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Assuring Mission Success

Avoiding stair-step artifacts in image registration for GOES-R navigation and registration assessment

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Overview

- Stair-step is a subpixel image registration artifact
- We have seen this before… ten years ago
- GOES-R Advanced Baseline Imager (ABI) Instrument Navigation and Registration (INR) assessment
- Methods to reduce the stair-step artifact
- Conclusions

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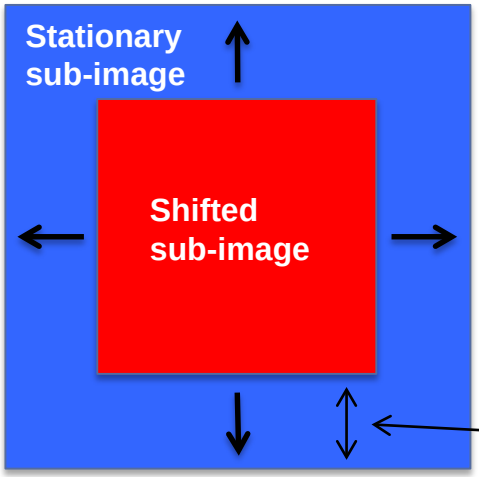
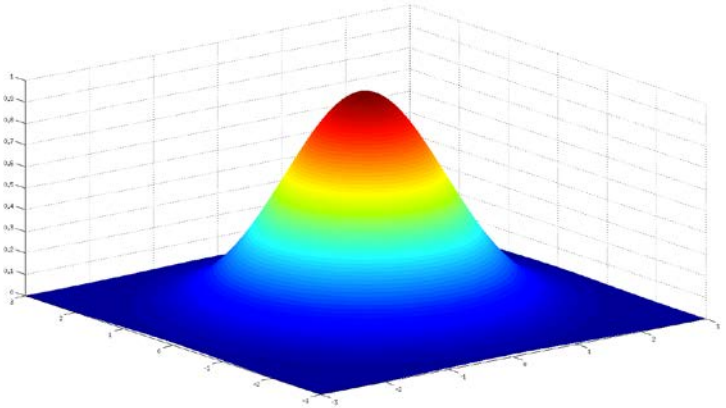
Shift Estimation using Image Registration



Calculation of similarity metric for each EW/NS shift in image plane produces 2D array of similarity metrics In correlation plane



Maximum anticipated misregistration

Location of similarity metric local maximum relative to unshifted location measures registration error

- **Similarity metric uses a form of image correlation**
  - ***Normalized cross-correlation (Pearson coefficient)***
  - ***Normalized Mutual Information (NMI)***
  - ***Phase Correlator (Fourier processing)***
- **Output increases as images are shifted towards perfect alignment**
  - ***Inputs are pixelated with same pixel size***
  - ***Output is similarly pixelated***
  - ***Maximum location shows image shift to nearest pixel***
- **Interpolation is required to estimate sub-pixel registration**
  - ***Stair-step is an interpolation artifact***

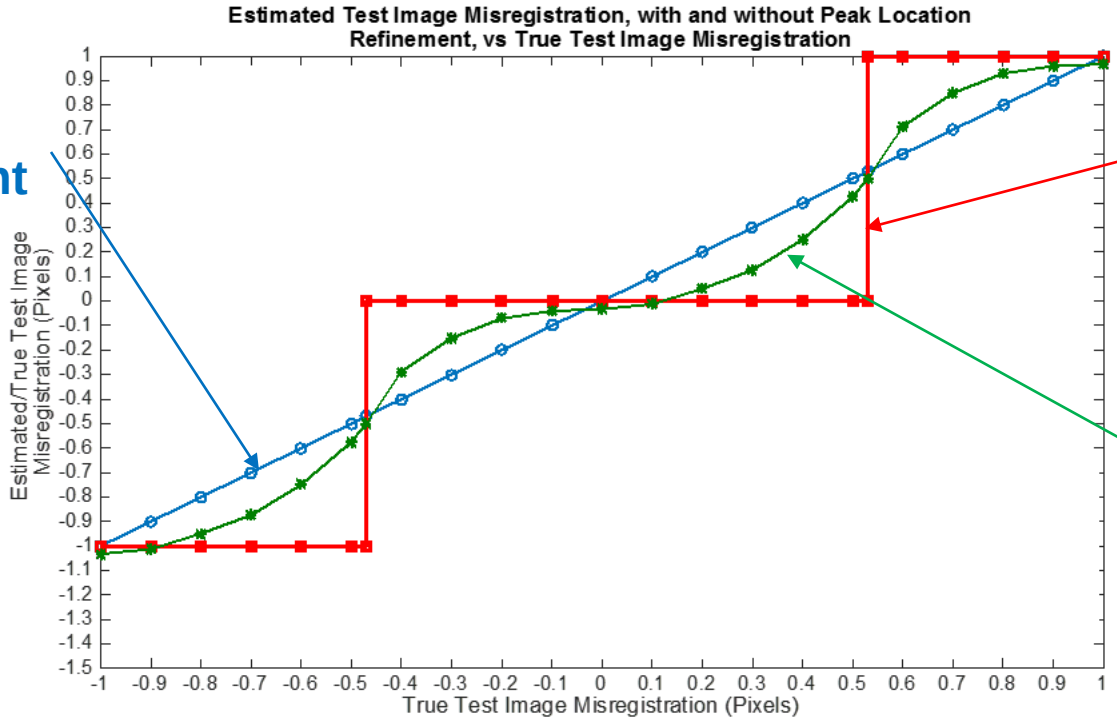
Illustrations from De Luccia et.al., Proc. SPIE 988119

Common concept for measuring GOES-R INR metrics

Characteristics of the Stair-Step Artifact

Subtitle

True Displacement



Initial Estimate (Nearest Pixel)

Final Estimate with Stair-Step

- This chart shows the position estimate for a pair of images as the true shift varies from -1 to 1 pixel
- The initial estimate of registration is the nearest-pixel location
- We fit the correlation peak with a quadratic for the final estimate
  - *Correct for offsets of an integer number of pixels*

Stair-step is a sub-pixel estimation artifact

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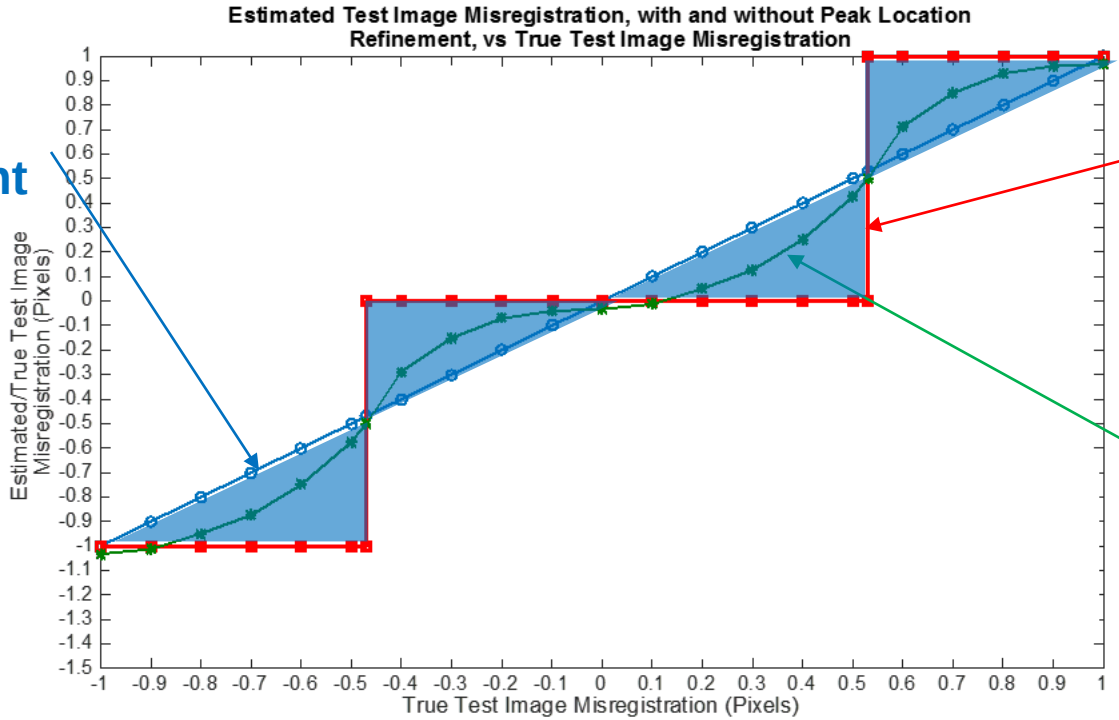
Characteristics of the Stair-Step Artifact

Subtitle

True Displacement



Initial Estimate (Nearest Pixel)

Final Estimate with Stair-Step

- We fit the correlation peak with a quadratic for the final estimate
  - *Correct for offsets of an integer number of pixels*
  - *Subpixel shifts require interpolation which can introduce stair-step*
    - Estimates with stair-step fall between the true location and the nearest neighbor in the blue zone

Stair-step is a sub-pixel estimation artifact

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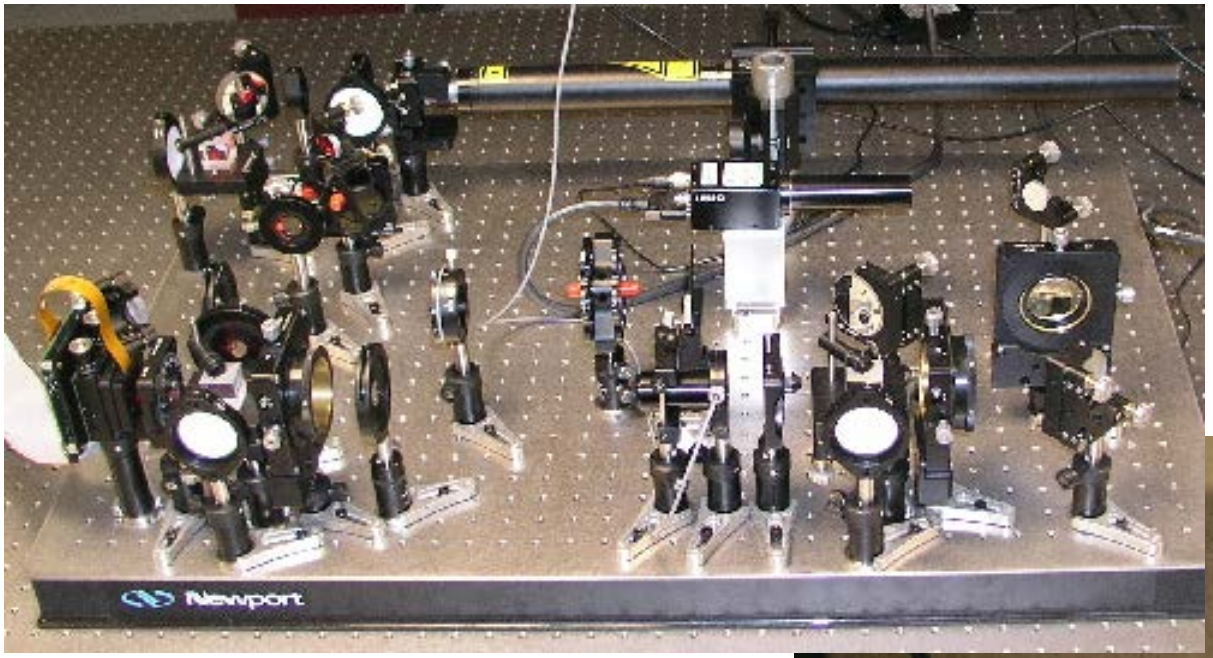
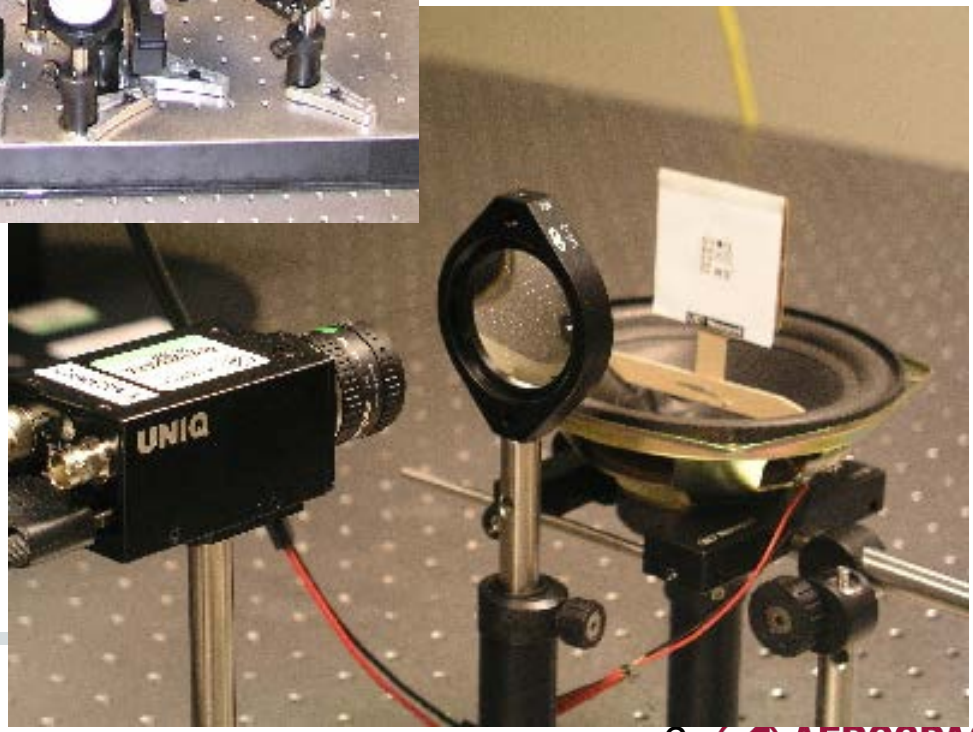
Ten Years Ago….



Third Generation (all optical) Correlator

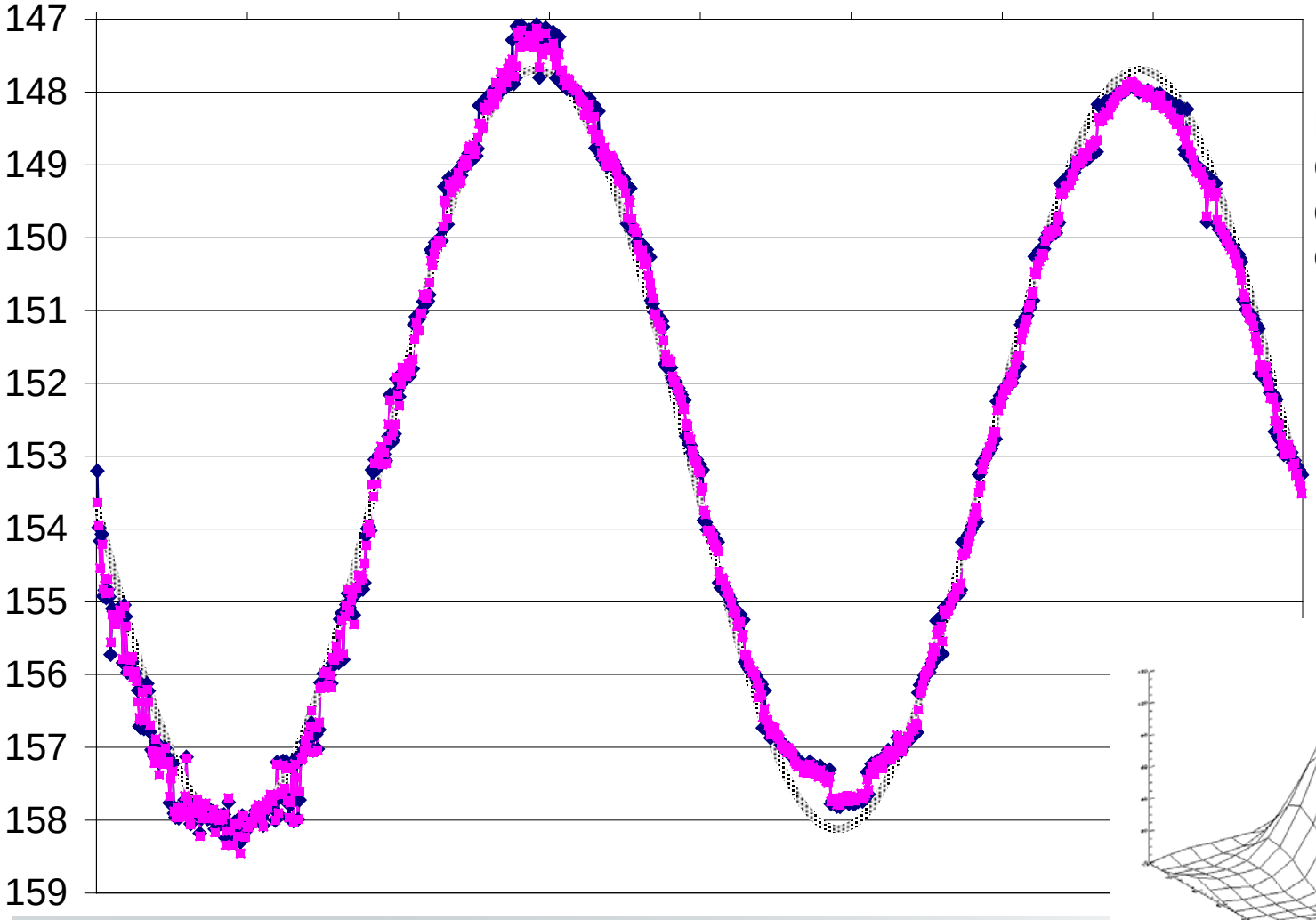
Spring 2006



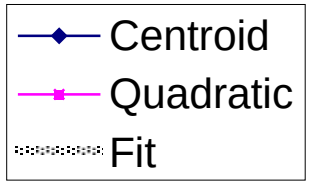
- Operated in burst mode (5-150 frames)
- Input camera operates at 400 FPS
- Input pre-processing at 50 FPS
- Optical correlator operates at 50 FPS
  - (Hamamatsu OASLM has ~12 ms response time)
- Correlation location calculated 50 FPS
- Output interpretation takes minutes

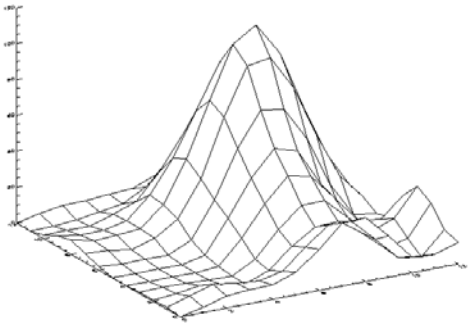
Material from Grycewicz et.al., Proc. SPIE 66950J

All-Optical Correlator Registration Results



RMS Fit Error
Centroid: 0.125
Quadratic: 0.115
Optical Gain: 2.74





Material from Grycewicz et.al., Proc. SPIE 66950J

Stair-Step is Hard to Detect

A sub-pixel artifact

- Stair-step is a sub-pixel artifact
  - *It won't be seen except in an experiment with sub-pixel image displacement and sub-pixel ground truth*
  - *Typically small—on order tenth pixel*
- Registration is typically a point estimate
  - *You don't typically have a line of motion to estimate*
  - *One estimate—one error*
  - *Error is a combination of many system noise terms, including stair-step*
- In the ABI case, our goal is to detect and measure subpixel misregistrations
  - *If present, the effect of stair-step will be to make the ABI images appear better registered than they actually are*

Stair-step is easy to miss, and easy to ignore

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GOES-R INR Assessment

- In March 2014 the GOES-R flight project initiated two efforts to develop tools for independent evaluation of on-orbit Image Navigation and Registration (INR) performance
  - *The Product Monitor (PM), developed by the ground project, provides heritage capability for INR performance assessment*
  - *An independently developed capability for INR performance assessment using different techniques for risk reduction*
- INR Performance Assessment Tool Set (IPATS) has been developed to:
  - *Independently measure INR performance characteristics*
  - *Generate image-level and multi-image-level statistics*
  - *Provide data visualization capability*
  - *Archive results*
- Aerospace is the primary architect and developer of IPATS, with final development and test ongoing jointly with SSAI and GST

Material from De Luccia et.al., Proc. SPIE 988119

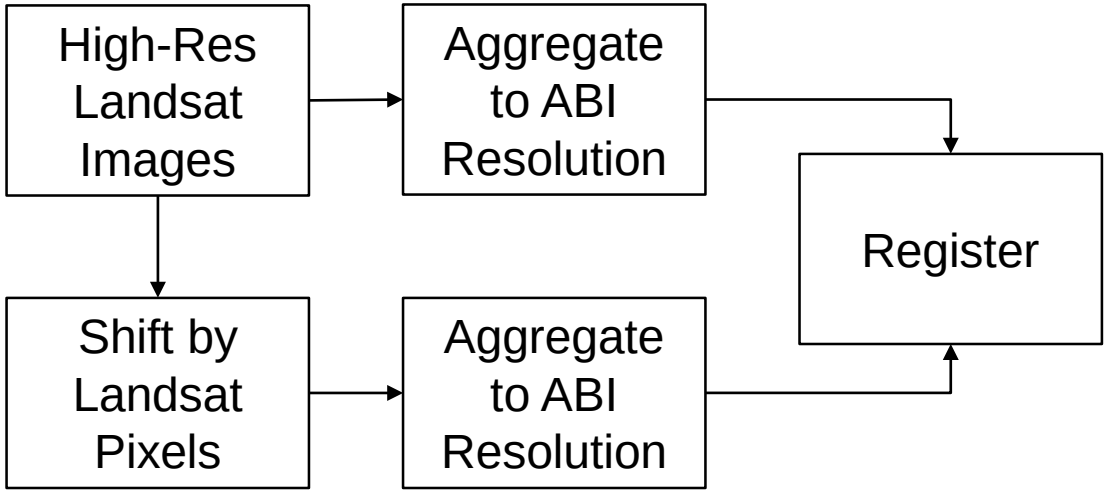
INR metrics of interest

- Navigation (NAV) error
  - *Difference between location of pixel in data product and true location*
- Frame-to-frame registration (FFR) error
  - *Relative navigation error of corresponding pixels of same band in consecutive images*
- Within-frame registration (WIFR) error
  - *Difference between radial separation of two pixels on the FG and their true angular separation*
- Swath-to-swath registration (SSR) error
  - *Relative navigation error of two neighboring pixels on opposite sides of image swath boundary*
- Channel-to-channel registration (CCR) error
  - *Relative navigation error of corresponding pixels of different bands in the same frame*

Material from De Luccia et.al., Proc. SPIE 988119

Key metric for any type of error is "3-sigma error", 99.73rd percentile of distribution of error magnitudes over a 24 hour data collection period.

Simulation Methodology



- Use IPATS tools and processes to register surrogate images
  - *Surrogate images have known ground truth*
- Landsat images aggregated 25x25 or 33x33
  - *Registered images have GOES-like GSD of 750-1000 m*
  - *Subpixel shifts in 0.03 or 0.04 pixel increments*
- Used to simulate in-channel and channel-to-channel registration

Register images with known relative shift

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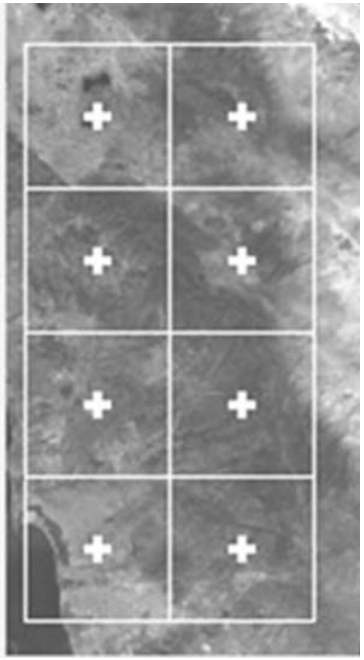
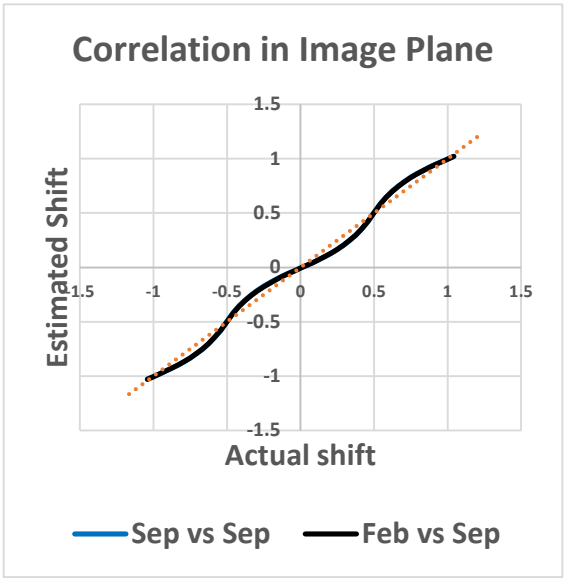
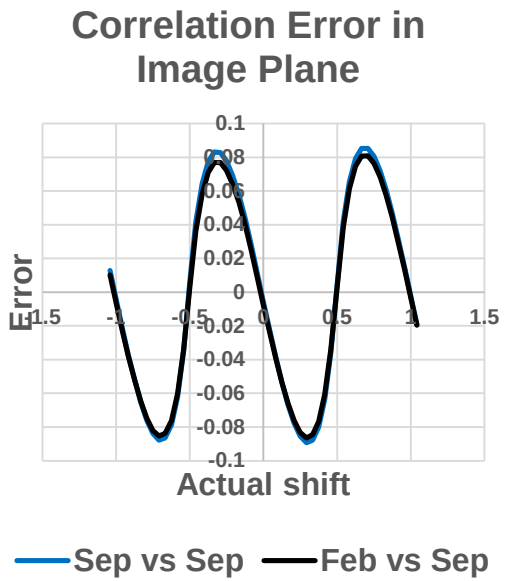
Stair-Step in Surrogate GOES-R Images

Simulations built with Landsat data







- Simulations use set of eight Landsat 64x64 pixel band 3 (red) chips
- Normalized cross-correlation (Pearson coefficient)
- Simulated motion by individual Landsat pixels (1/25 GOES pixel)
- RMS error 0.06 pixels

Stair-step seen in early simulations

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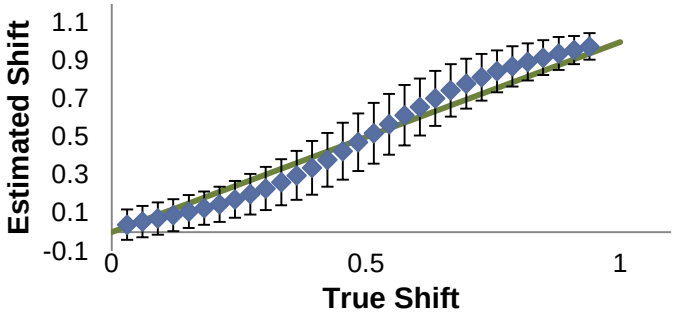
Stair-Step Artifact in Simulated GOES-R Images

- 30x30 pixel chip simulated from Landsat 7 band 3 (red)

- Set of 961 images
- Shifted by multiples of 1/33 pixel

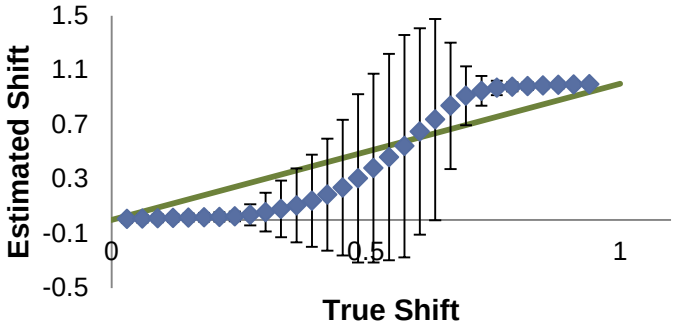
Cross Correlation

Max 3*STD = 0.160
Min 3*STD = 0.070



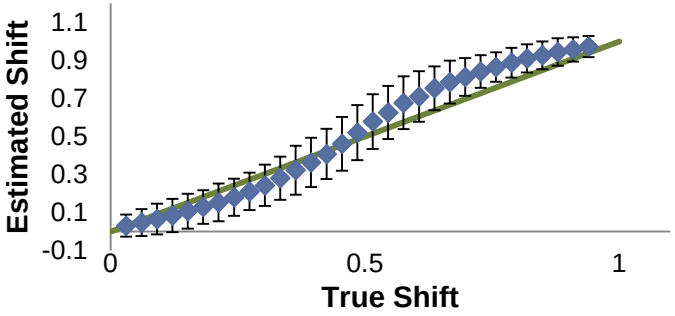
CC + Sobel

Max 3*STD = 0.816
Min 3*STD = 0.023



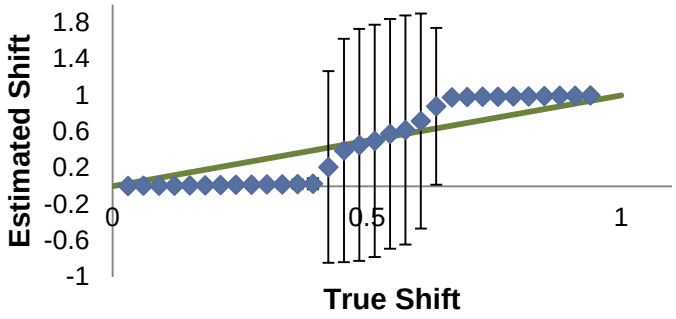
Normalized Mutual Information

Max 3*STD = 0.144
Min 3*STD = 0.055



NMI + Sobel

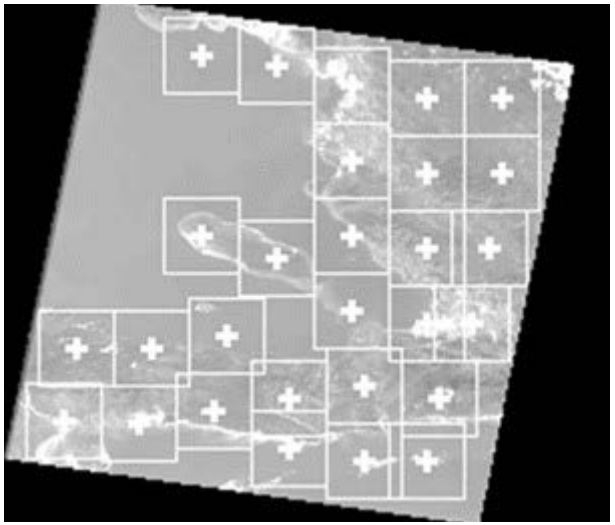
Max 3*STD = 1.279
Min 3*STD = 0.017

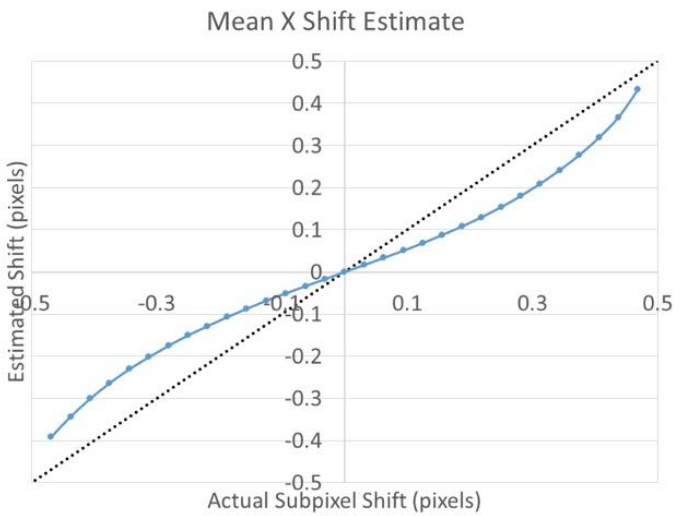


Stair-step is seen with many correlator types

Image Set Run in IPATS

Simulation set used to characterize correlation techniques





- This Landsat image of Haiti was used for simulations both within and outside of the IPATS framework
- The boxes define 30 pixel x 30 pixel ABI correlation regions
- Visible and infrared bands were correlated

How can we reduce the size of the stair-step artifact?

- Increase the resolution
  - *By estimating with high-resolution inputs, we get a high-resolution output*
  - *Need to start with high-resolution inputs, otherwise its just interpolation*
- Estimate the error and subtract
  - *If we can estimate the error, we can compensate*
  - *A sinusoidal estimate works well for mild stair-step*
- Choose a different correlator
  - *Different correlators have different stair-step response*
- Choose a different output interpolator
  - *Stair-step is an interpolation artifact*
  - *Choosing a good interpolator is critical*

We are in the middle of a performance trade

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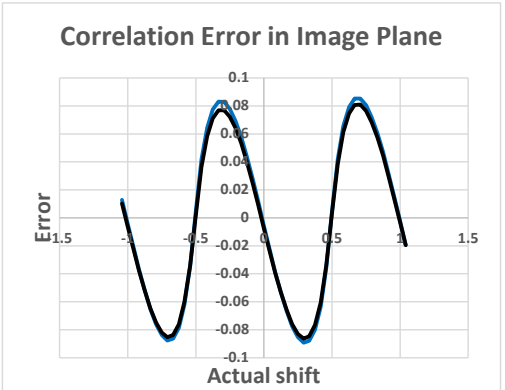
Increase Reference Resolution

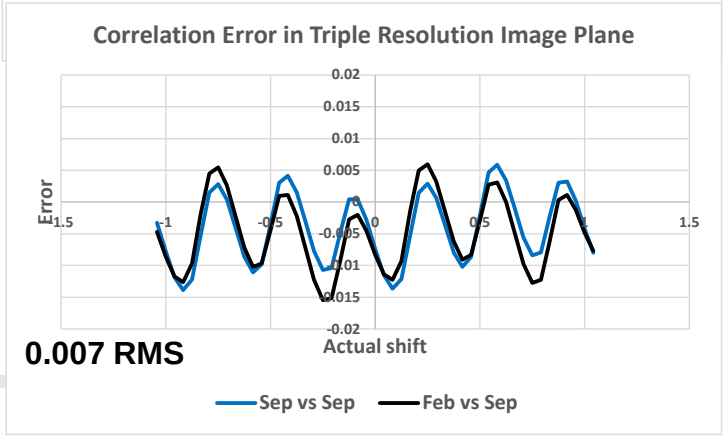
Data from surrogate ABI images on slide 12

- Increasing the reference resolution results in a large reduction in the magnitude of stair-step
- Correlation done at the smaller pixel size
  - *The spatial period of the stair-step is reduced to the smaller pixel size*
- This works well for NAV assessment
  - *Reference chips can have arbitrary scale*
- Requires that one of inputs is available at high-resolution
  - *Not helpful for CCR or FFR*
  - *When both images are rescaled, interpolating the inputs is similar to interpolating the output, but has computational disadvantages*



0.06 RMS

0.01 RMS



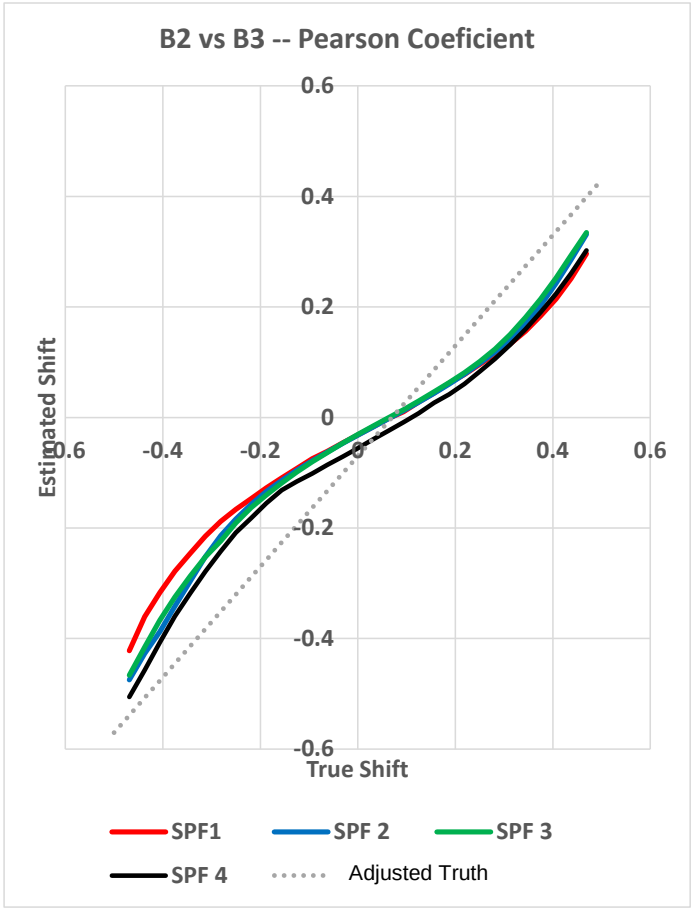
0.007 RMS

Good NAV technique

Increasing Resolution by Interpolation of Both Inputs

Data from surrogate ABI images on slide 14

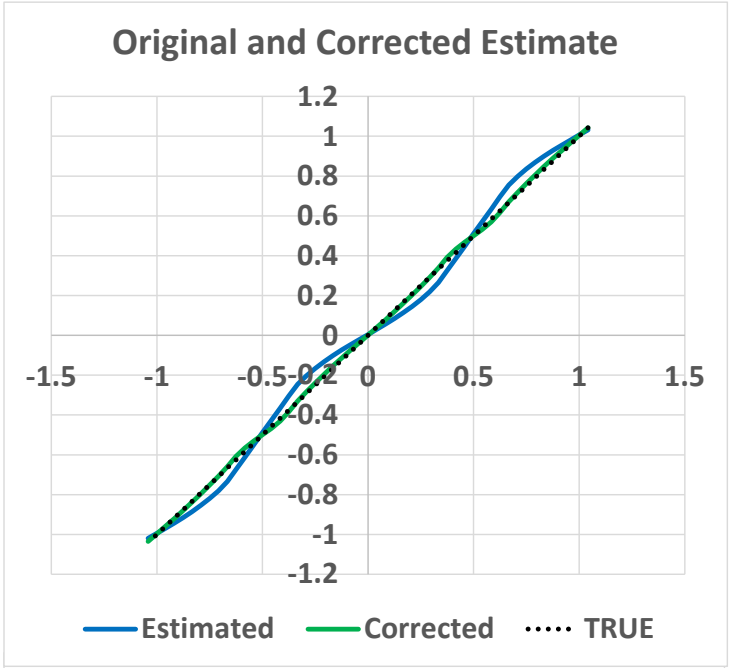
- Linear interpolation results in similar registration metrics at all zoom factors
  - *Here, SPF = Sub-Pixel Factor = amount of linear interpolation*
- These correlations were all done within IPATS
- Very little difference is seen in the results
- “Truth” line has been adjusted for observed channel-to channel offset

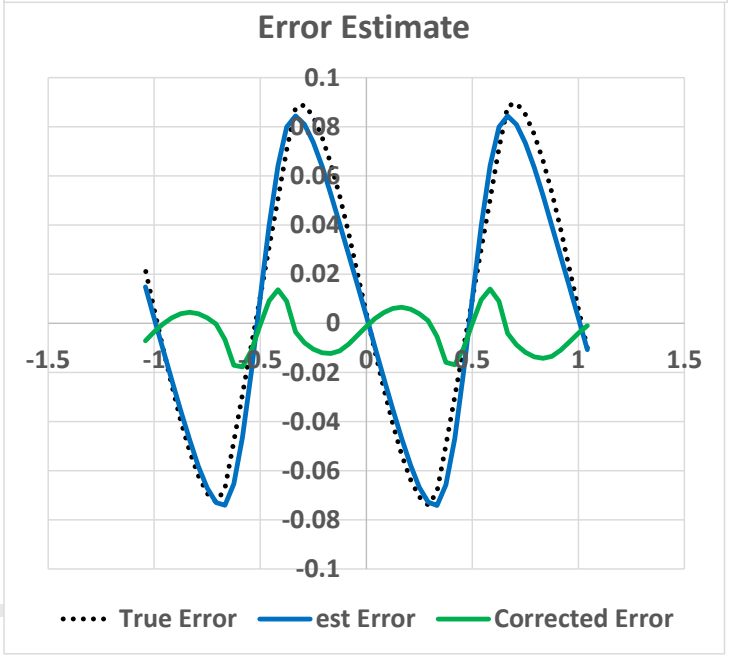


Estimate the Error and Subtract

Data from surrogate ABI images on slide 12

- A small stair-case is estimated by a sinusoidal offset
  - *Zeroes at whole and half pixel shifts*
  - *Maxima at ¼ and ¾ pixel shifts*
  - *Magnitude can be estimated by modeling*
- Stair-case cannot be eliminated this way, but can be greatly reduced





Method-of-choice for FFR, SSR, and CCR

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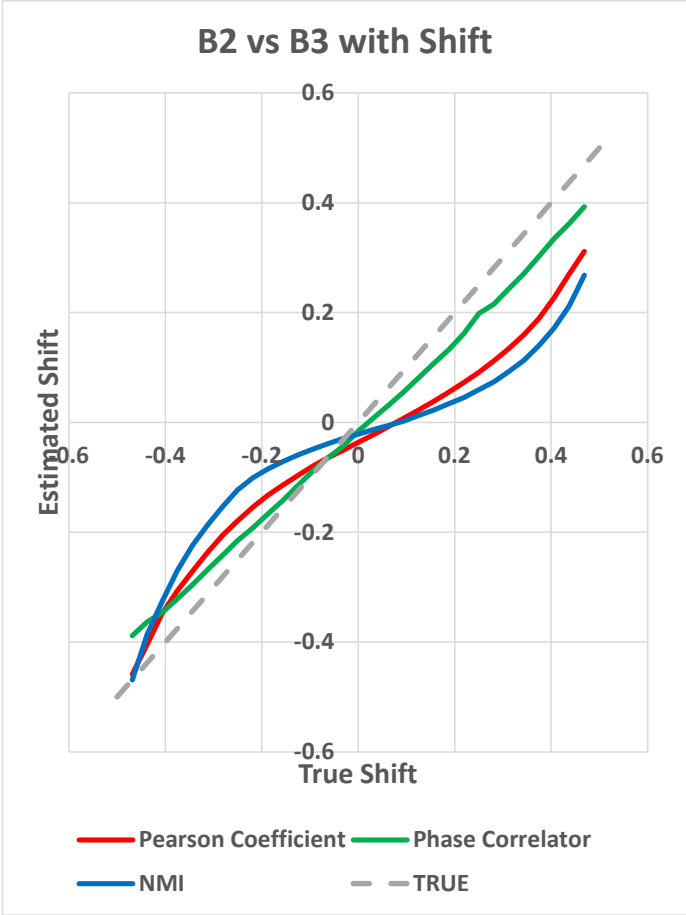
Choose a Better Correlator

Data from surrogate ABI images on slide 12

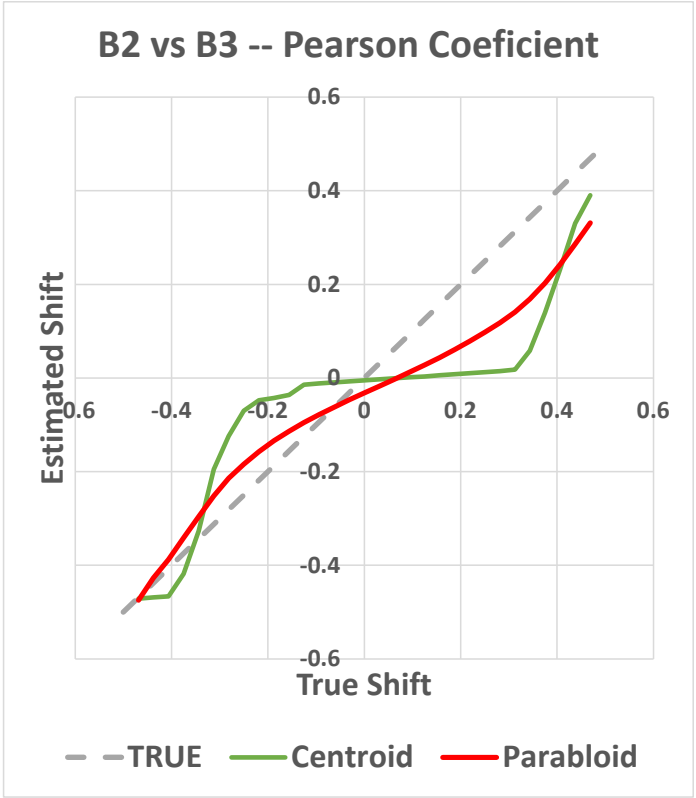
- Normalized Cross-Correlation (NCC) performs better than NMI when images are in similar bands
  - *NMI has an advantage for dissimilar CCR combinations—visible to IR*
- A phase-space correlator operating in the Fourier domain is being evaluated as an alternate solution



Choose a Better Output Interpolator

Data from surrogate ABI images on slide 12

- The goal is to find the location of the primary peak in the output correlation plane at subpixel accuracy
- We have evaluated two interpolators
  - *Both interpolators start at the location defined by the largest value in the correlation plane*
  - *The "Centroid" interpolator finds the center-of-mass of the pixels in a 5x5 region about the peak in the correlation plane*
  - *The "Parabolic" interpolator fits one-dimensional parabolas to the correlation peak in the x and y dimensions*



Conclusions

- We have described the stair-step registration artifact
- We have shown this may be an issue for GOES-R ABI registration
  - *Of order tenth pixel if misregistration is spread across a full pixel*
  - *Much smaller if misregistration is always a quarter pixel or less*
  - *Estimated subpixel misregistration smaller than actual*
- Effect of stair-step can be minimized
  - *Good choice of correlator*
  - *Good choice of interpolator*
  - *Remaining effect can be estimated and compensated*

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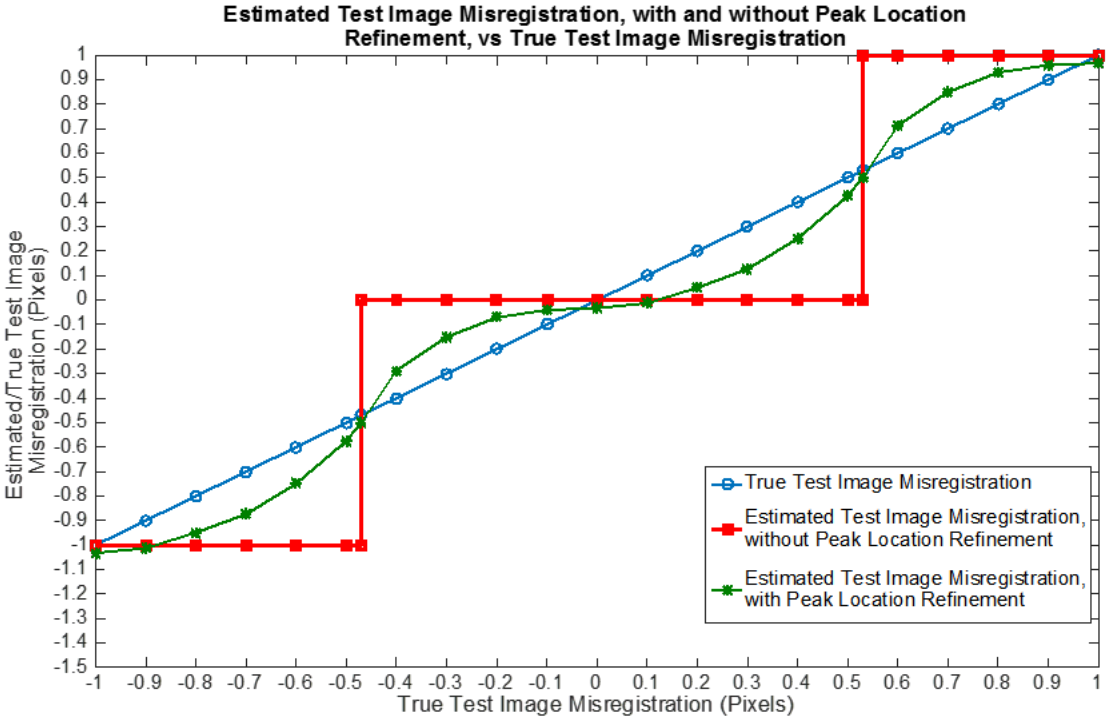
Backup

But Why?

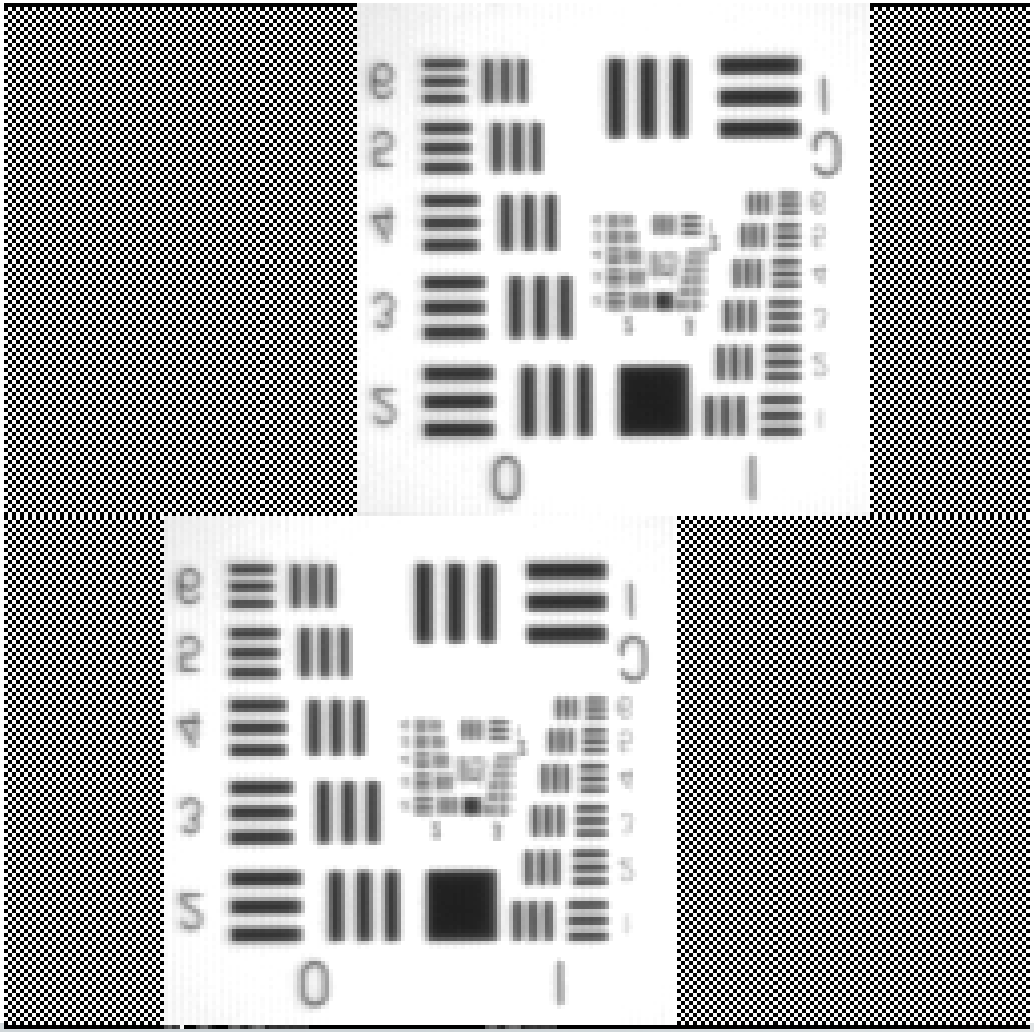
A Notional Explanation

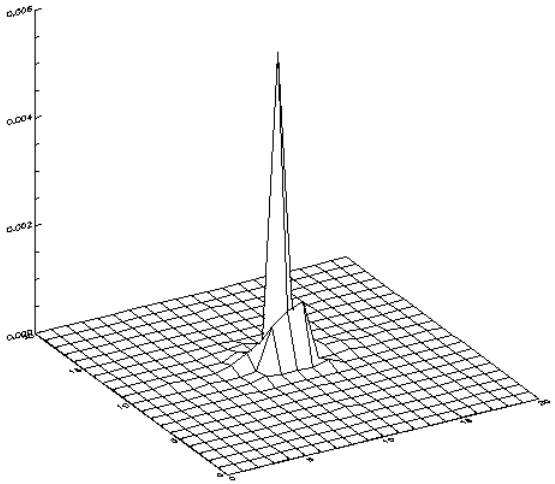


- I plan to build an animation here showing how the stair-step must arise if you start with an assumption that the measured values are correct in a region around the sample point
  - *That is, you get stair-step if you estimate the points but don't estimate or under-estimate the slopes*
  - *Frank—I believe that the parabolic refinement will estimate the line with minimum slope that passes through three points. Is this true?*

We assume an area around the measurement to be correct

Linear JTC Input and Correlation Peak





- Correlation computed digitally

Material from Grycewicz et.al., Proc. SPIE 66950J

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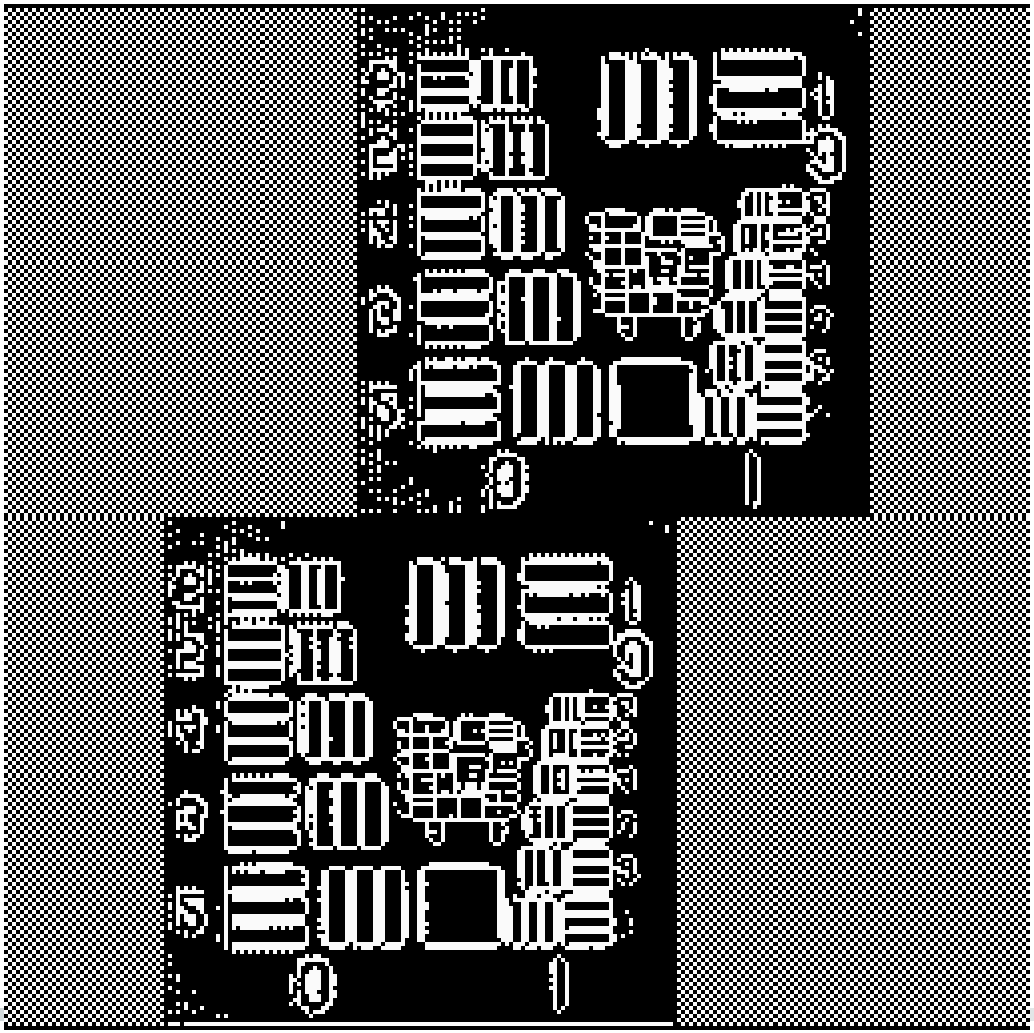
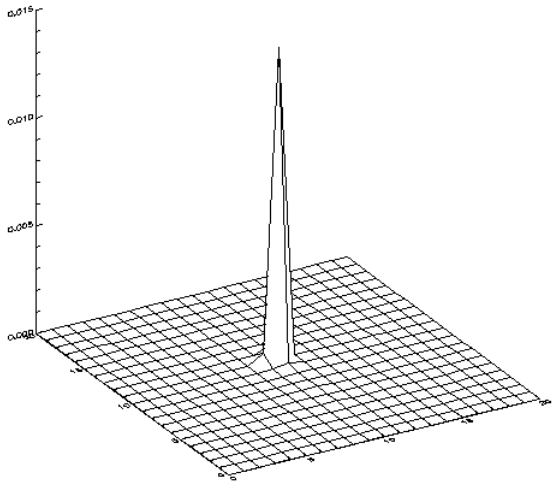
Binary JTC Input and Correlation Peak

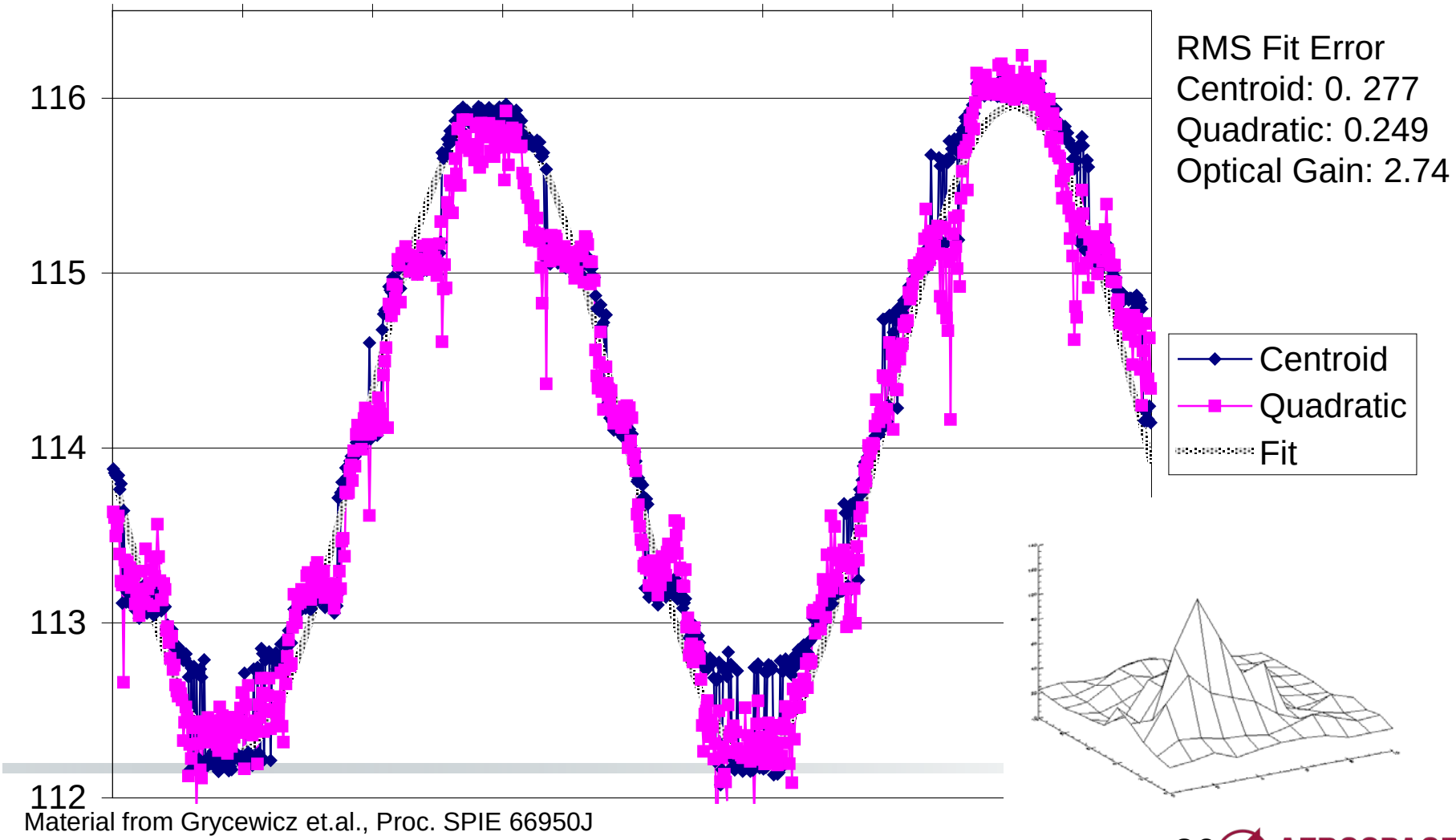




- Binarized by convolving with Laplacian kernel and thresholding
- Correlation computed digitally

Material from Grycewicz et.al., Proc. SPIE 66950J

Two-Stage Joint Transform Correlator, Binary Input



Material from Grycewicz et.al., Proc. SPIE 66950J

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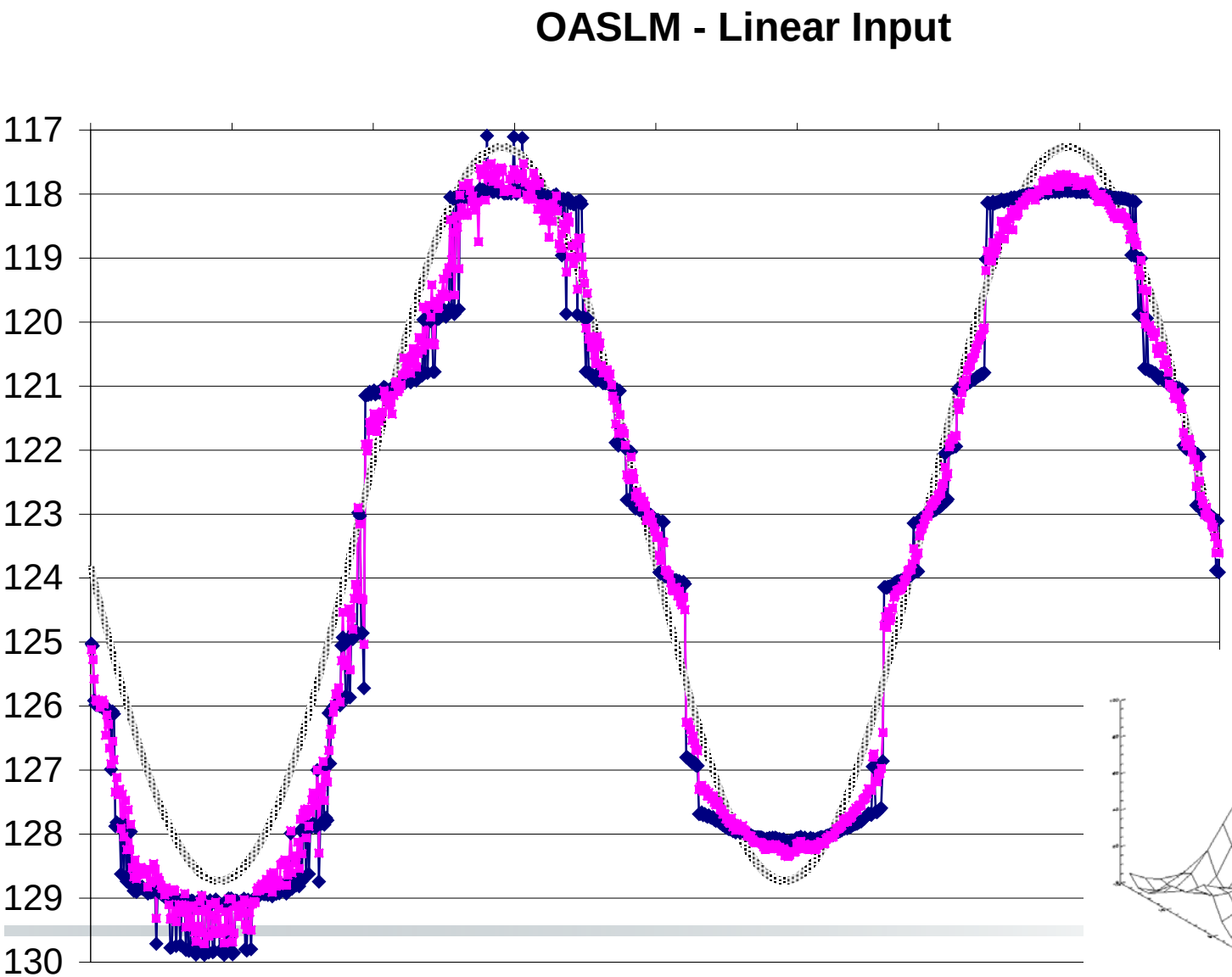
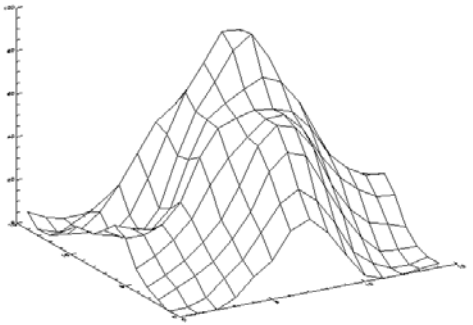
All-Optical JTC, Linear Input





Material from Grycewicz et.al., Proc. SPIE 66950J