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Autofocus correction of SAR images exhibiting excessive residual migration

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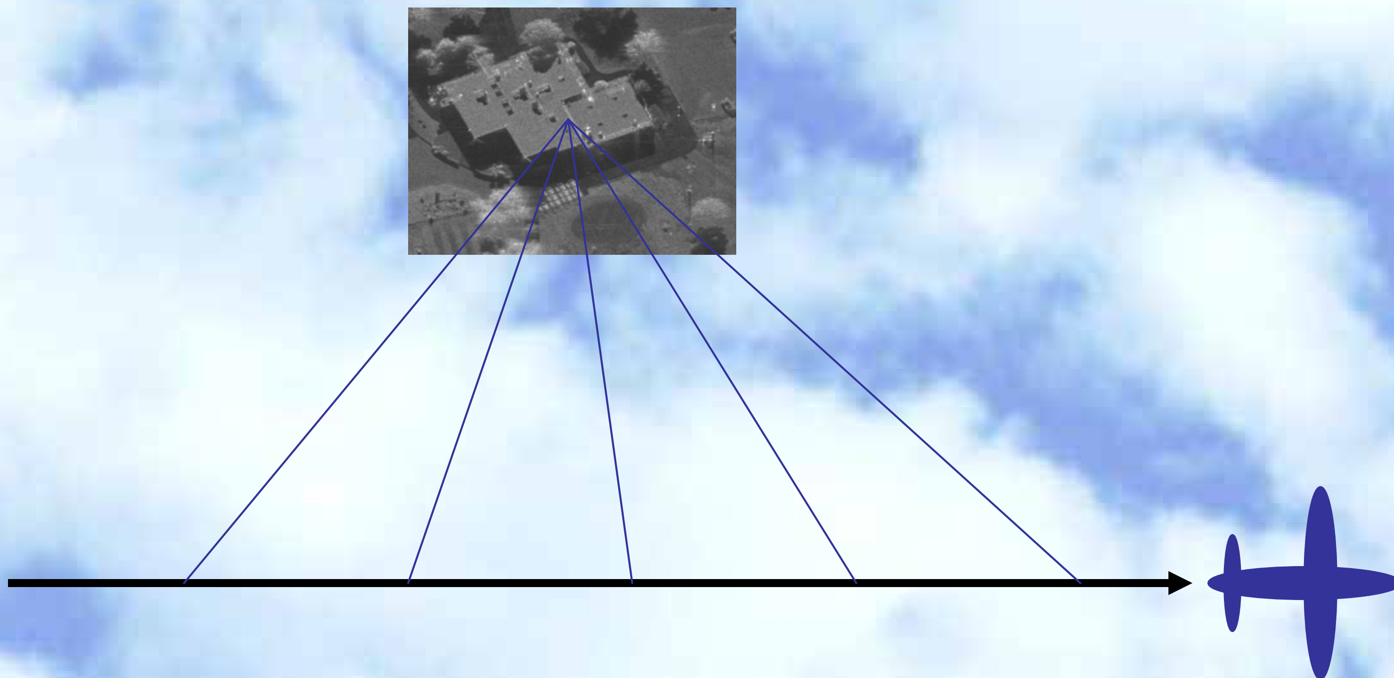
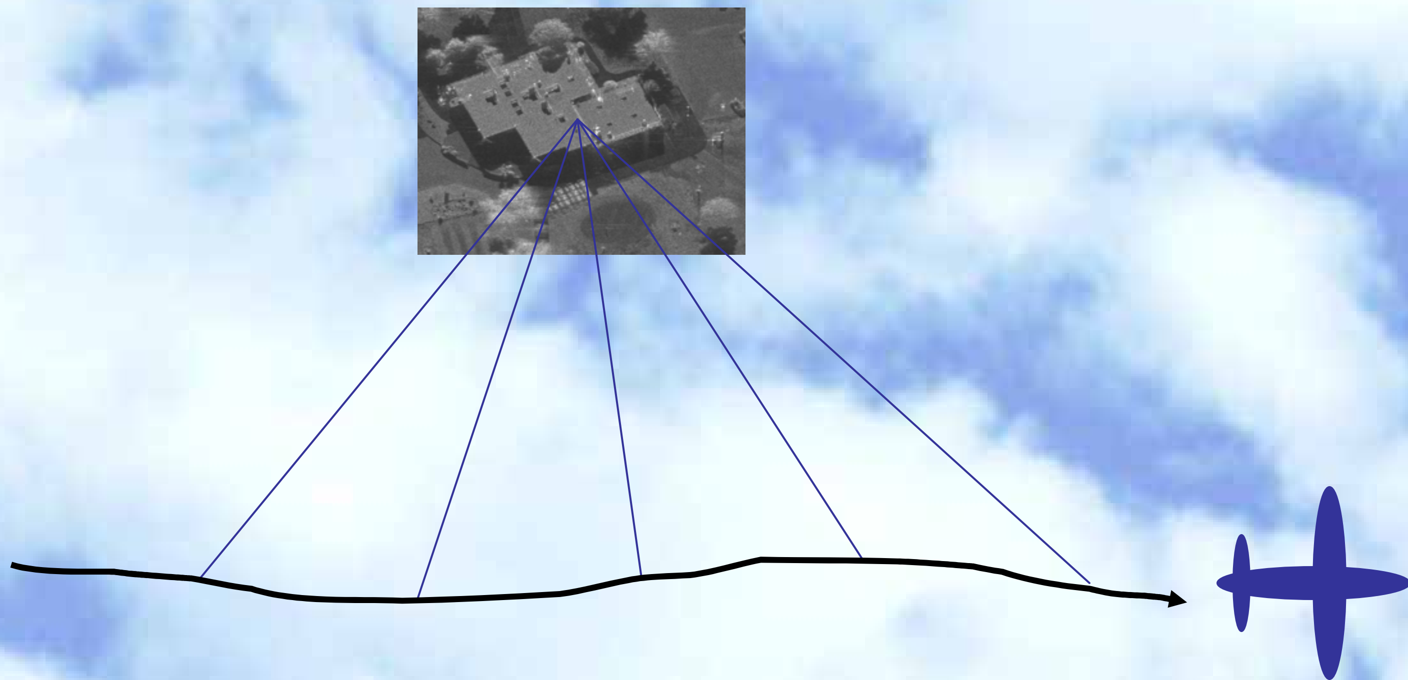
The problem



Forming a well-focused SAR image requires coherently combining the data from all the pulses along a synthetic aperture. This in turn requires precise and accurate motion measurements – to within a small fraction of the radar's wavelength.

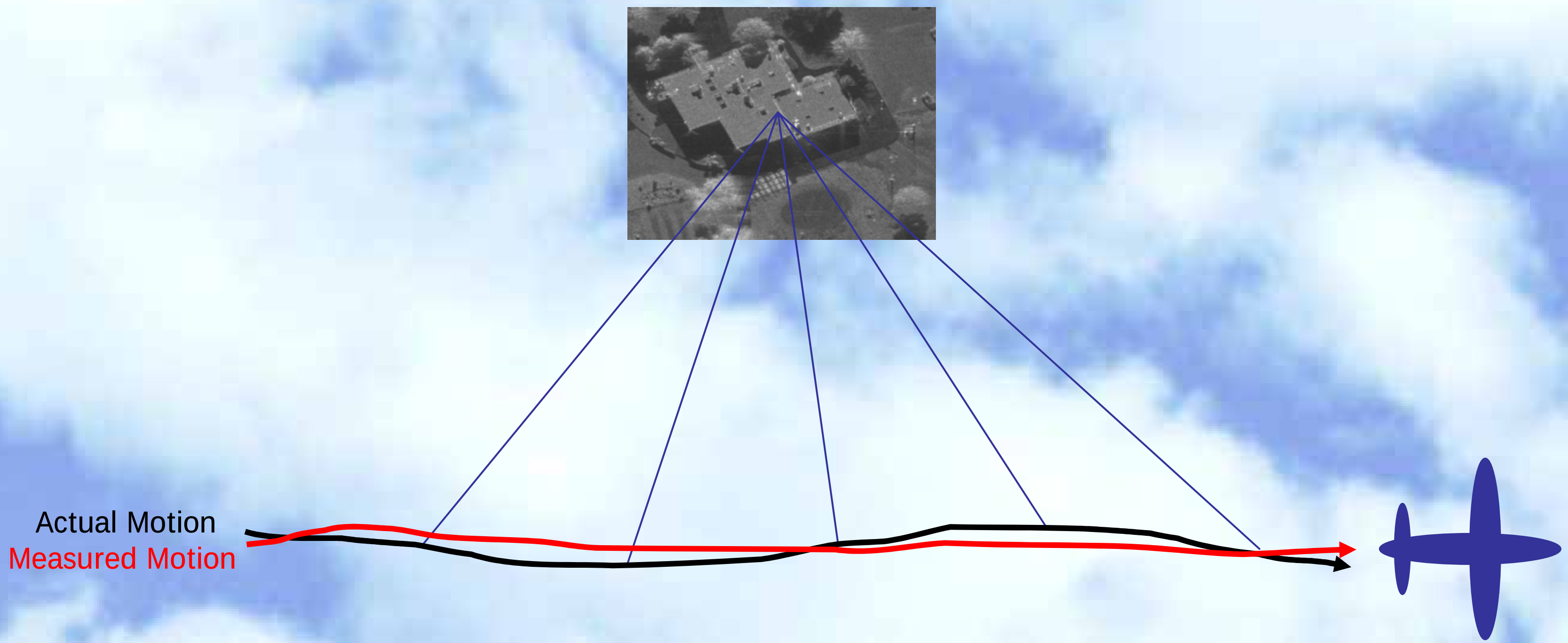
The problem



Aircraft don't fly absolutely perfect flight paths, but as long as the motion can be measured, the data can be compensated.

→ Motion Compensation

The problem

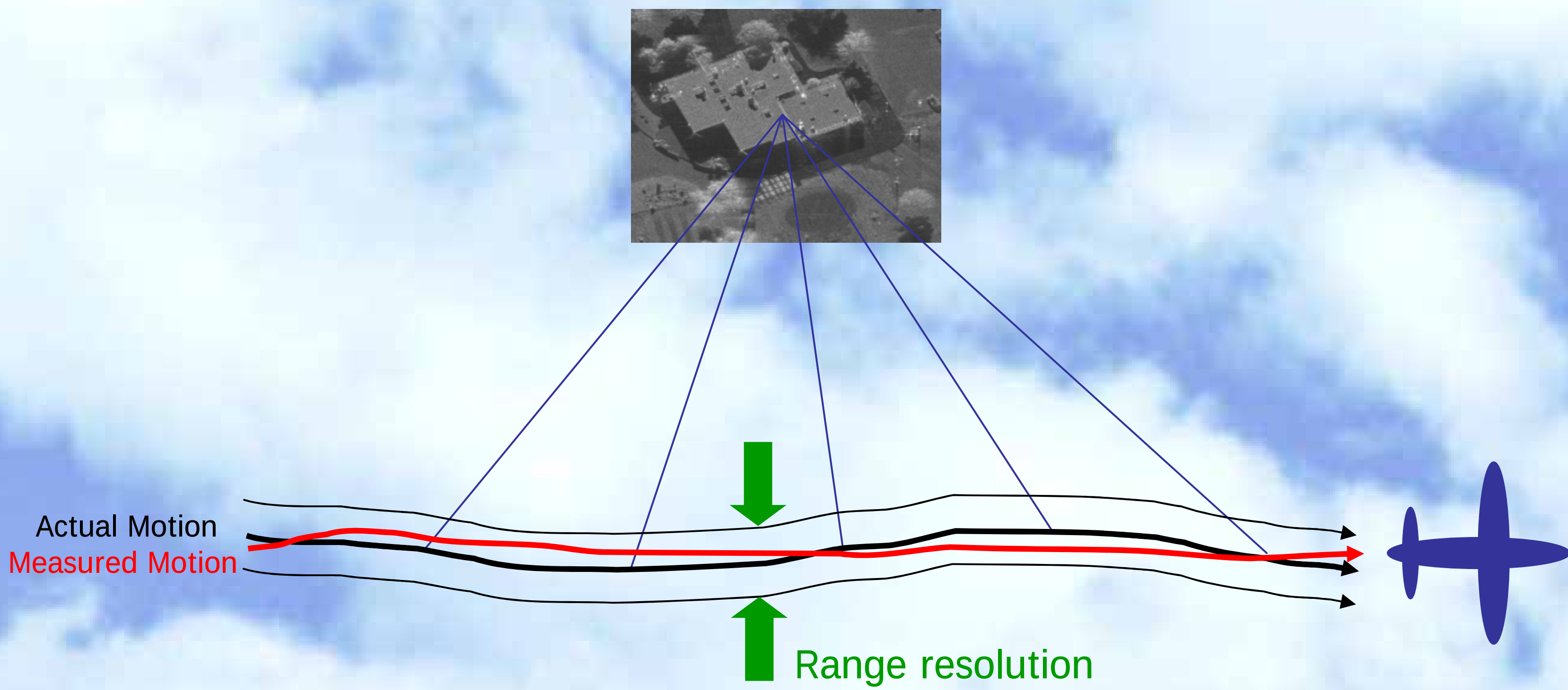


When the measured motion is different than the actual motion, then data coherence suffers, because the motion is not properly compensated. This results in blurring and smearing in the image.

The motion error can often be estimated from the image data, and be compensated after the fact. The blurring function is then deconvolved from the data.

→ Autofocus

The problem



Nearly all Autofocus algorithms presume that the motion measurement error is less than the range resolution of the radar image. This allows treating the motion error as a phase error, allowing mitigation with a phase error correction.

The problem

Jakowatz, et. al,[1] state that “maintaining relative-position uncertainties of the SAR platform to well less than a range-resolution cell size (e.g., 1 meter) is easily achievable by modern inertial navigation systems.” Furthermore, “[i]n practice the size of the [range error] shift, ec/2, is a small fraction of the resolution cell size.”

[1] C. V. Jakowatz Jr., D. E. Wahl, P. H. Eichel, D. G. Ghiglia, P. A. Thompson, *Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach*, ISBN 0-7923-9677-4, Kluwer academic Publishers, 1996.

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The problem is that radar systems have advanced to the point to where this is no longer always true.

The problem

Denny & Scott[2] claim that "the performance of future high-resolution SAR modes will be limited by anomalous propagation effects, rather than by platform measurement errors or focusing algorithm limitations, or RF wavelength." Their conclusion is based on the assumption that uncompensated apparent (due to anomalous propagation) range variations equal to the range resolution is "the rule-of-thumb limit that can be achieved, using autofocus."

[2] M. Denny, I. Scott, "Anomalous Propagation Limitations to High-Resolution SAR Performance", Proceedings of the 2002 IEEE Radar Conference, Long Beach, CA, USA, p. 249-254, 22-25 April 2002.

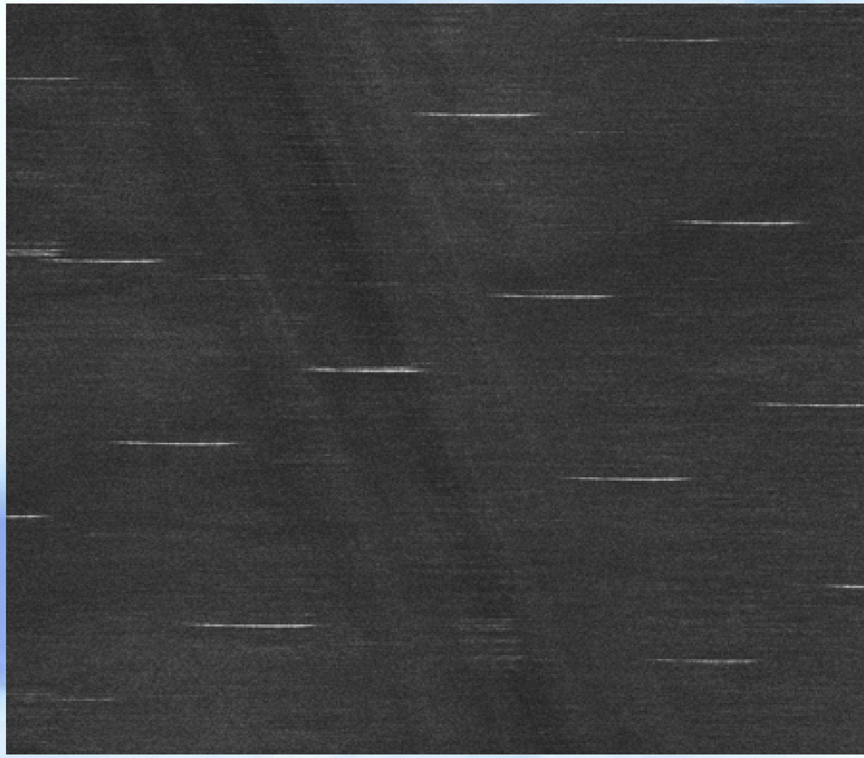
The problem

Factors include:

- **Ultra-fine resolutions of high-performance systems**
- **Less expensive motion measurement systems to facilitate inexpensive systems**
- **Atmospheric effects at long ranges**

The problem

Sandia radar test facility



Unfocused SAR image showing severe smearing due to apparent motion errors (4-inch resolution at 41 km range).

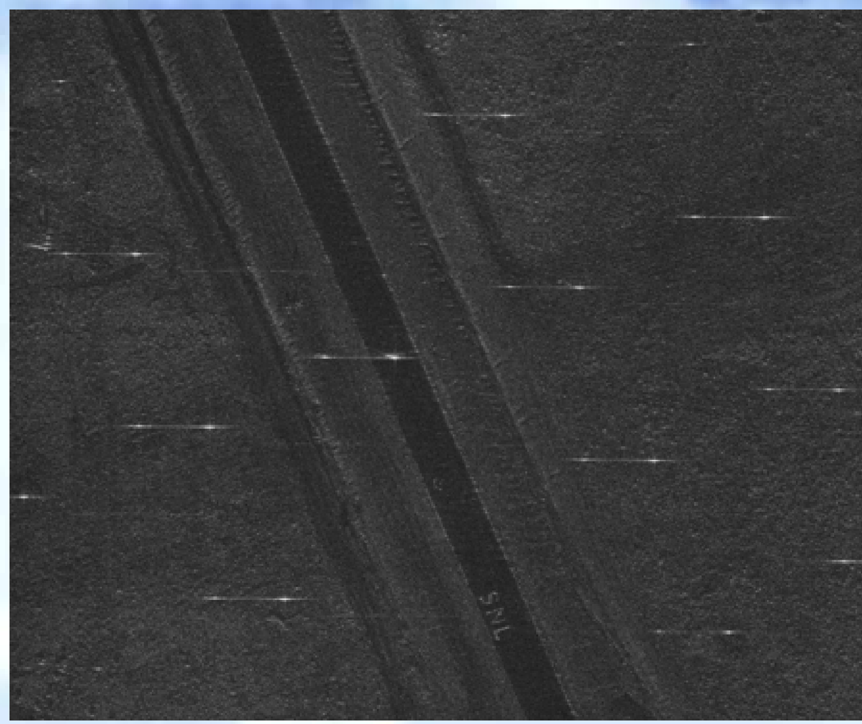
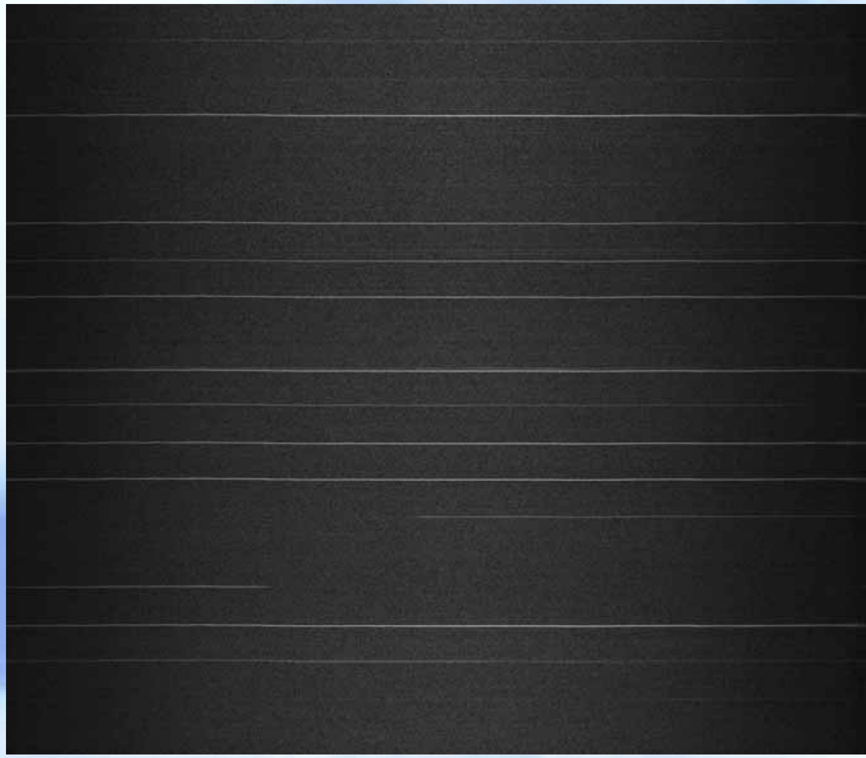


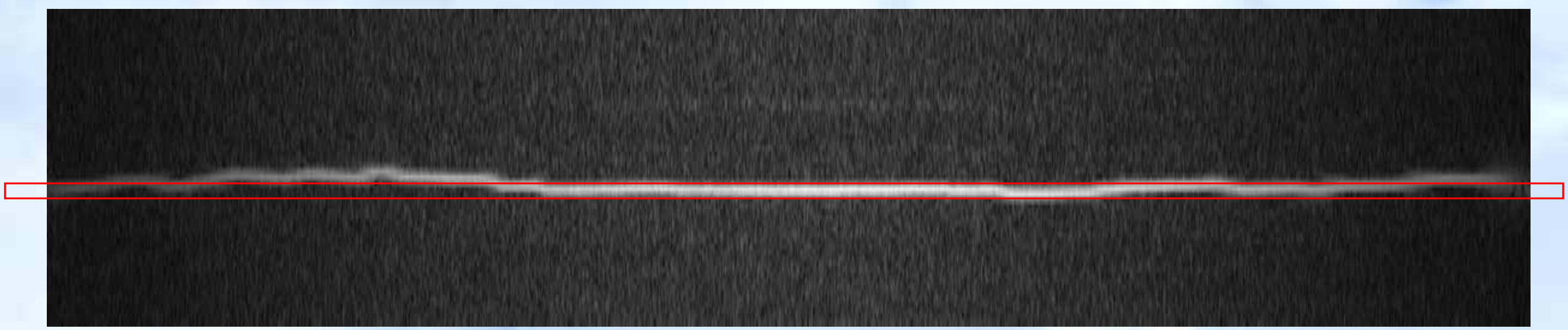
Image autofocused with conventional Phase-Gradient autofocus technique

The problem



Range-compressed phase history data, with Deterministic migration has been compensated.

Close-up of single corner-reflector response showing residual range variations greater than the range resolution.



Solution

Recognize the following:

- **the motion error manifests itself as more than a simple phase error – it involves perhaps many 2π wraps**
- **mitigation requires a frequency shift in the phase-history domain**
- **A well-focused image requires point targets to present as a straight line in the range-compressed data**

Two techniques are available to do this.

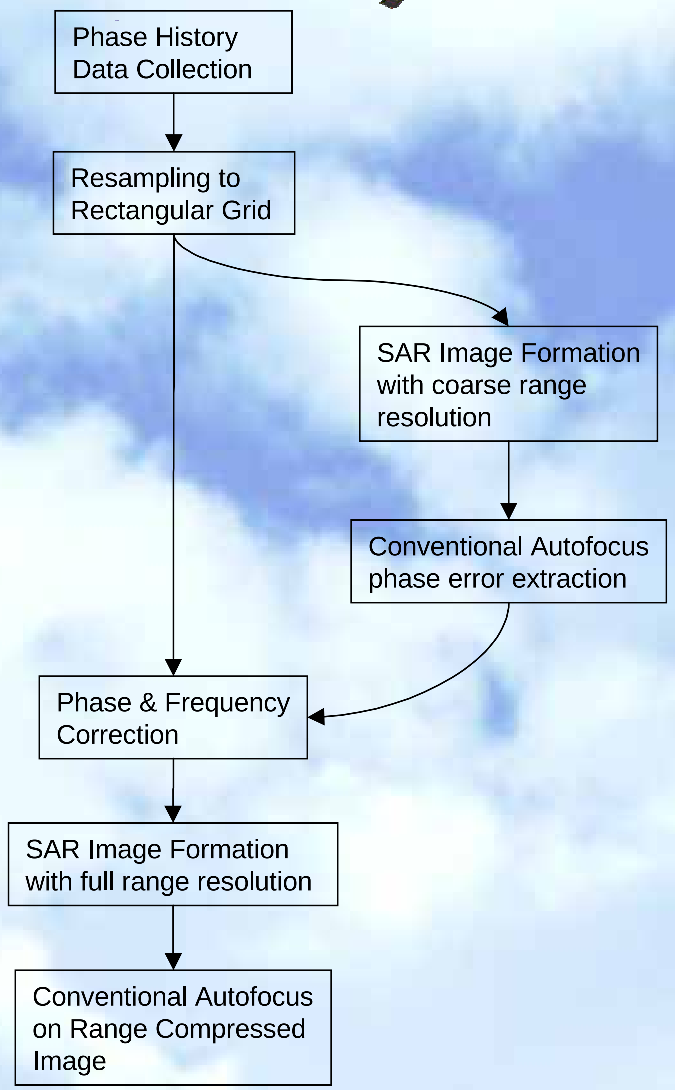
Solution 1

If conventional motion error measurement techniques require the motion error to be less than the range resolution...

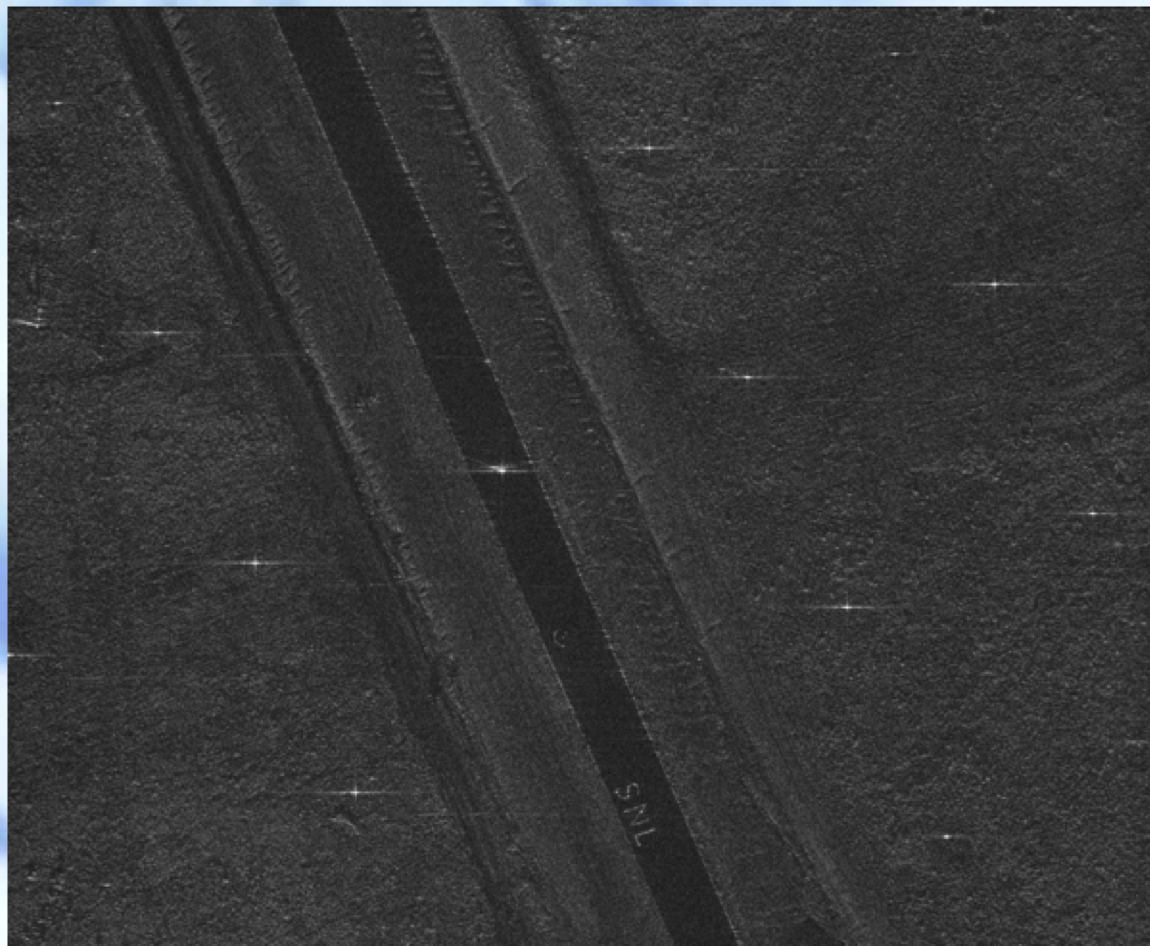
then make this measurement on a range-resolution-degraded data set, where the degraded resolution is coarser than the anticipated motion error.

Conventional autofocus techniques can be used to measure the corresponding phase error.

The phase error so extracted can be used to calculate the phase and frequency shift for the full-resolution data set.

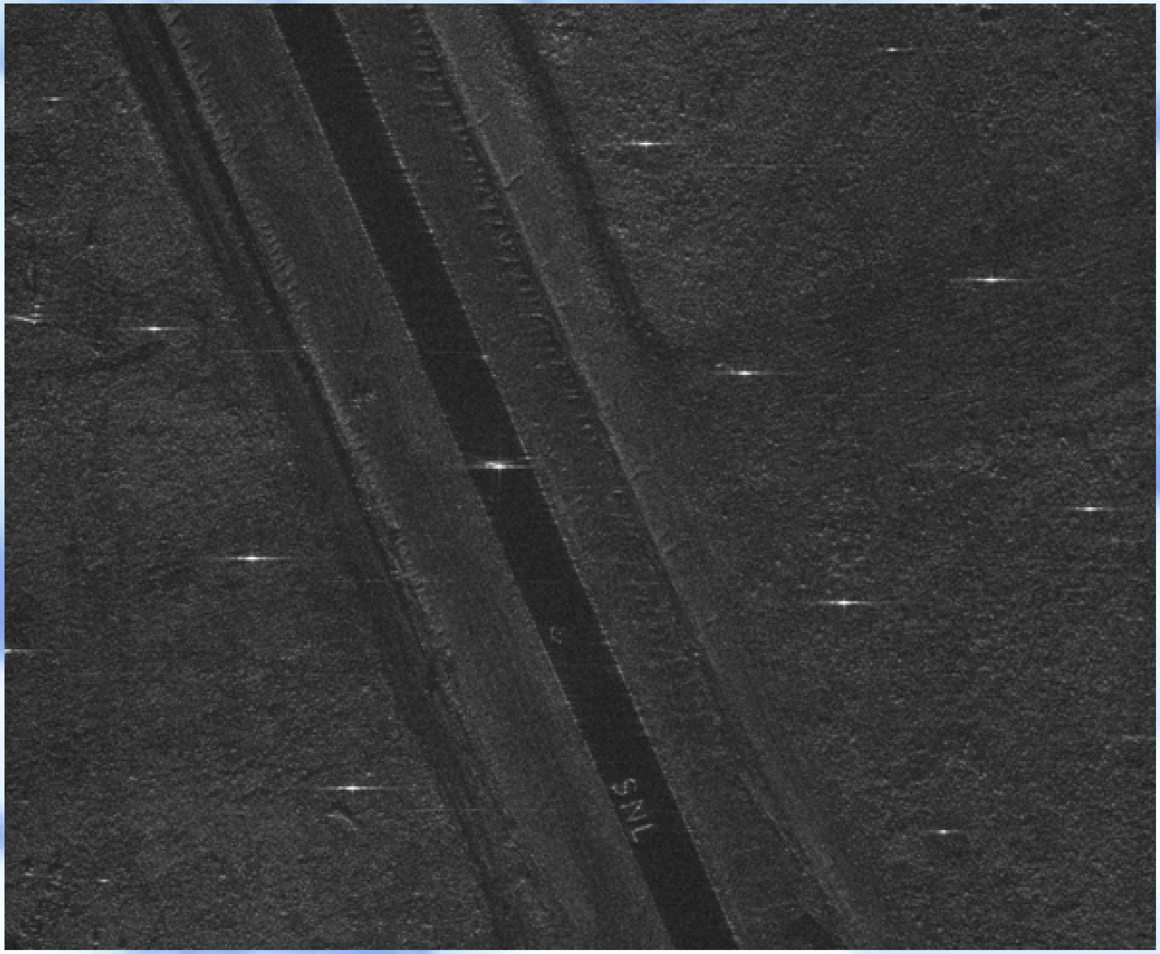


Solution 1



It works...

Solution 1 – phase only correction



Applying a phase-only correction gets rid of the 'double-image' effect, but does not optimally focus the image.

Solution 1 - caveats

The relationship between phase error and motion offset must be intact… that is, no phase-only autofocus must have been previously applied.

The necessary coarsening of the range resolution must be sufficient to encompass the residual range migration, which is not known a priori.

Because the data has been re-sampled from a polar grid to a rectangular grid, there is a coupling that requires correction for both the motion error as well as the azimuthal derivative of the motion error.

Solution 2

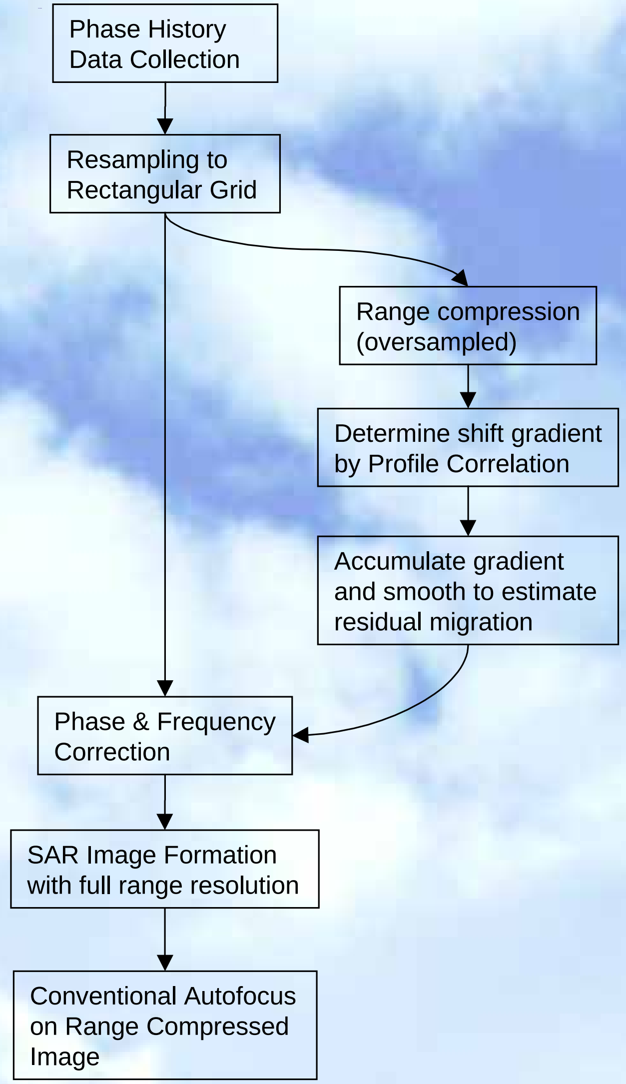
If the problem is that the target scene is not adequately 'lined-up' in azimuth...

then measure just how not 'lined-up' the energy is, and shift the data accordingly.

Range profiles do not change significantly from pulse to pulse, so correlating adjacent pulse's range profiles can yield a shift-gradient that can be integrated to find the apparent motion error.

Increased sensitivity to shift gradient can be accomplished by oversampling the range profile, and by comparing pulses that are somewhat separated.

The apparent motion error so extracted can be used to calculate the phase and frequency shift for the original data set.



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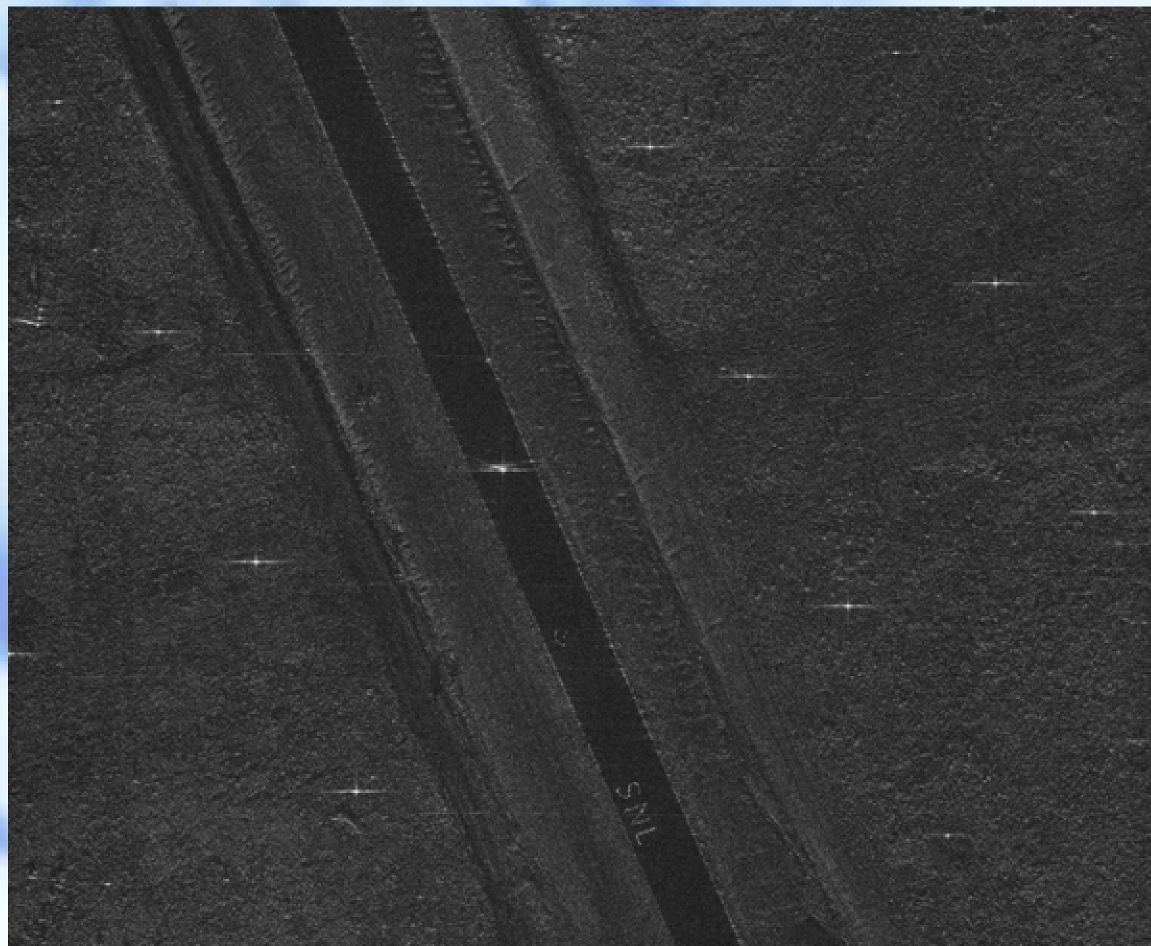
Solution 2



It works…

Solution 2 - caveats

Removing the residual migration by ‘straightening’ the phase history data via frequency shifts does not automatically by itself correct phase errors.

This technique will work on data that has already had phase-only corrections applied to it, however subsequent additional phase-only corrections may still need to be applied.

Summary & Conclusions

- **Excessive residual migration due to apparent motion errors are not correctable with conventional autofocus algorithms.**
  - Excessive migration errors require both a frequency correction as well as a phase correction to be applied before final range compression.
- **Excessive migration can be determined by performing conventional autofocus steps on a reduced-range-resolution image.**
  - provided the reduced range-resolution is coarser than the residual migration.
- **Excessive migration can also be determined by correlating range profiles in range-compressed data.**
  - Sensitivity to range profile shifts, and hence migration, can be enhanced by oversampling the range compressed data in the range dimension.
  - Sensitivity to profile shifts, and hence migration, can also be enhanced by correlating range profiles that are separated in the slow-time dimension.

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