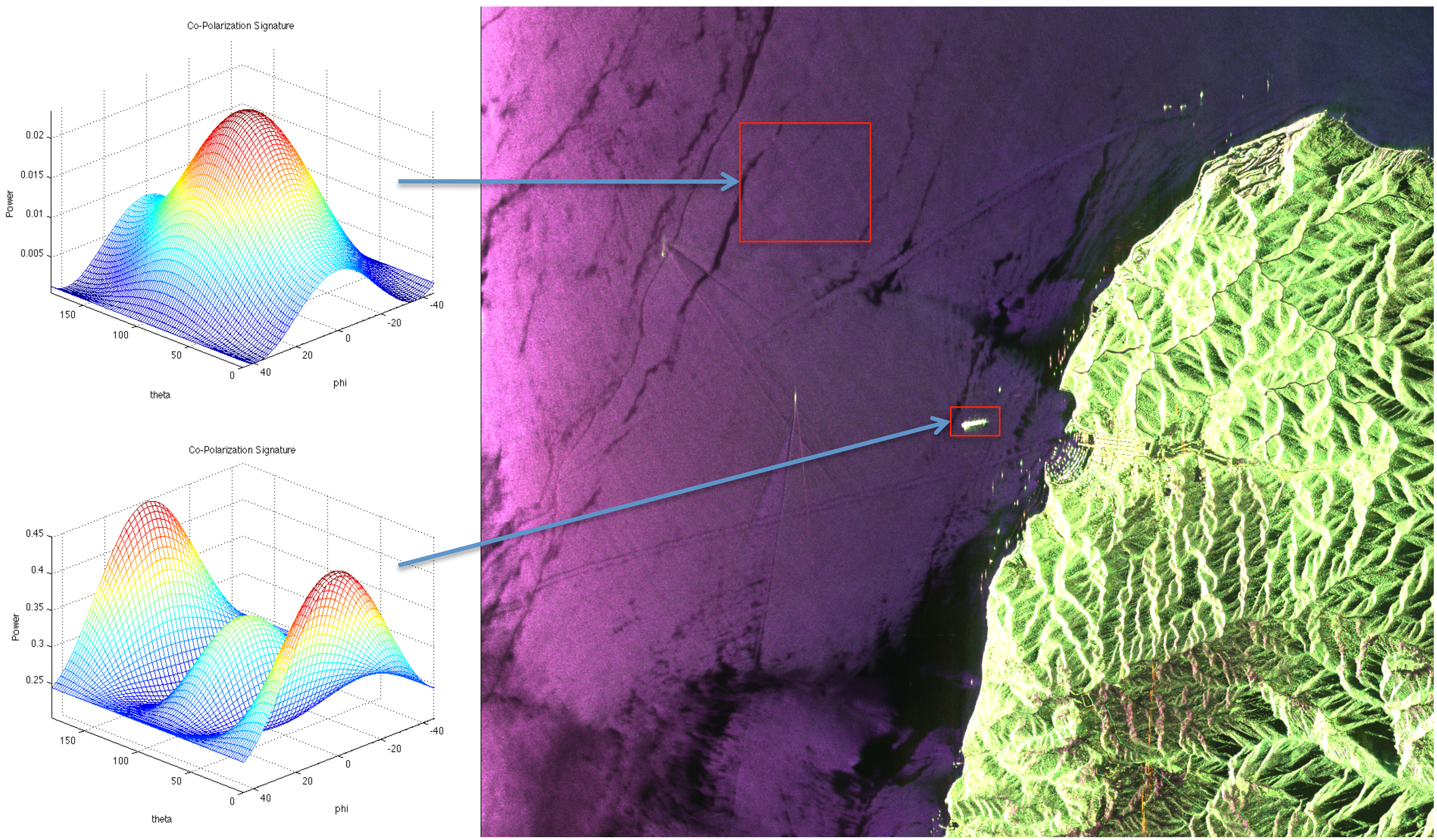
Trihedrals No Calibration:



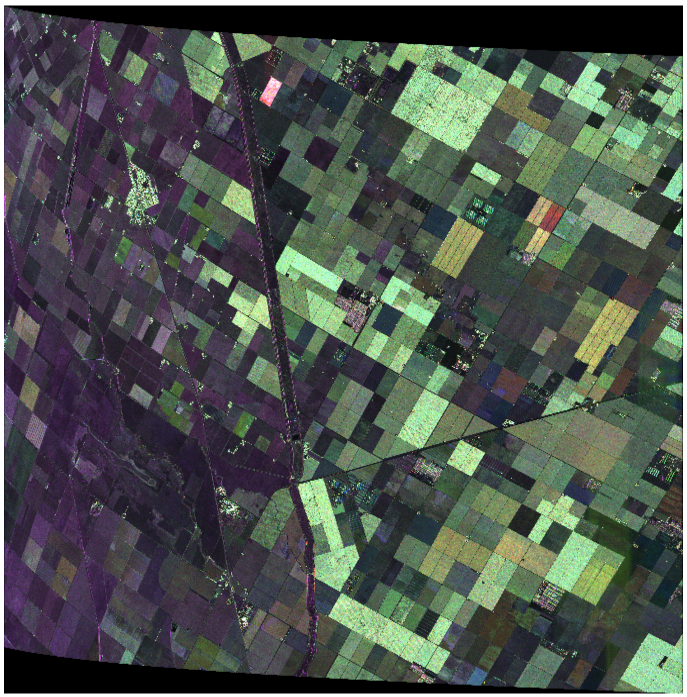
Trihedrals After Calibration:

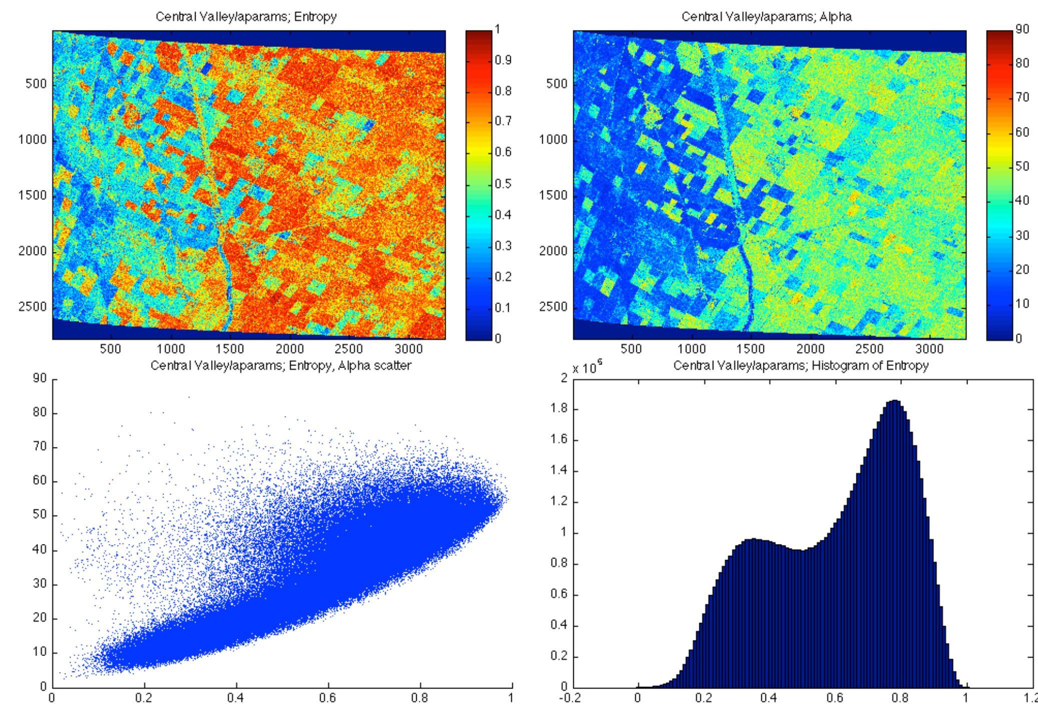


Channel Islands

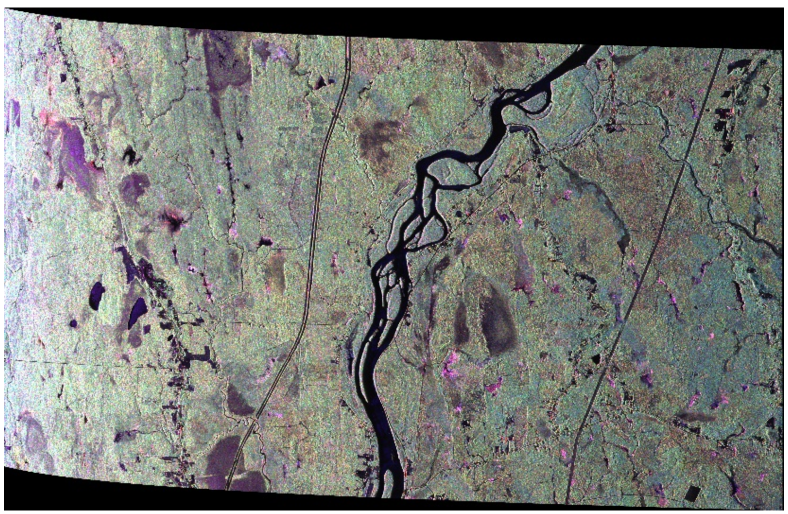


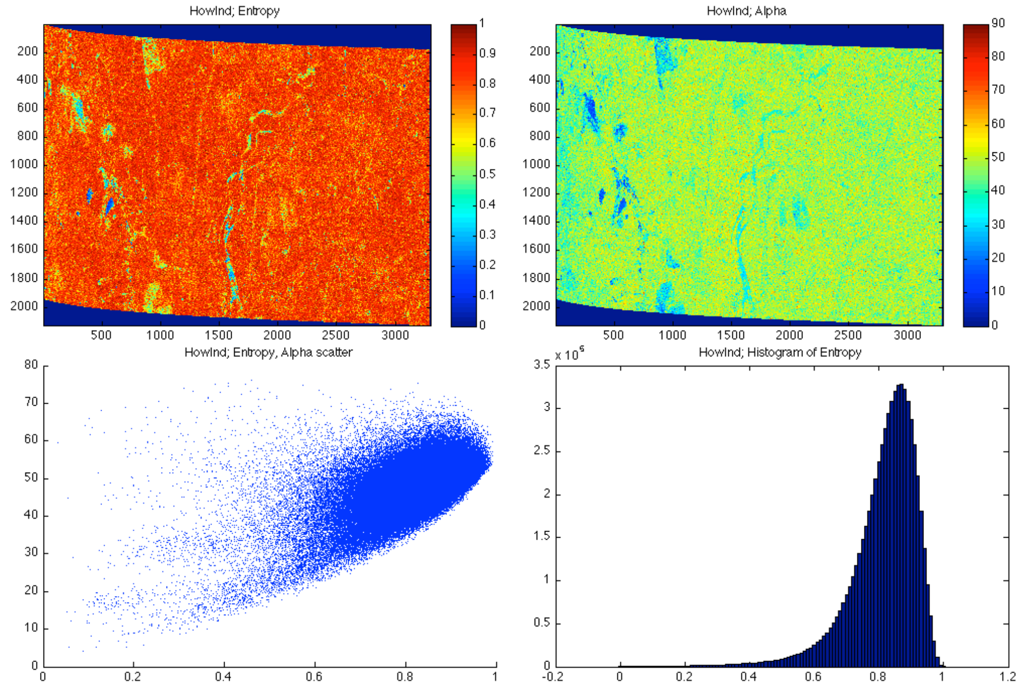
Entropy/Alpha -- Central Valley



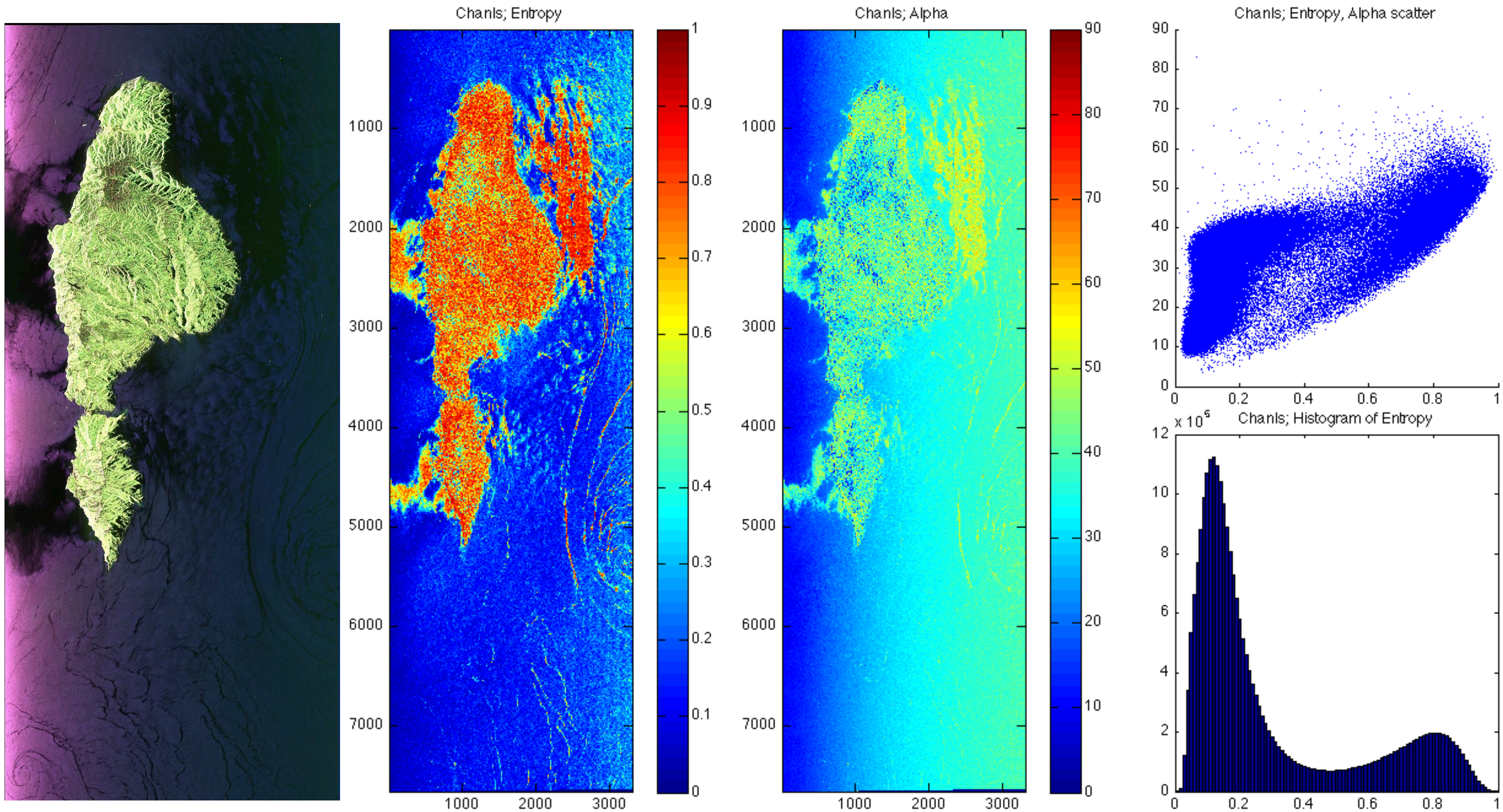


Entropy/Alpha – Howland Forest





Entropy/Alpha -- Channel Islands



Conclusion

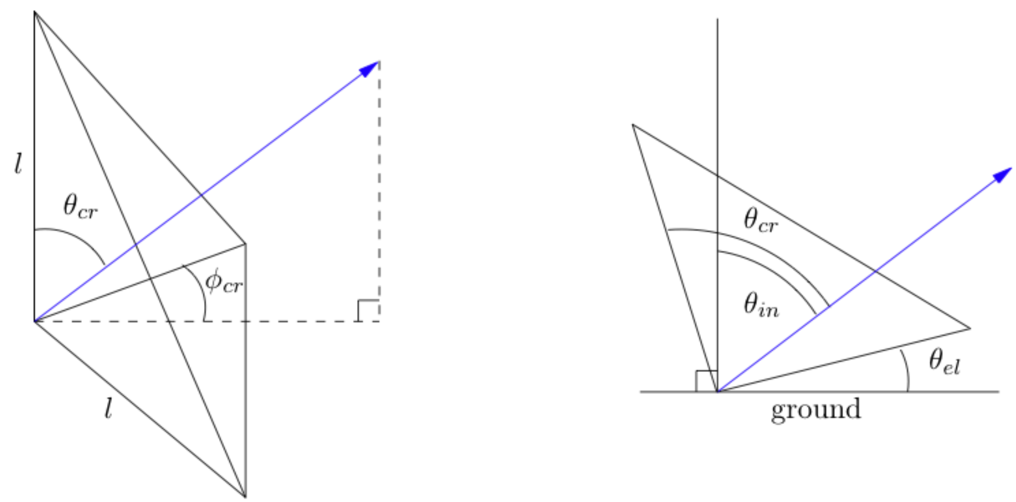
- We have shown that UAVSAR is a well-calibrated airborne SAR.
  - Radiometric calibration within 1 dB.
  - Phase calibration within 6 deg.
  - Cross-talk *power* about -30 dB *before* cross-talk correction.
- We have explored various cross-talk removal algorithms.
  - We use a sliding window to compute the covariance matrix.
  - We find that the method of Quegan gives cross-talk estimates that show significant “structure” from the target.
  - We find that the method of Ainsworth gives more consistent cross-talk estimates that Quegan.

Extra Slides

Predicted Corner Response

$$\sigma_{cr} = \frac{4\pi l^4}{\lambda^2}\left[\cos\theta_{cr} + \sin\theta_{cr}\left(\sin\phi_{cr} + \cos\phi_{cr}\right) - \frac{2}{\cos\theta_{cr} + \sin\theta_{cr}\left(\sin\phi_{cr} + \cos\phi_{cr}\right)}\right]^2$$

Figure 6: Diagrams of a triheaderal corner reflector where the vector (blue) points towards the UAVSAR aircraft imaging pod. The incidence angle relative to the corner reflector, $\theta_{cr} := \theta_{in} + \theta_{el}$, where θ_{in} is the incidence angle, and θ_{el} is the elevation of the corner reflector relative to the ground. ϕ_{cr} is the azimuth angle relative to one of the vertical sides of the corner reflector. The maximum response of the corner reflector is for $\phi_{cr} = 45\,\text{deg}$ and $\theta_{cr} = 54.736\,\text{deg}$.



Cross-Talk

Distortion Model:

$$\begin{pmatrix} O_{hh} \\ O_{vh} \\ O_{hv} \\ O_{vv} \end{pmatrix} = Y \begin{pmatrix} 1 & w & v & vw \\ u & 1 & uv & v \\ z & wz & 1 & w \\ uz & z & u & 1 \end{pmatrix} \begin{pmatrix} \alpha & 0 & 0 & 0 \\ 0 & \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} k^2 & 0 & 0 & 0 \\ 0 & k & 0 & 0 \\ 0 & 0 & k & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_{hh} \\ S_{vh} \\ S_{hv} \\ S_{vv} \end{pmatrix} + \begin{pmatrix} N_{hh} \\ N_{vh} \\ N_{hv} \\ N_{vv} \end{pmatrix}$$

u,v,w,z - Cross-Talk Parameters

k - Co-pol channel imbalance

α - Cross-pol channel imbalance

With k=1/√α; Y=1:

$$\begin{pmatrix} O_{hh} \\ O_{vh} \\ O_{hv} \\ O_{vv} \end{pmatrix} = D \begin{pmatrix} S_{hh} \\ S_{vh} \\ S_{hv} \\ S_{vv} \end{pmatrix} \qquad D := \begin{pmatrix} 1 & w\sqrt{\alpha} & v/\sqrt{\alpha} & vw \\ u & \sqrt{\alpha} & uv/\sqrt{\alpha} & v \\ z & wz\sqrt{\alpha} & 1/\sqrt{\alpha} & w \\ uz & z\sqrt{\alpha} & u/\sqrt{\alpha} & 1 \end{pmatrix}$$

Equivalent formulation:

$$\begin{pmatrix} O_{hh} & O_{hv} \\ O_{vh} & O_{vv} \end{pmatrix} = Y \begin{pmatrix} k & w \\ ku & 1 \end{pmatrix} \begin{pmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{pmatrix} \begin{pmatrix} \alpha k & \alpha kz \\ v & 1 \end{pmatrix} + \begin{pmatrix} N_{hh} & N_{hv} \\ N_{vh} & N_{vv} \end{pmatrix}$$

Calibration Matrix:

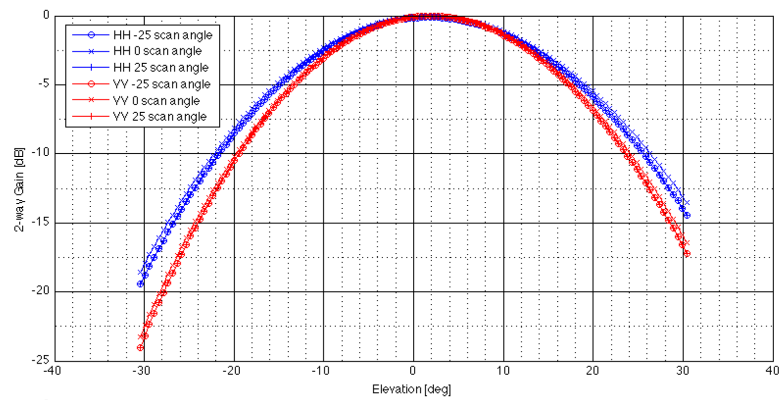
$$D^{-1} = \frac{1}{(uv-1)(vz-1)} \begin{pmatrix} 1 & -w & -v & vw \\ -u/\sqrt{\alpha} & 1/\sqrt{\alpha} & uv/\sqrt{\alpha} & -v/\sqrt{\alpha} \\ -z\sqrt{\alpha} & wz\sqrt{\alpha} & \sqrt{\alpha} & -w\sqrt{\alpha} \\ uz & -z & -u & 1 \end{pmatrix}$$

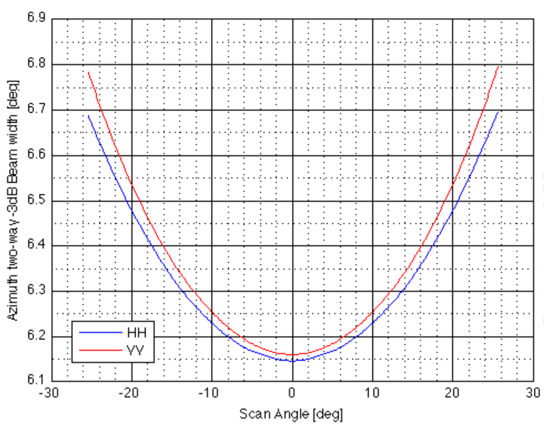
- References:

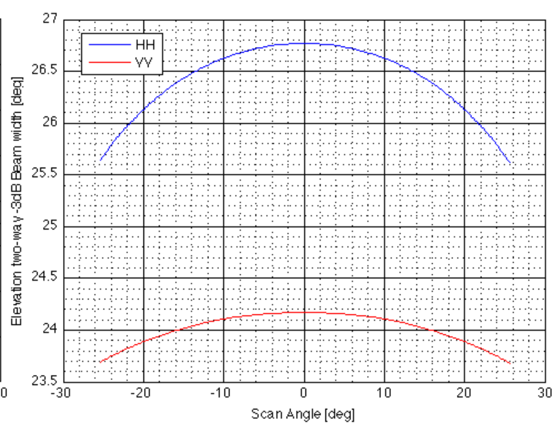
  - T.L. Ainsworth, L. Ferro-Famil, and Jong-Sen Lee. Orientation angle preserving a posteriori polari- metric sar calibration. IEEE Transactions on Geoscience and Remote Sensing, 44(4):994–1003, April 2006.
  - S. Quegan. A unified algorithm for phase and cross-talk calibration of polarimetric data-theory and observations. IEEE Transactions on Geoscience and Remote Sensing, 32(1):89–99, Jan 1994.

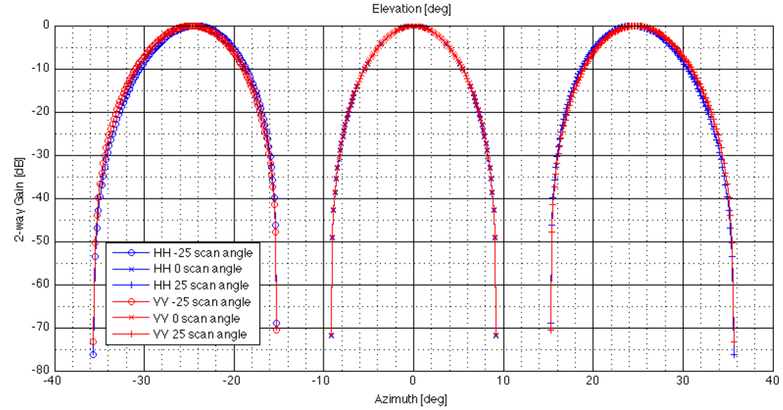
Antenna Pattern

- UAVSAR uses an electronically steered array
- 12 elements in the azimuth direction; 4 in elevation.

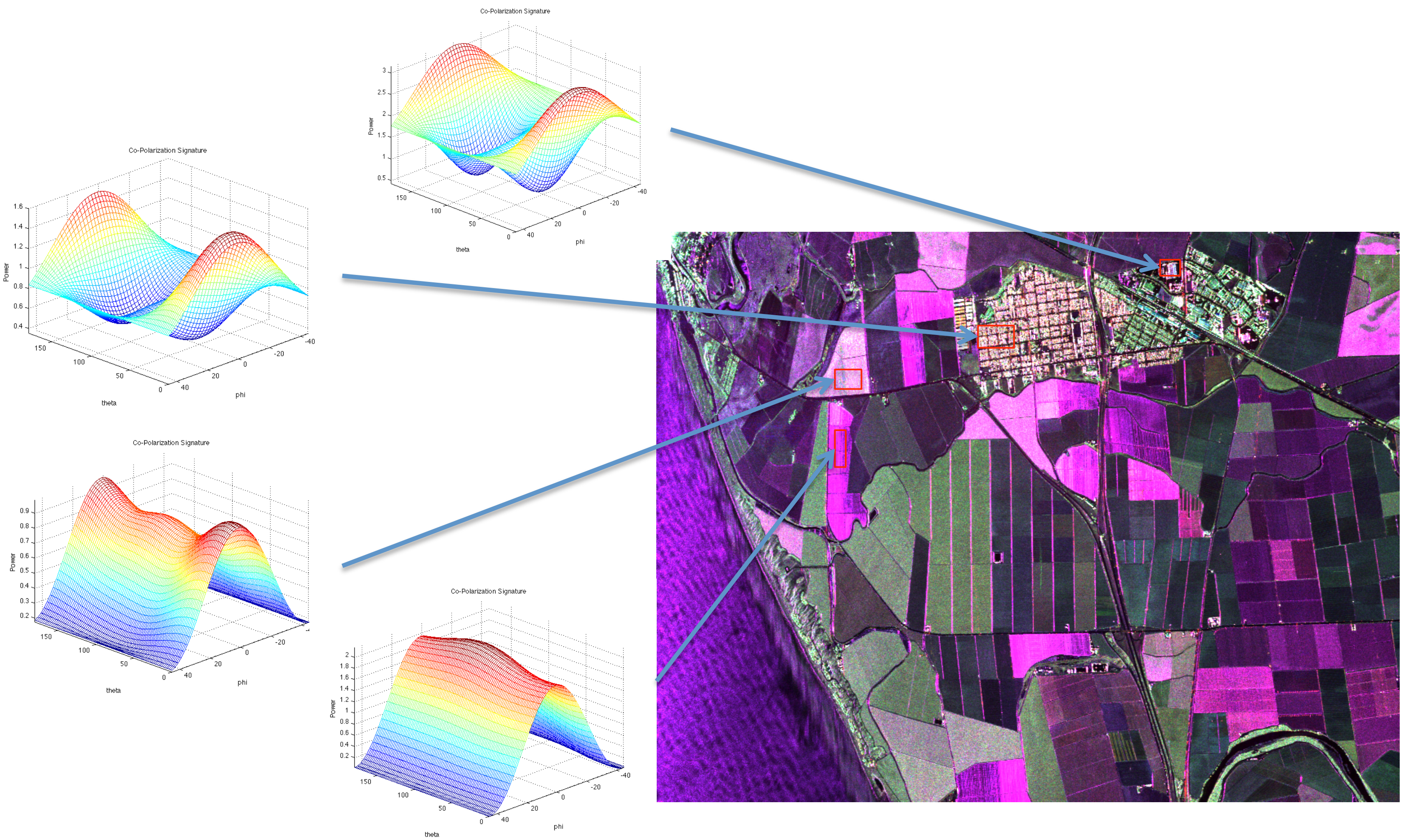








San Andreas


Co-Polarization Signature
Power
theta
phi
Co-Polarization Signature
Power
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Co-Polarization Signature
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theta
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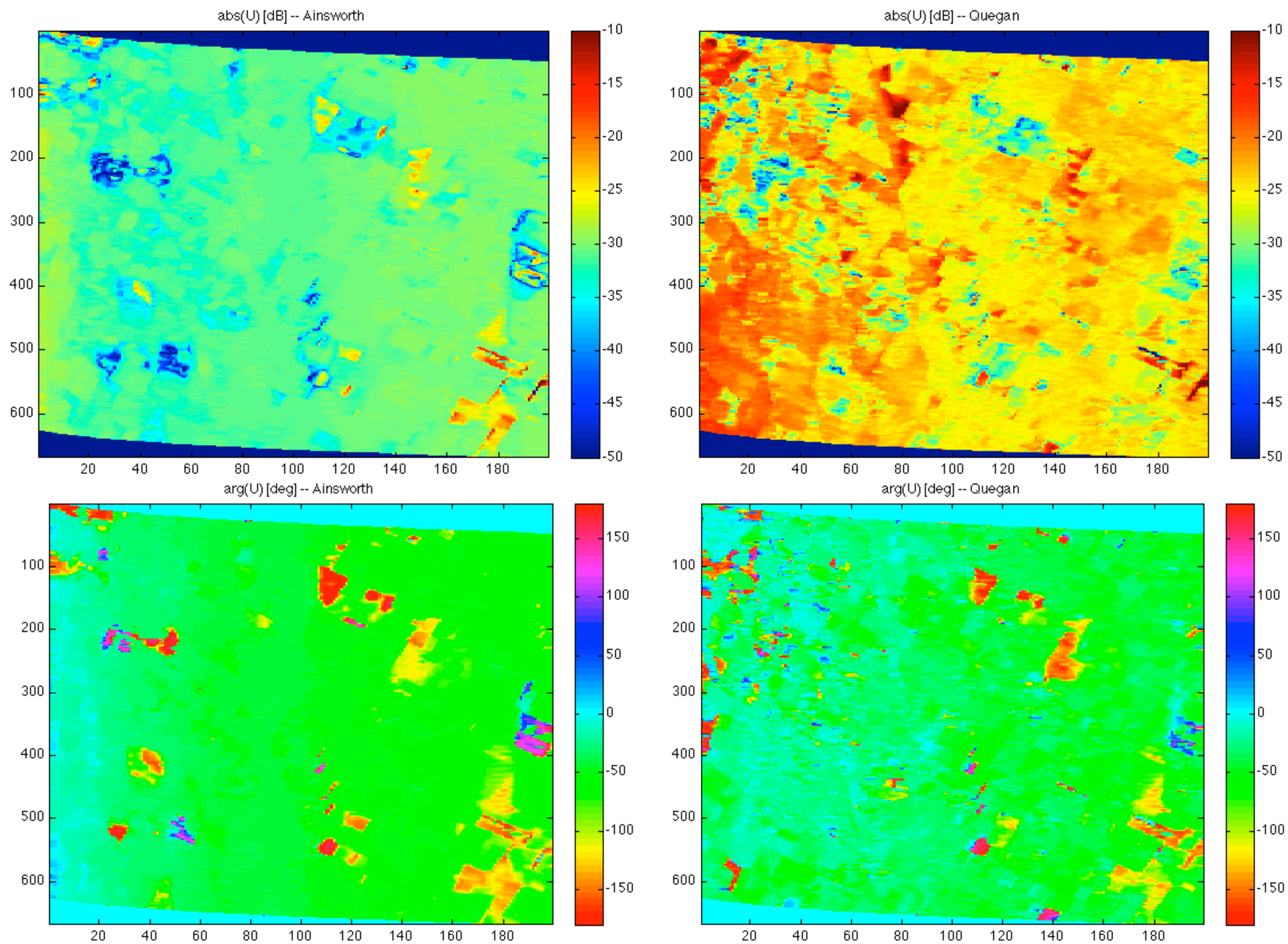
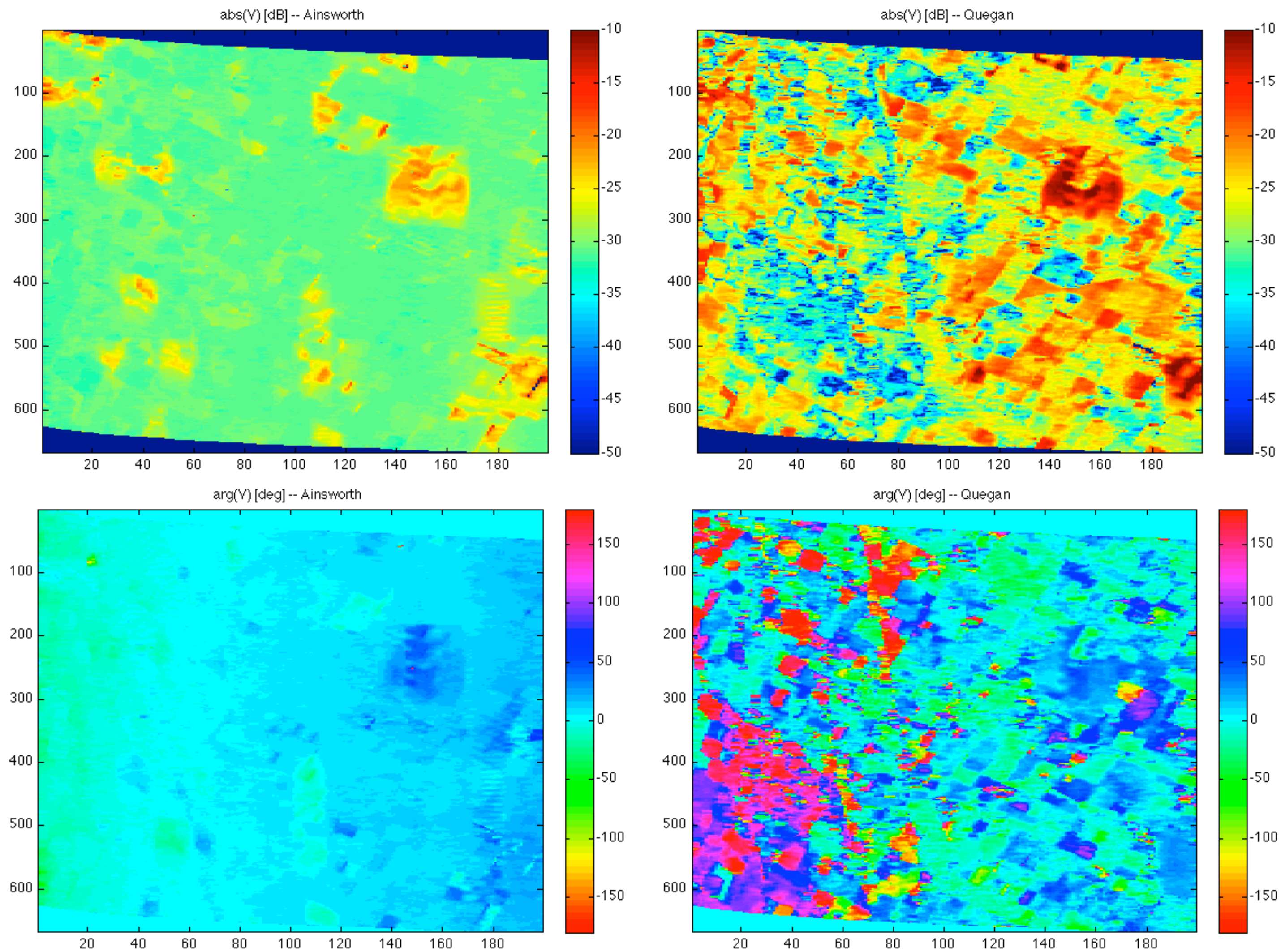
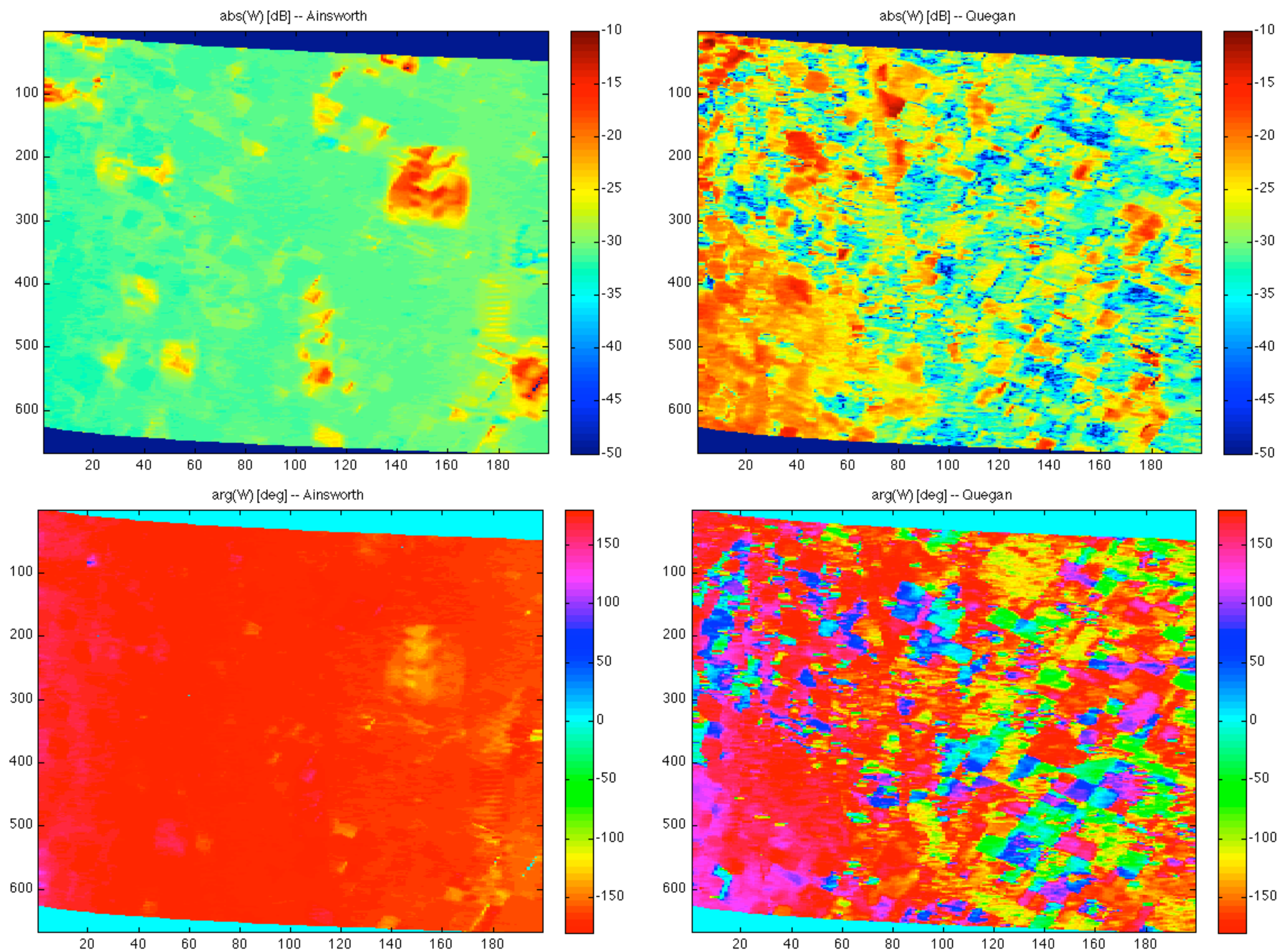
U parameter – Central Valley



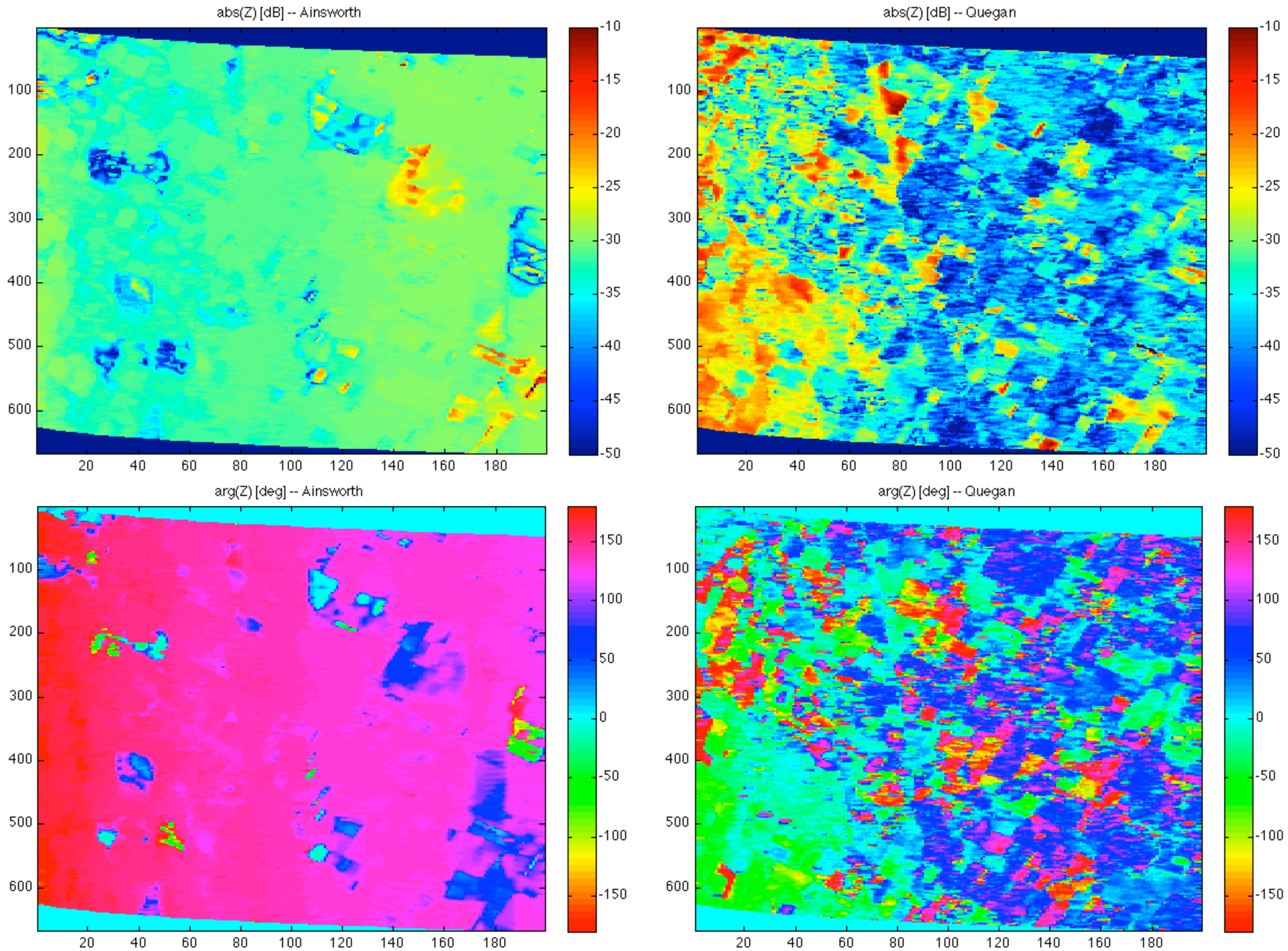
V parameter – Central Valley



W parameter – Central Valley

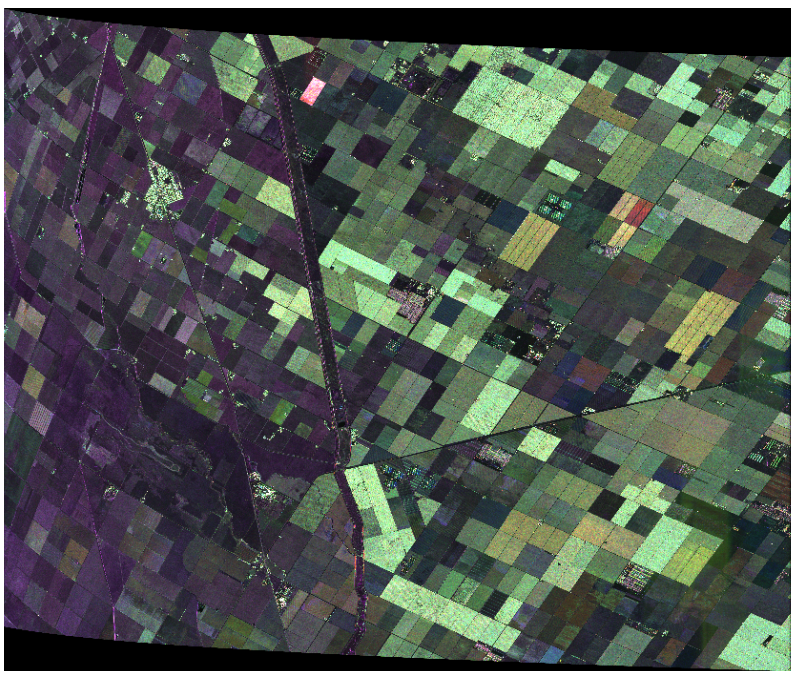


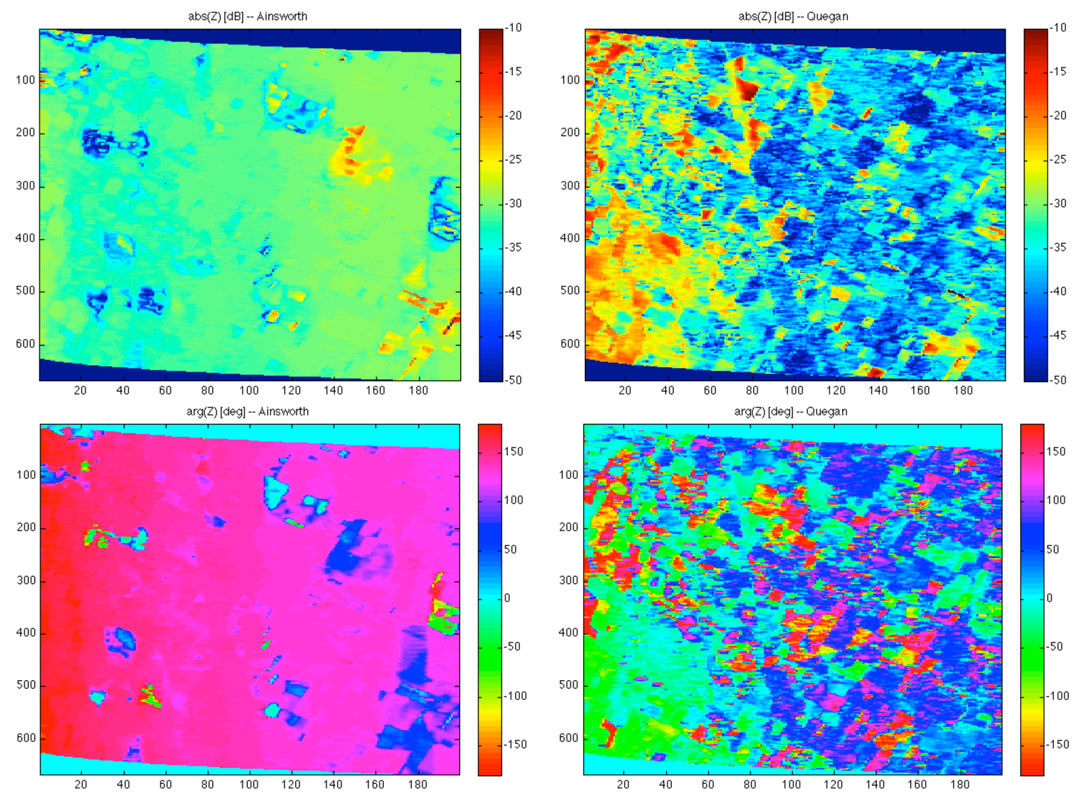
Z parameter – Central Valley



Z parameter – California Central Valley

- Quegan Z parameter varies significantly as the ground scattering changes
  - Wet/dry; fallow/active; …etc.
  - This is not physical, but due to the model imposing constraints that are not valid. (i.e. hh-hv correlation == 0).
- Ainsworth method gives much more stable results, both for the magnitude and phase of the Z parameter.
  - Other parameters (u,v,w) show similar behavior.





More on Antenna Pattern

$$g(\alpha,\epsilon,\alpha_0) = \frac{(\cos\alpha\cos\epsilon)^{1.5}}{1+a_2}\,\mathtt{sinc}\left[\frac{\pi L_e}{\lambda}(\sin\alpha-\sin\alpha_0)\right]\left\{\cos\left[\frac{\pi L_{d_1}}{\lambda}(\cos\alpha\sin\epsilon)\right]+a_2\cos\left[\frac{\pi L_{d_2}}{\lambda}(\cos\alpha\sin\epsilon)\right]\right\}.$$

Here, $\lambda = 0.238$ meters is the wavelength, α is the antenna azimuth angle, ϵ is the antenna elevation angle, α_0 is the antenna azimuth angle to which we electronically steer the antenna array, $L_e = 1.5$ meters is the antenna length in the $\hat{e}$ direction, $L_{d_1} = 0.1$ meters is the spacing between the two inner rows of the antenna array, and $L_{d_2} = 0.3$ meters is the spacing between the two outer rows of the antenna array.

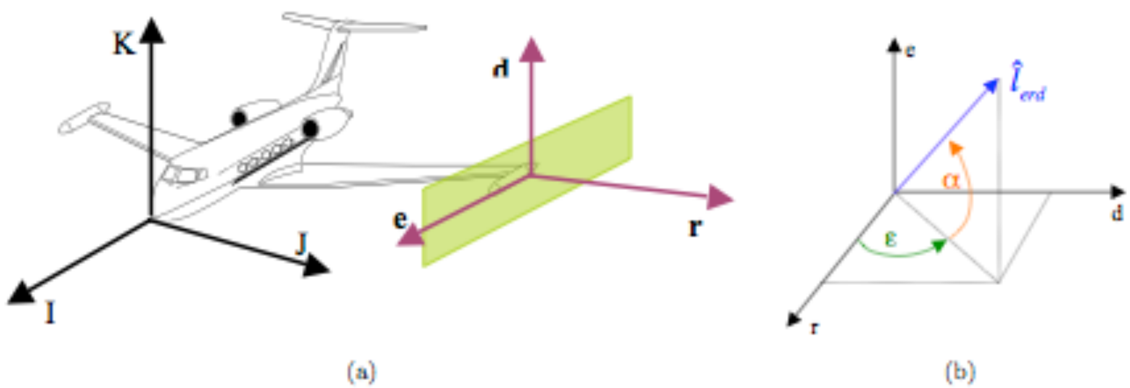
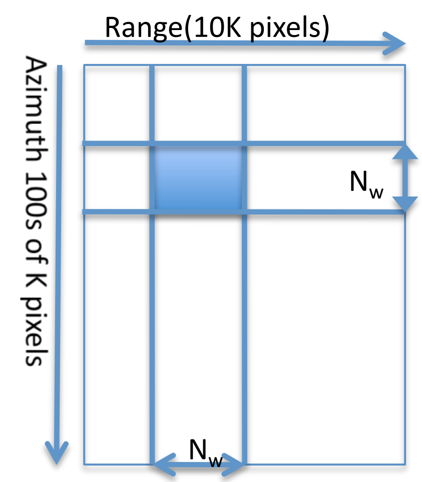


Figure 7: In Figure (7(a)) we show a diagram of the UAVSAR antenna geometry and antenna-face coordinates. Note that the antenna is actually mounted to the aircraft with an additional rotation about the $\hat{I}$ direction of -45 deg. In Figure (7(b)) we show the definition of the elevation ϵ and azimuth α directions. Figures are from [4].



Range(10K pixels)
Azimuth 100s of K pixels
N_w
N_w