Landsat 8 L1T Product Radiometric Pixel Uncertainty

Approach and Algorithm Overview

CEOS WGCV IVOS 34

US Geological Survey, Reston Virginia

August 31, 2022

Special Thanks and Acknowledgements

- This work has been funded by the USGS at the EROS Data Center under Subcontract SMS0004450 through Prime Contract Number 140G0121D0001 with KBR Services, LLC

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Outline

- Overview and Approach
- L1T Radiometric Uncertainty Algorithm Discussion
  - Uncertainty Components
  - Uncertainty Component Magnitudes
- Summary and Next Steps
  - GUI-based Landsat-8 Pixel Uncertainty Tool
  - Expanding to L2 products

Relationship to Previous Work

- Gorrono et. al[1] developed the S-2 Radiometric Uncertainty Tool (RUT)
  - Emphasized SI traceability based on first principles
  - Produced per-pixel radiometric uncertainty but did not include resampling
- Developed a similar uncertainty propagation framework for L8 with additional extensions
  - SI traceability provided by Ball Aerospace
  - Greater emphasis on interpolation related errors
    - Intrinsic interpolation error
    - Sensor noise propagation
    - Coupling of geometric and radiometric uncertainties

[1]*Gorroño, Javier, Ferran Gascon, and Nigel P. Fox. 2015. "Radiometric Uncertainty per Pixel for the Sentinel-2 L1C Products." In Proceedings of SPIE, edited by Roland Meynart, Steven P. Neeck, Haruhisa Shimoda, Toshiyoshi Kimura, 96391G. Toulouse, France. https://doi.org/10.1117/12.2192974.*

Pixel Uncertainty Goal

- Develop algorithms to estimate radiometric uncertainties of Landsat 8 L1T and L2 products (OLI and TIRS)
- Quantify the magnitudes of the effects for data users → When do they matter?

Presentation focused on OLI L1T products

Propagation of Uncertainty

ISO Guide to the Expression of Uncertainty of Measurement

The uncertainty in a quantity y formed by combining N measured quantities x_i through the relationship $y = f(x_1, x_2, \ldots x_N)$ is given by:

$$u^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + \sum_{i=1}^{N} \sum_{j \neq i=1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

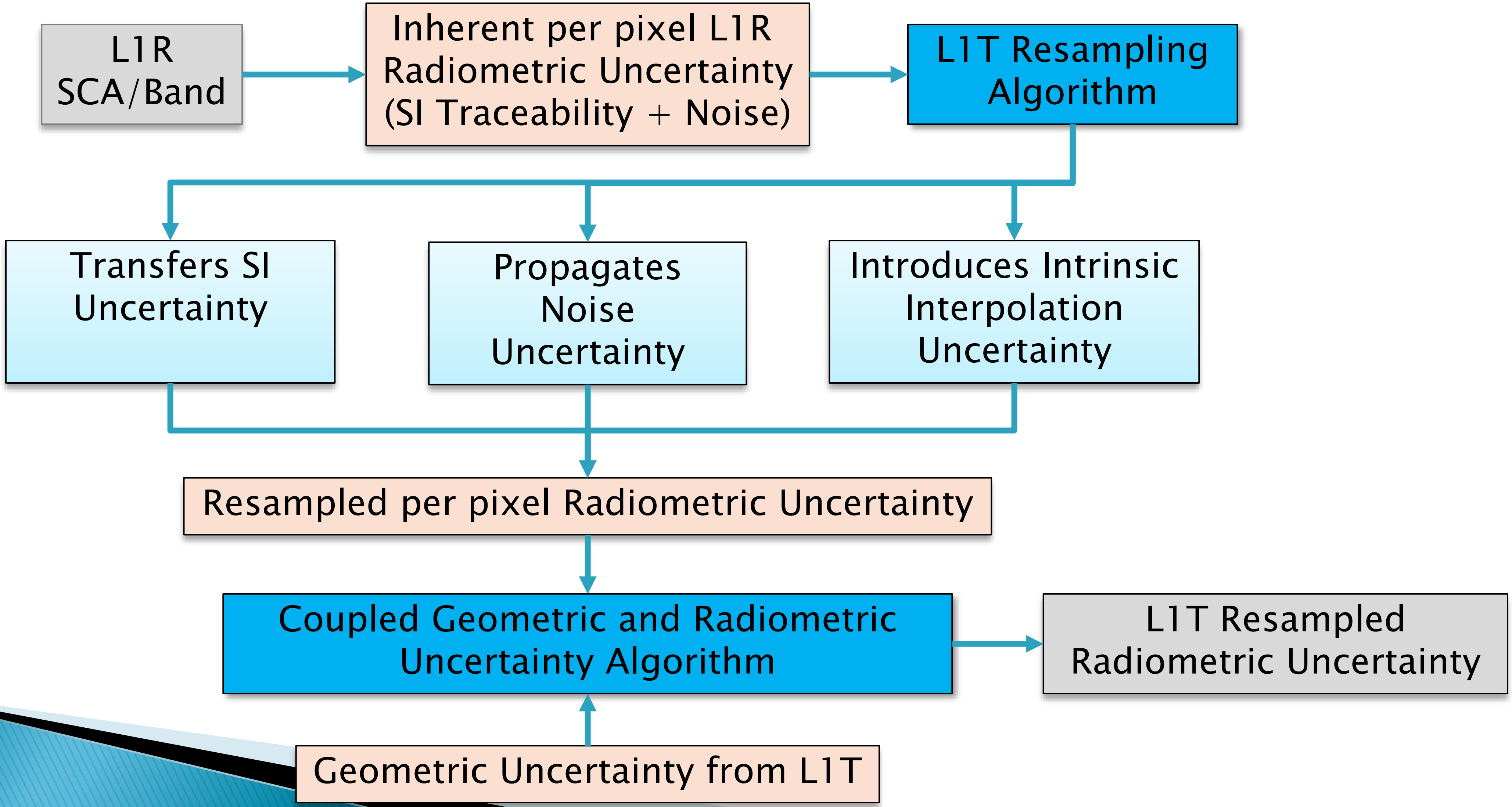
Where: $u(x_i)$ is the uncertainty in x_i and $u(x_i, x_j)$ is the covariance between x_i and x_j. If the combined x_i and x_j are independent (i.e., uncorrelated), the term reduces to zero and the above expression reduces to the "sum of squares" commonly applied.

Approach

- Use the L8 Cal/Val Algorithm Development Document (ADD)[1] processing algorithms to calculate partial derivatives and build up uncertainty estimates
- Developing signal-dependent, per-pixel radiometric uncertainty
  - Includes radiance/reflectance gain uncertainty (SI uncertainties)
  - Integrates updated per-detector radiometric noise model
- Developing algorithms to propagate radiometric uncertainty through interpolation
  - Landsat resampling algorithm, including intrinsic interpolation errors
  - Coupled radiometric and geometric uncertainty
  - Identifying pixels affected by saturation
  - Currently not focused on algorithm speed or data management

[1]*Landsat, U.S.G.S. "Landsat 8-9 Calibration Validation Algorithm Description Document—Version 3.0, Document Number LDCM-ADEF-001." US Geological Survey: Sioux Falls, SD, USA (2013).*

L1T Radiometric Resampling Uncertainty

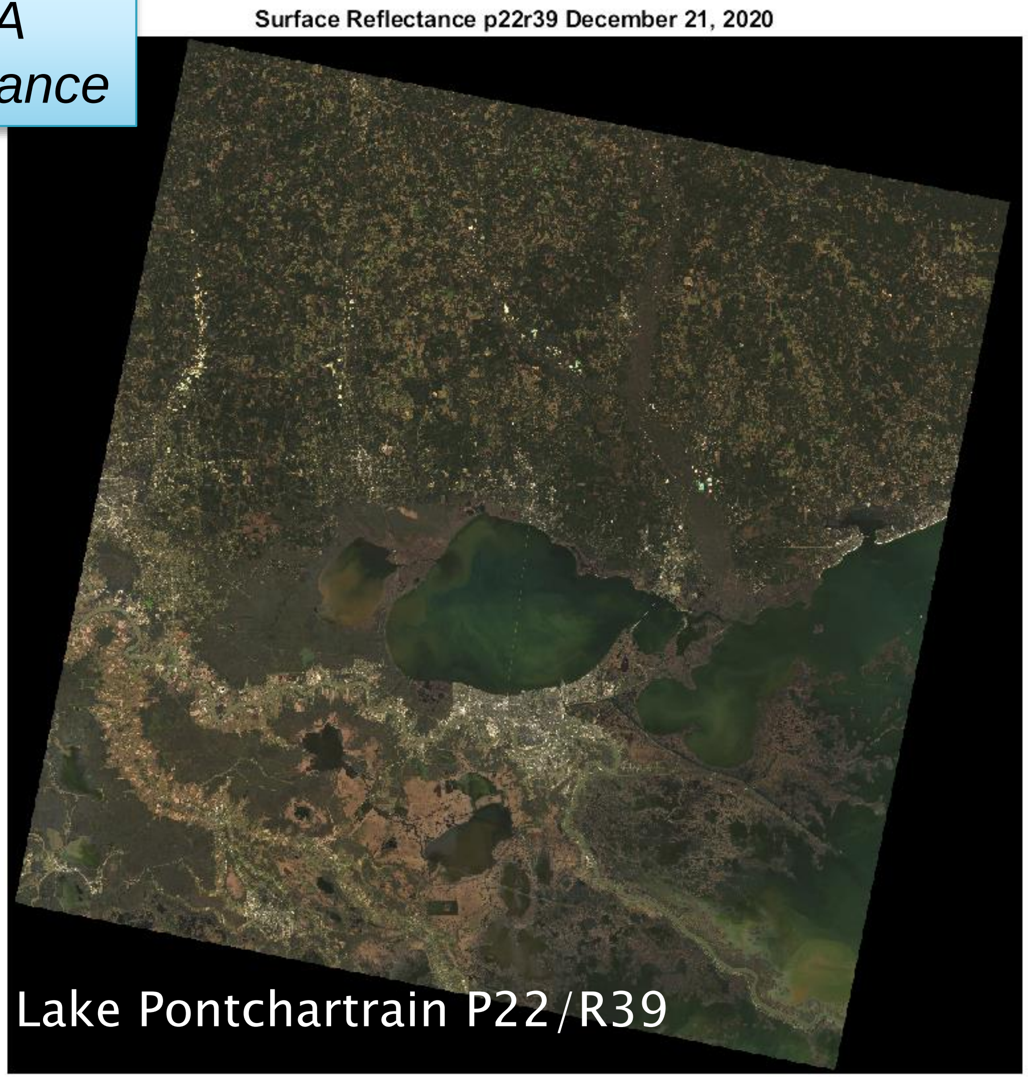


When Does Each Component Matter??

- SI radiometric uncertainty
  - Dominant term for most scenes
  - Only driver on uniform scenes
- Sensor noise (e.g., read noise, fixed pattern noise, photon noise, …)
  - Increases with low signal
  - Important for low light level/dark scenes
- Intrinsic interpolation uncertainty
  - Is larger over strong radiance/reflectance gradients
  - Increases near sharp transitions/features
- Coupled geometric/radiometric uncertainty
  - Is larger over strong radiance/reflectance gradients
  - Increases near sharp transitions/features

Landsat 8 Test Imagery (RGB)

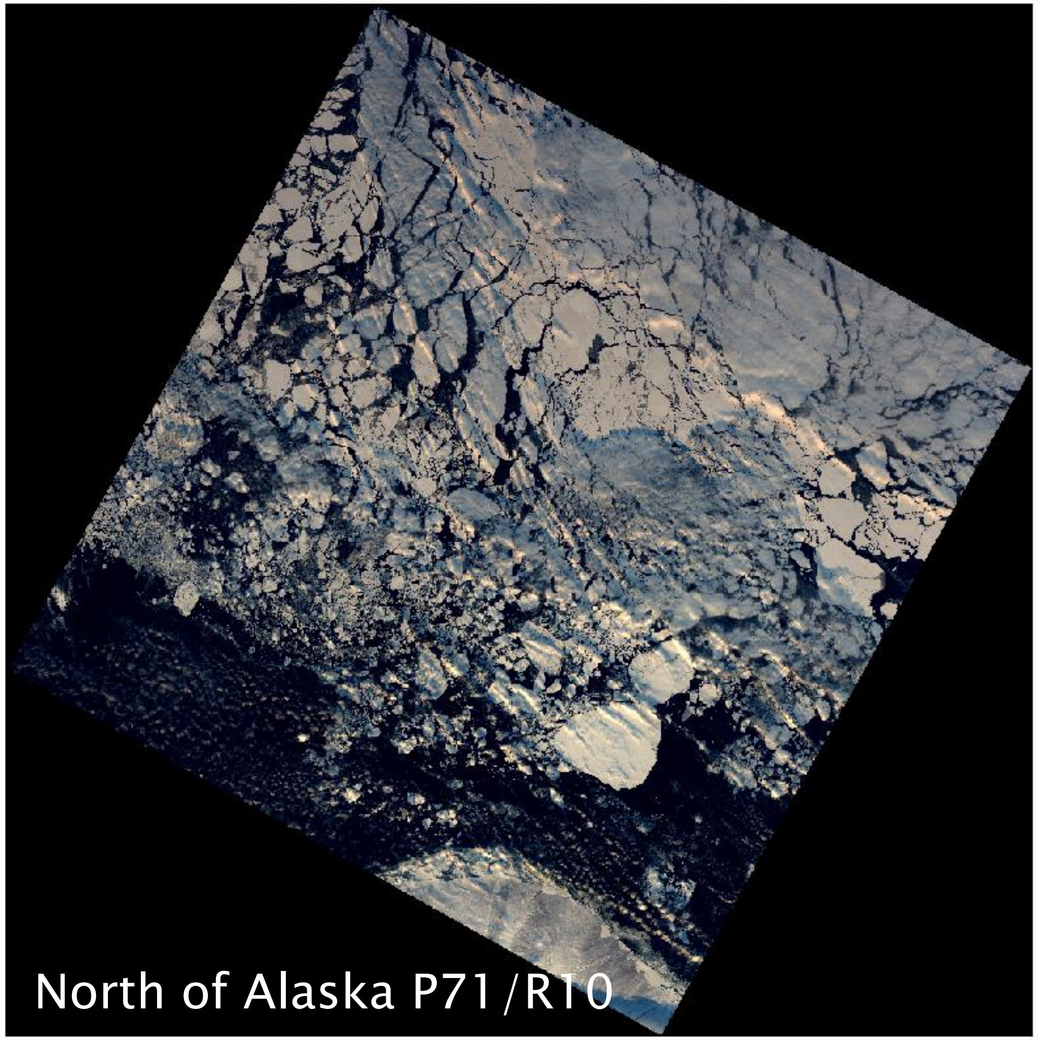
BOA Reflectance



Landsat 8 Test Imagery (RGB)

TOA Reflectance

TOA Reflectance p71r10, October 25, 2020



L1R (Inherent) Radiometric Uncertainty

SI Radiometric Uncertainty

Sensor Noise

SI Radiance/Reflectance Uncertainty Values

Band	TOA Radiance High Radiance (L_{typ} – 0.9*L_{max})	TOA Radiance Low Radiance (0.3*L_{typ} – L_{typ})	TOA Reflectance High Radiance (L_{typ} – 0.9*L_{max})	TOA Reflectance Low Radiance (0.3*L_{typ} – L_{typ})
Coastal Aerosol	3.4 %	3.7 %	2.1 %	2.7 %
Blue	3.1 %	3.4 %	1.9 %	2.6 %
Green	3.0 %	3.3 %	1.7 %	2.5 %
Red	2.9 %	3.2 %	1.7 %	2.4 %
NIR	3.0 %	3.3 %	1.7 %	2.4 %
SWIR1	3.3 %	3.7 %	2.2 %	2.8 %
SWIR2	3.2 %	3.6 %	2.0 %	2.6 %
Pan	3.4 %	3.7 %	1.7 %	2.5 %
Cirrus	4.1 %	4.5 %	2.3 %	2.8 %

Ball Aerospace provided uncertainties

- Emerging on-orbit calibration techniques may improve the SI uncertainty
  - Cross-calibration with advanced SI traceable hyperspectral calibrators
    - CLARREO PF, TRUTHS and others
  - Improved vicarious calibration methods

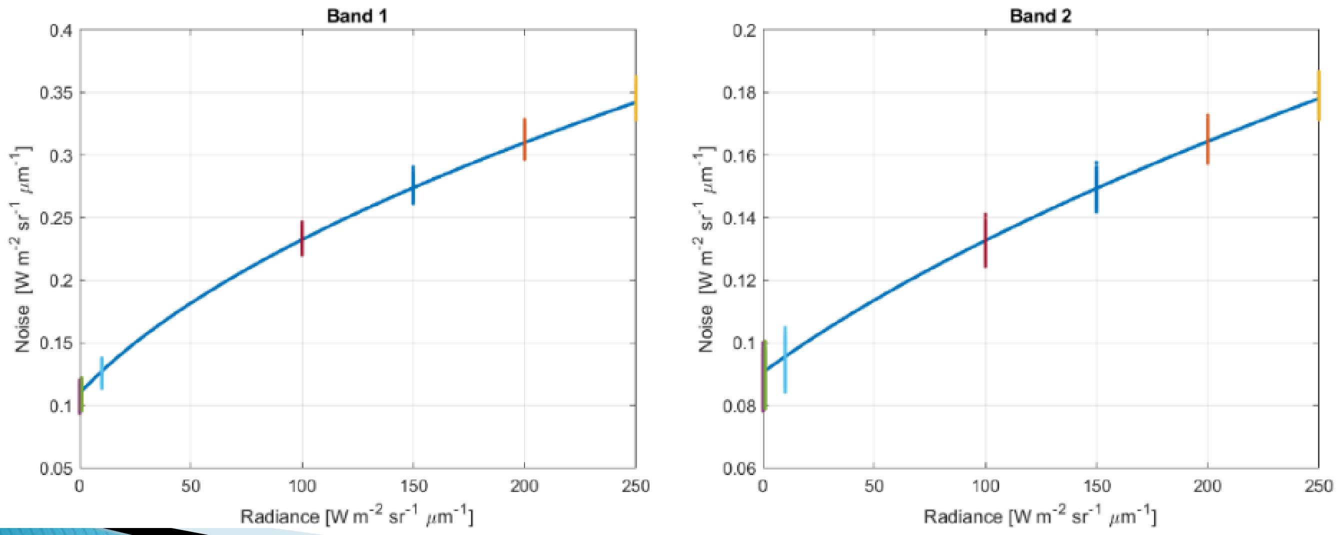
Initial Algorithm SI Radiance/Reflectance Uncertainty Values

Band	$L_{typical}$ (W/m^2 sr µm)	L_{max} (W/m^2 sr µm)	TOA Radiance Uncertainty At/Above $L_{typical}$	TOA Radiance Uncertainty Below $L_{typical}$	TOA Reflectance Uncertainty At/Above $L_{typical}$	TOA Reflectance Uncertainty Below $L_{typical}$
Coastal Aerosol	40	190	3.4 %	3.7 %	2.1 %	2.7 %
Blue	40	190	3.1 %	3.4 %	1.9 %	2.6 %
Green	30	194	3.0 %	3.3 %	1.7 %	2.5 %
Red	22	150	2.9 %	3.2 %	1.7 %	2.4 %
NIR	14	150	3.0 %	3.3 %	1.7 %	2.4 %
SWIR1	4.0	32	3.3 %	3.7 %	2.2 %	2.8 %
SWIR2	1.7	11	3.2 %	3.6 %	2.0 %	2.6 %
Pan	23	156	3.4 %	3.7 %	1.7 %	2.5 %
Cirrus	6.0	N/A	4.1 %	4.5 %	2.3 %	2.8 %

Morfitt, R., J.Barsi, R.Levy, B.Markham, E.Micijevic, L.Ong, P.Scaramuzza, and K.Vanderwerff. "Landsat-8 Operational Land Imager (OLI) radiometric performance on-orbit." Remote Sensing 7, no. 2 (2015): 2208-2237.

OLI Radiometric Noise Model

- Per-detector radiometric noise model was developed for L8 bias subtracted DNs
  - Noise model coefficients were calculated from paired illuminated (solar diffuser/stim lamp) and dark calibration data sets
  - Coefficients are applied to bias subtracted DN values and estimated noise is converted back to radiance
- Per-detector radiometric noise model was verified against published system noise model coefficients[1]



Verification results shown for L8 Bands 1& 2
- *Blue curve calculated using published noise coefficients*
- *Points at discrete radiance values calculated using the per-detector noise model*

[1]Morfitt, R., J.Barsi, R.Levy, B.Markham, E.Micijevic, L.Ong, P.Scaramuzza, and K.Vanderwerff. "Landsat-8 Operational Land Imager (OLI) radiometric performance on-orbit." Remote Sensing 7, no. 2 (2015): 2208-2237.

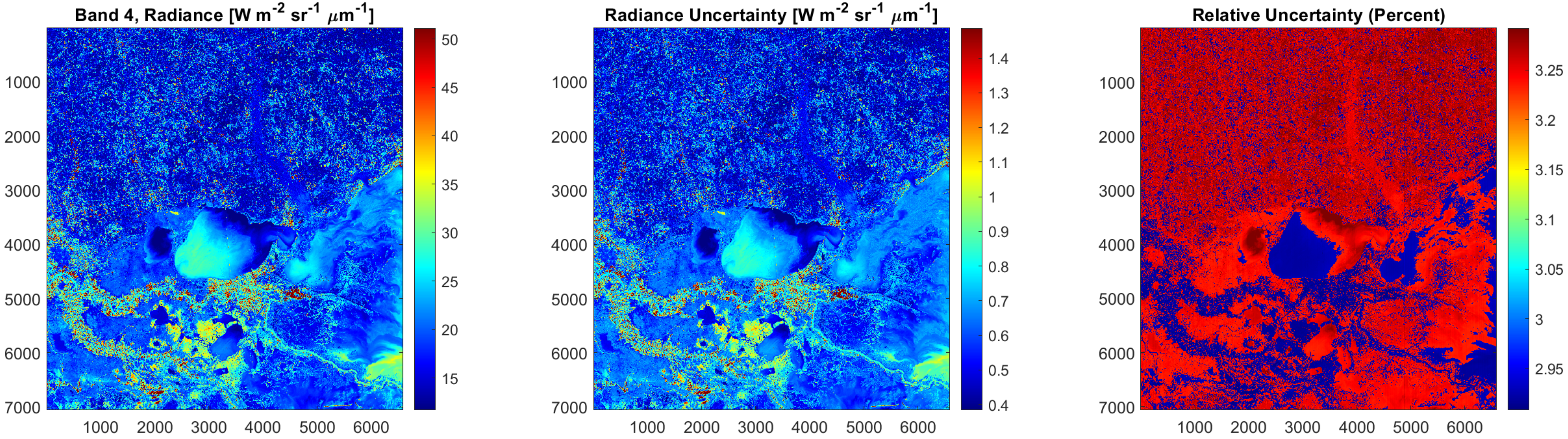
Inherent L1R Per Pixel Radiometric Uncertainty

- OLI L1R radiometric uncertainty combines SI traceable gain uncertainty and radiometric noise model
  - Ball Aerospace provided pre-launch SI traceable uncertainty values for OLI
    - Uncertainties depend on image radiance
  - Per-detector radiometric noise model coefficients were developed
    - Validated against published noise model coefficients
- OLI inherent radiometric uncertainty can be estimated for L1R radiance or reflectance output

$$u(i,j) = \sqrt{\left(\frac{\rho_{noise}(i,j)}{\rho(i,j)}\right)^2 + (\rho_{SI}(i,j))^2} \quad \text{or} \quad u(i,j) = \sqrt{\left(\frac{L_{noise}(i,j)}{L(i,j)}\right)^2 + (L_{SI}(i,j))^2}$$

where,
u = relative radiometric uncertainty
i, j = L1R pixel position
ρ, L = input reflectance or radiance
ρ_{noise}, L_{noise} = reflectance or radiance noise
ρ_{SI}, L_{SI} = reflectance or radiance SI gain uncertainty

L1R TOA Radiance Uncertainty (Inherent)



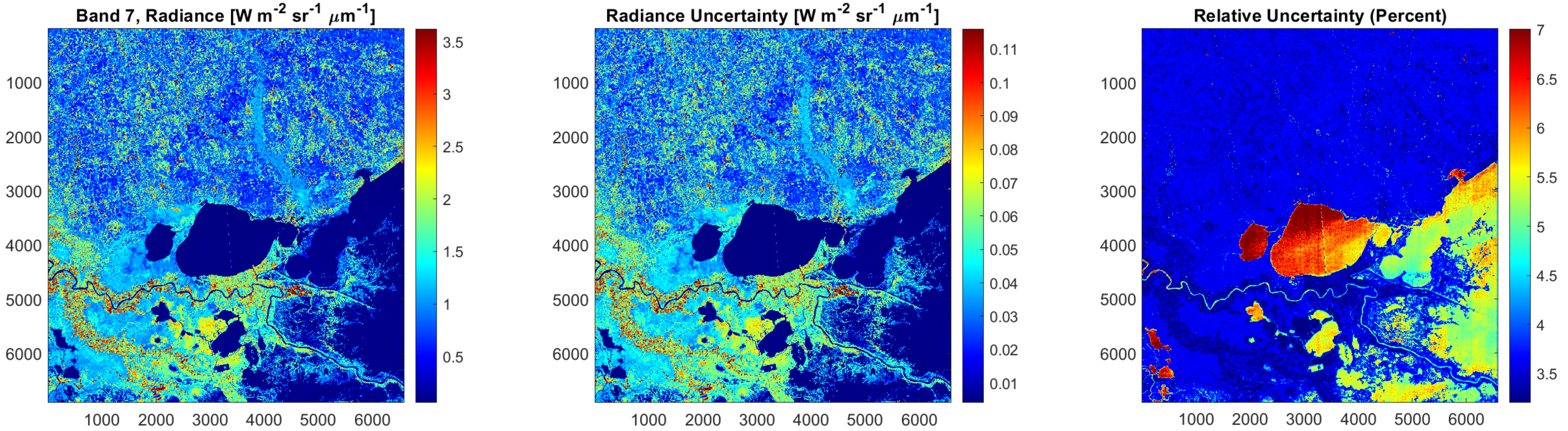
Band 4 $L_{typical}$=22 $Wm^{-2}sr^{-1}um^{-1}$

SI Radiance Uncertainty (High)=2.9%
SI Radiance Uncertainty (Low)=3.3%

SI uncertainty dominates throughout the scene

Lake Pontchartrain P22/R39
Red (Band 4) TOA Radiance Absolute and Relative Uncertainty

L1R TOA Radiance Uncertainty (Inherent)



Band 7 $L_{typical}$ radiance = 1.7 $Wm^{-2}sr^{-1}um^{-1}$
Corresponds to reflectance = 0.0633

SI Radiance Uncertainty (High)=3.2%
SI Radiance Uncertainty (Low)=3.6%

Low signal in SWIR shows increased relative uncertainty due to noise

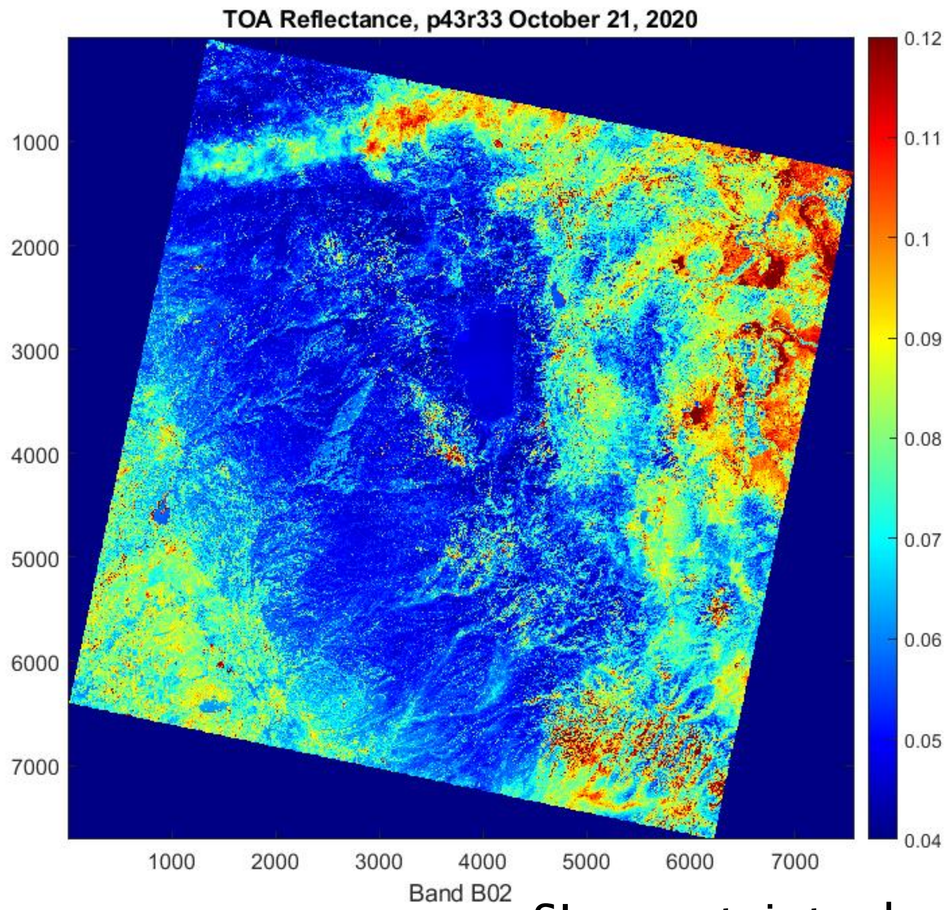
Lake Pontchartrain P22/R39
SWIR2 (Band 7) TOA Radiance Absolute and Relative Uncertainty

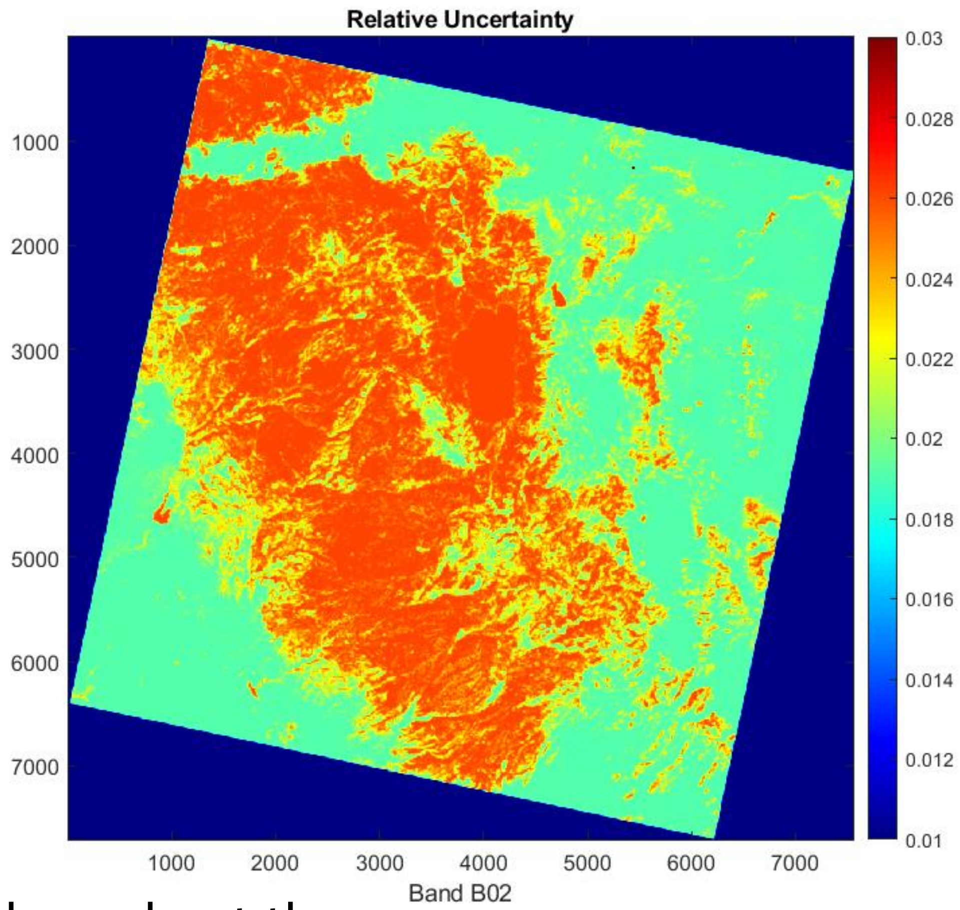
Resampling Uncertainty

Sensor Noise Propagated through Resampling

- Landsat 8 L1R data is resampled to L1T using cubic convolution (in the line or in-track direction) followed by modified Akima (in the sample or cross-track direction) interpolation
  - Interpolation offsets and kernel weights are defined for every pixel
  - 24 pixels are used in the interpolation
- Landsat resampling algorithm was modified to include the resampling uncertainty calculation
  - Partial derivatives calculated for cubic convolution and modified Akima interpolators propagate the noise through the resampler
  - Most uncertainty values estimated directly from the interpolation equations

Resampled Radiometric Output (Reflectance)

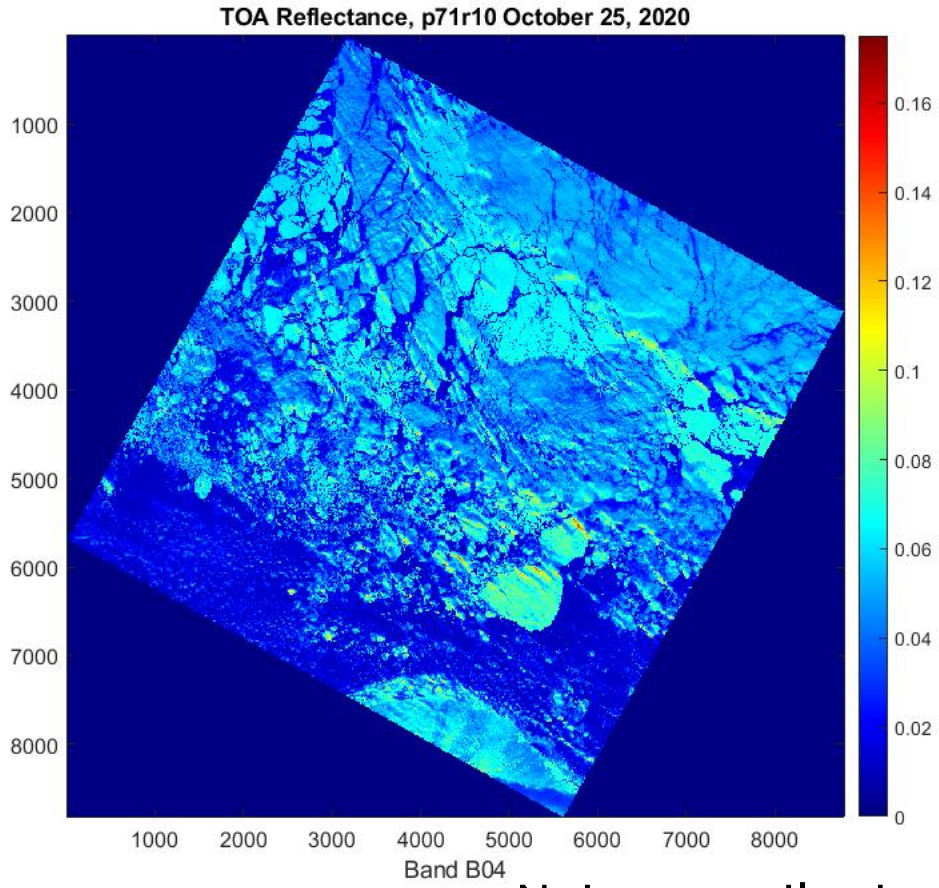


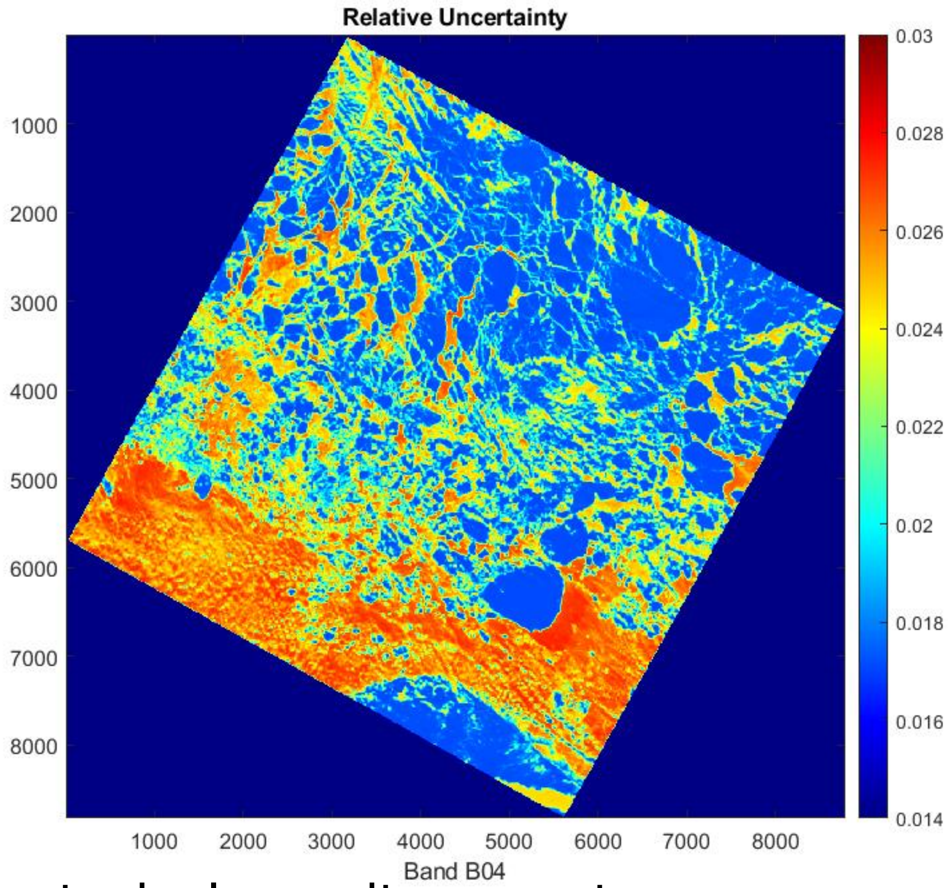


SI uncertainty dominates throughout the scene

Lake Tahoe P43/R33; Blue (Band 2)

Resampled Radiometric Output (Reflectance)





Noise contribution apparent in the low radiance region

Artic North of Alaska P71/R10 Red (Band 4)

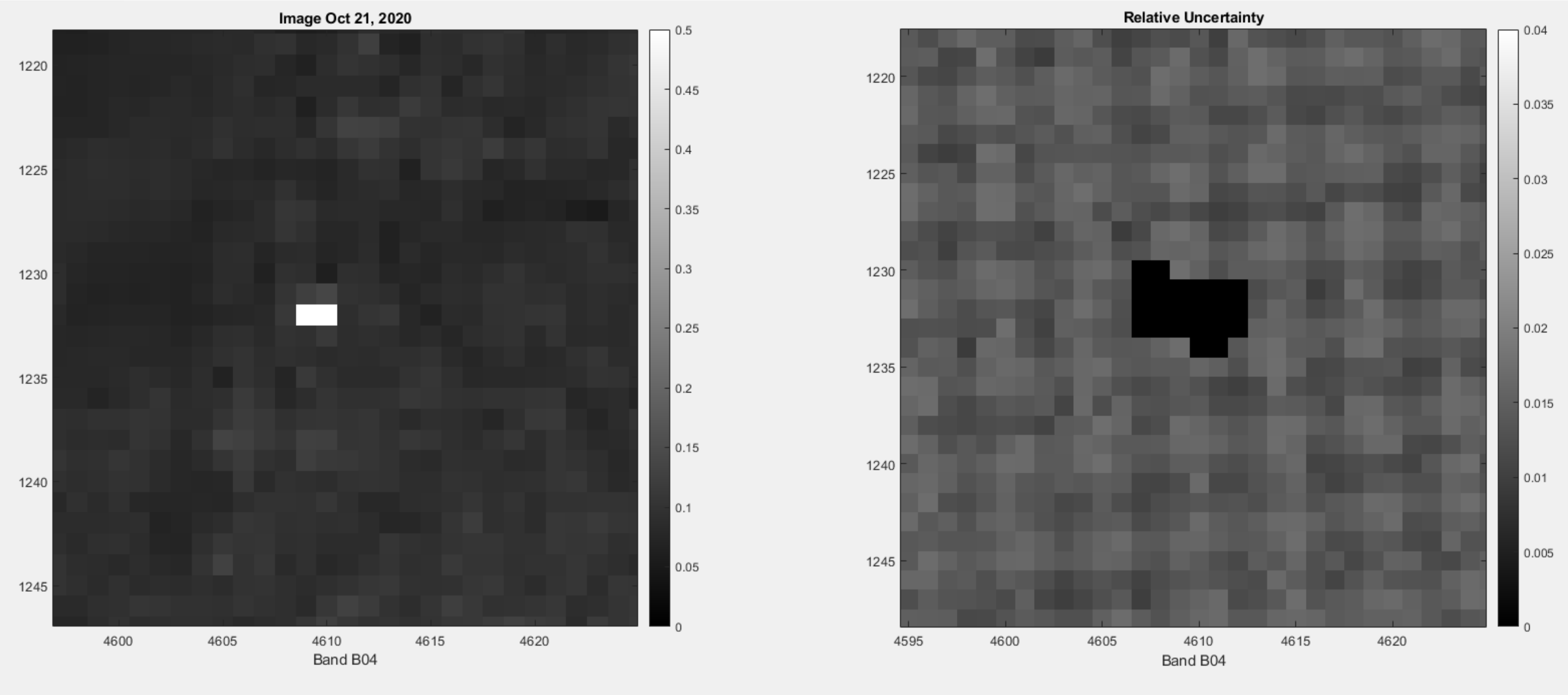
Saturated Pixels

Saturated Pixels

- Some pixels that pass through the resampling algorithm may be saturated
  - Uncertainty is not known
  - Identified in the saturated pixel replacement file
  - The difference between images interpolated with and without bad pixel correction is used to identify extent of saturated pixel effect
  - All resampled pixels affected by saturation are assigned an “unknown” uncertainty value (-9999)

Saturated Pixel Example 1

Red (Band 4)

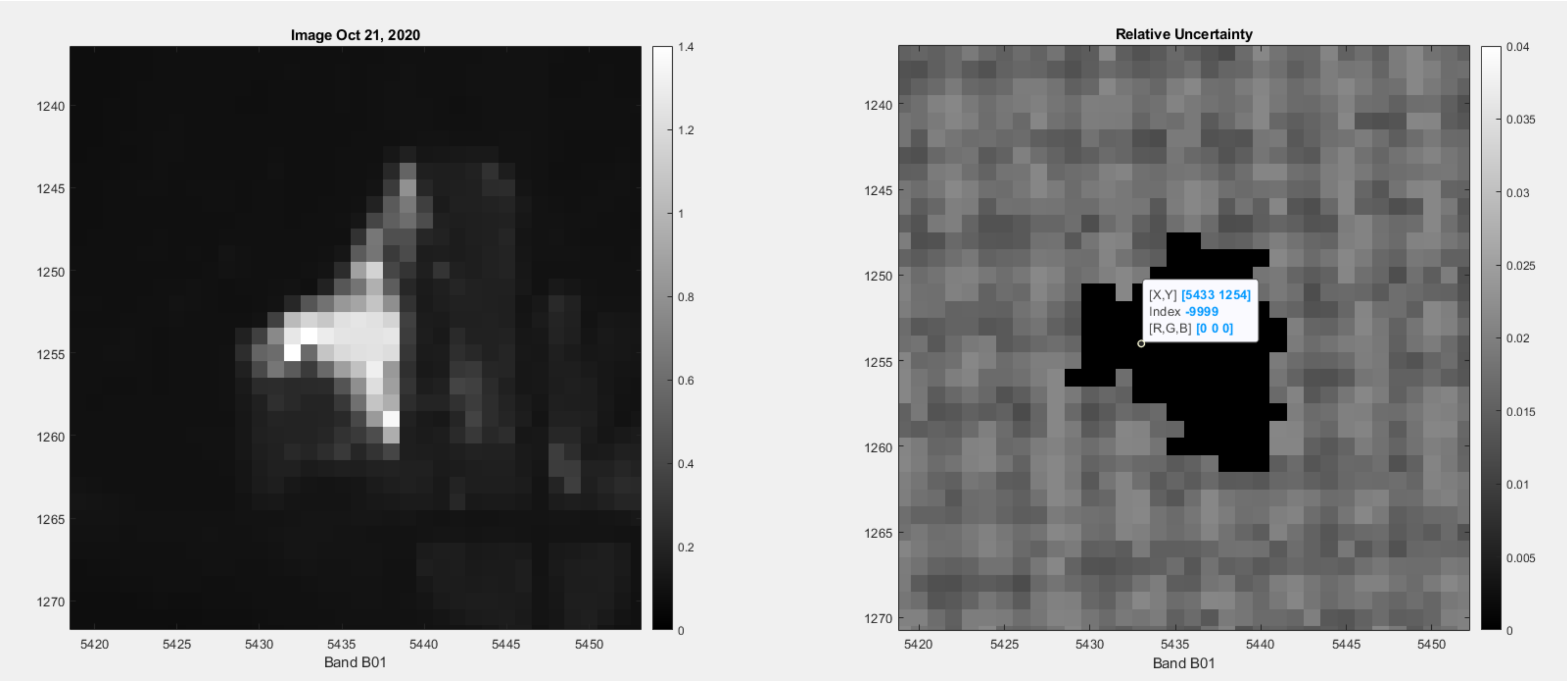


Level 1T TOA Reflectance Output

Level 1T SI Radiometric Uncertainty Propagation

Saturated Pixel Example 2

Coastal Aerosol (Band 1)



Level 1T TOA Reflectance Output

Level 1T SI Radiometric Uncertainty Propagation

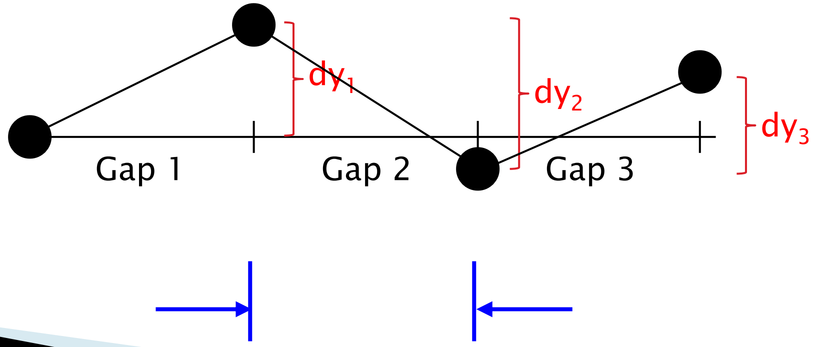
Intrinsic Interpolation Uncertainty

Intrinsic Interpolation Uncertainty Overview

- There is an inherent uncertainty in the estimation of values using interpolation
  - Interpolation errors are dependent on interpolator, signal shape (which is not known), interpolation offset and sampling
    - Largest errors occur for rapidly changing regions (edges) due to large slopes and aliasing
  - Modified Akima (uneven spacing) and cubic convolution interpolator uncertainties are different due to mathematical formulation
- Built an uncertainty model to populate a look-up-table (LUT) based on the slopes of the intervals of each interpolator

Cubic Convolution Interpolator

- The cubic convolution interpolator uses four evenly spaced points to estimate the value between the center two
- Because the observations are evenly spaced, the driving factor is only the differences between the observations
  - The interpolator shape is not affected by scale
  - Slopes in the LUT are scaled and range from −1 to 1, with a spacing of 0.1
  - Uncertainty estimated from the LUT must be scaled back to the original units to determine the error from interpolation

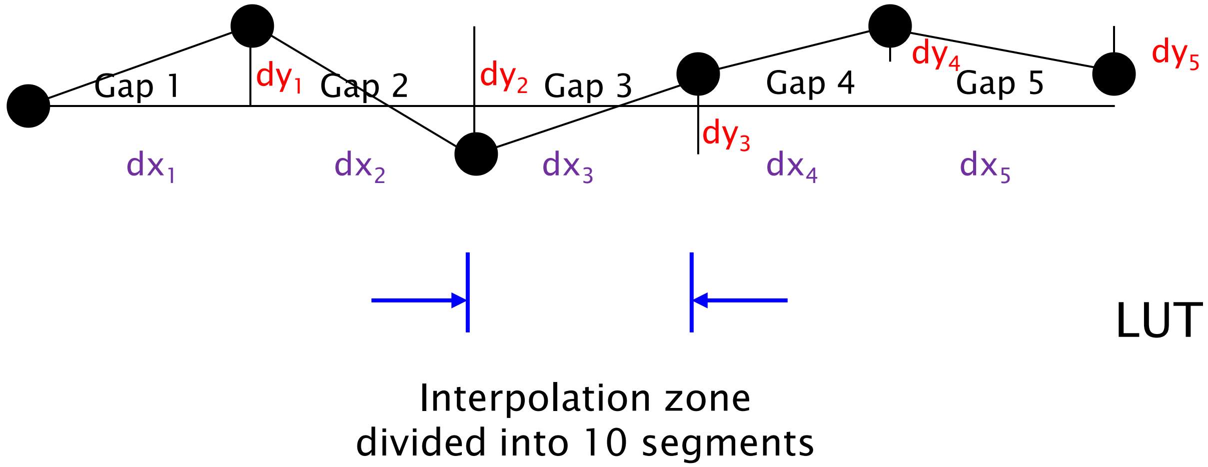


Interpolation zone
divided into 10 segments

LUT coordinate: $$(dy_1, dy_2, dy_3) * \frac{\mathrm{sign}(dy_1)}{\max_i(|dy_i|)}$$

Modified Akima Interpolator

- The modified Akima interpolator implemented uses six points, not all evenly spaced
  - Data is scaled so that the slope ranges from -1 to 1, with a spacing of 0.1
  - Uncertainty estimated from the LUT must be scaled back to the original units to determine the error from interpolation



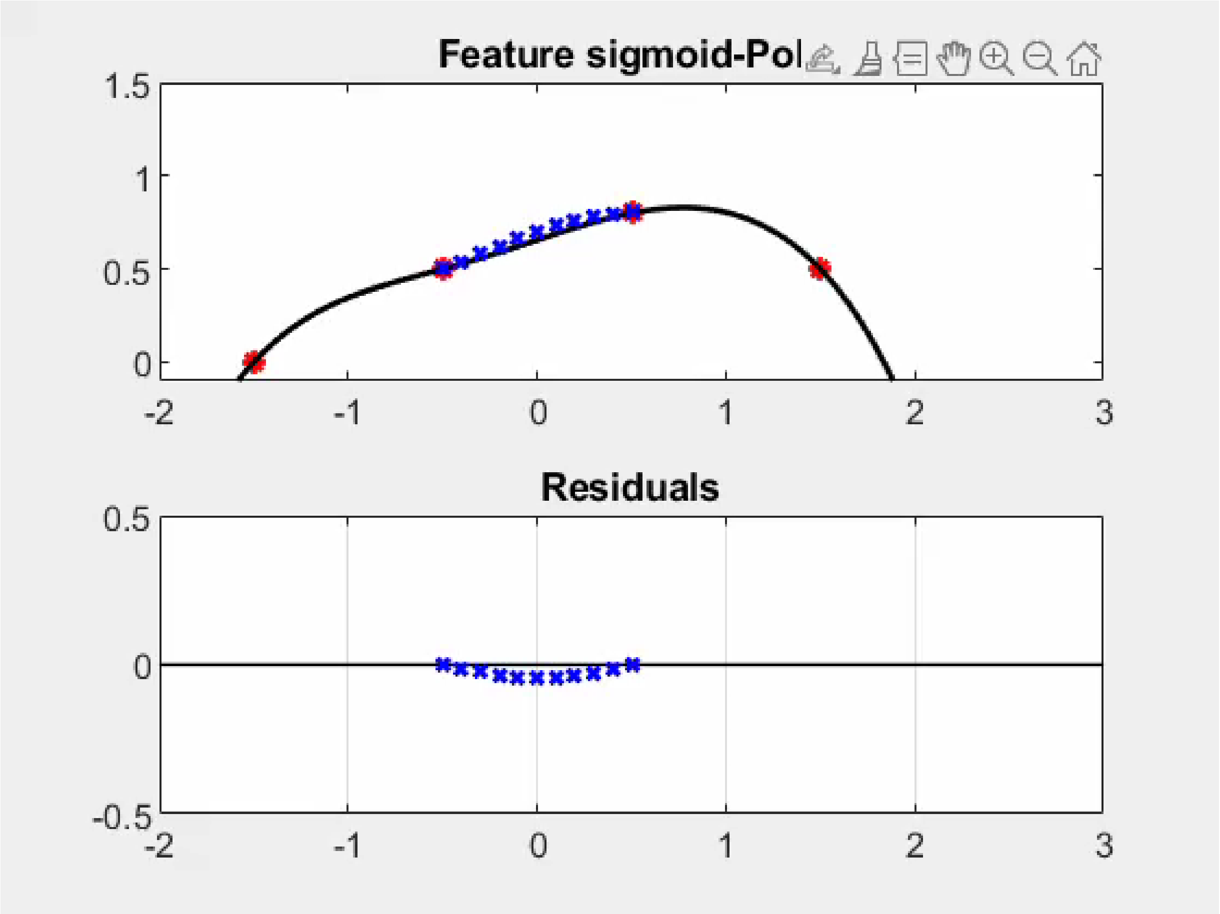
LUT coordinates:

$$m_i = \frac{dy_i}{dx_i}$$

$$\hat{m}_i = \frac{\mathrm{sign}(m_1)}{\max_j(|m_j|)} * m_i$$

Estimating the Interpolator Uncertainty for a Particular Observation

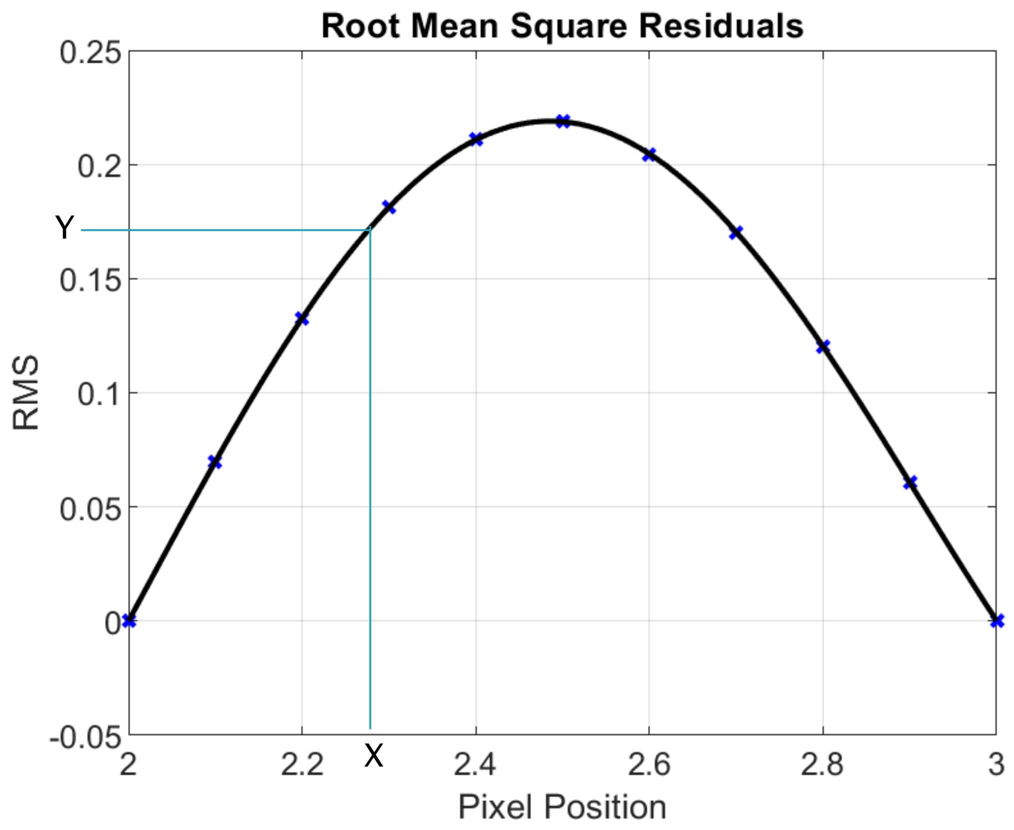
- Technique: create a population of functions based on Sigmoid and Gaussian functions added to polynomials so that they pass through the observation points
- Compare these functions to the interpolation value at nine points (dividing the region into 10 equal areas) in the region of interest



Cubic Convolution example

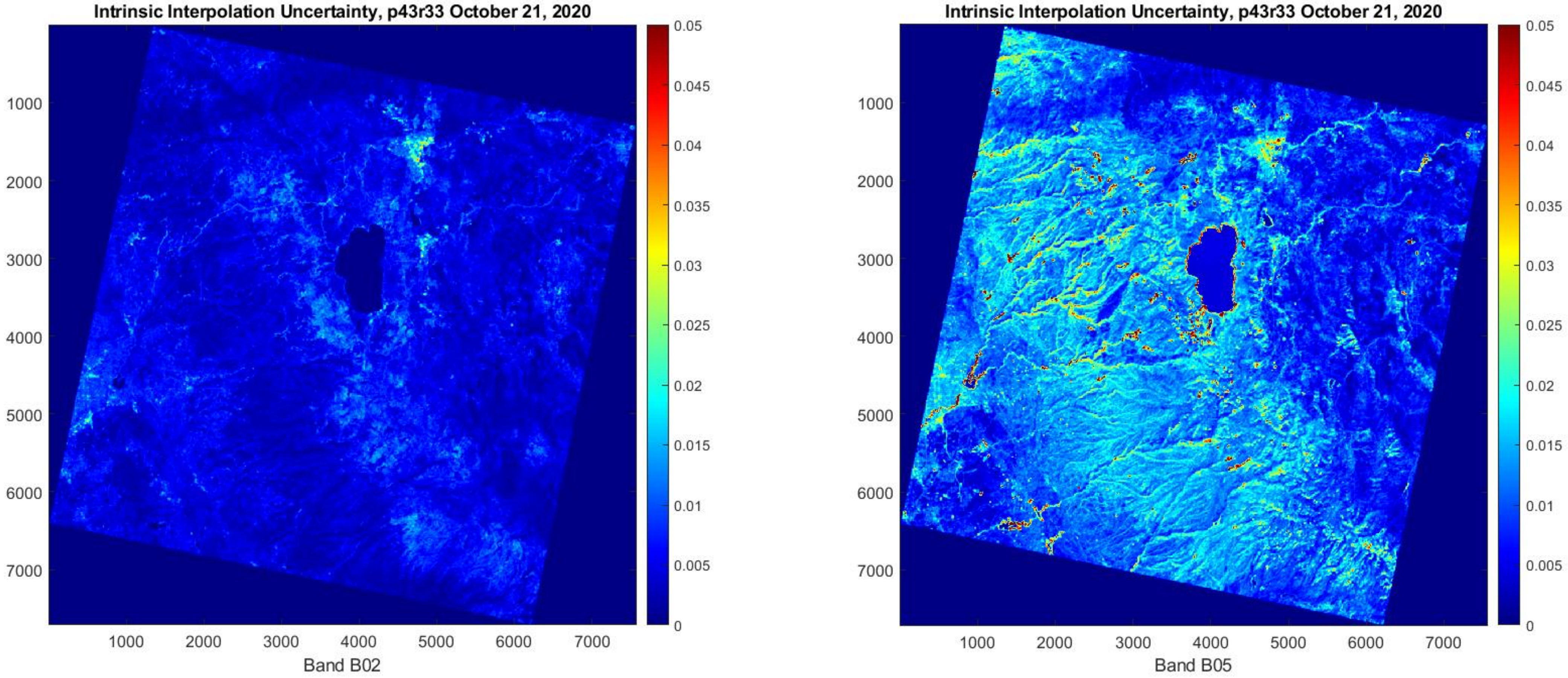
Estimating the Uncertainty

- The blue 'x''s mark the root mean square residuals for the feature shown. The black line shows a 4^{th} order fit of these points.
- The 4^{th} order polynomial is then used to estimate the uncertainty Y at any point X within the interpolation region (between the location of the 2^{nd} and 3^{rd} pixels in the interpolation kernel).



Technique relies on the underlying functions being representative of the features being interpolated

Intrinsic Interpolation Example



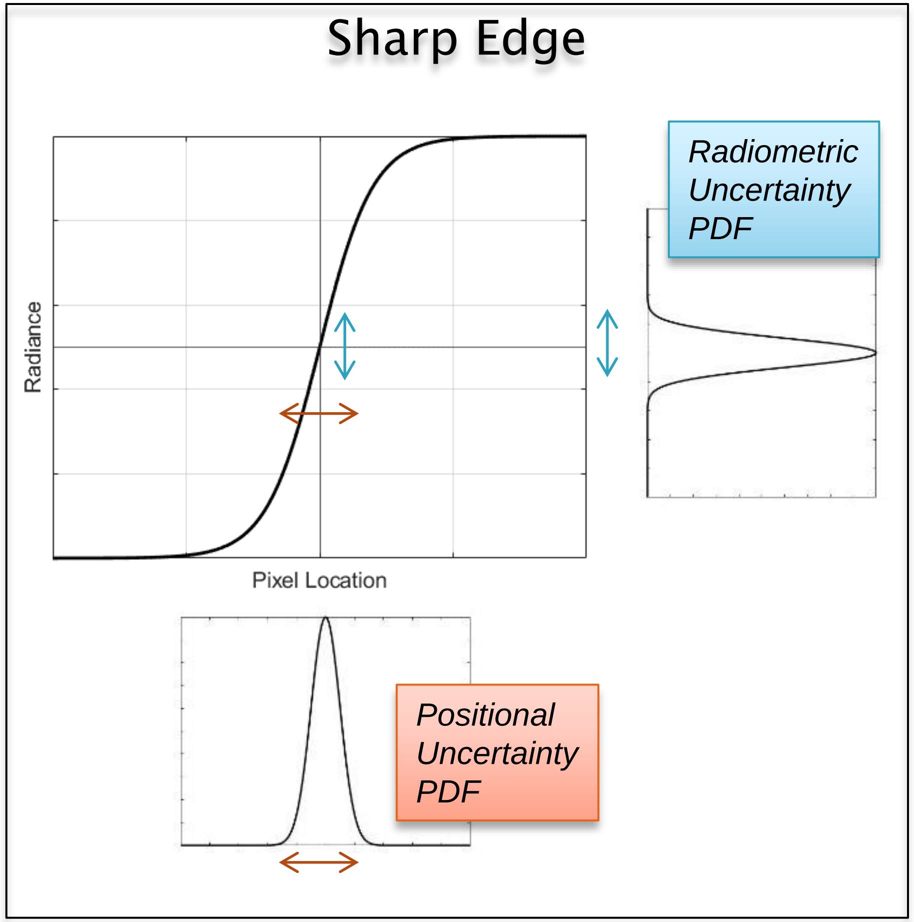
October 21, 2020, P43/R33, Blue Band 2 (left) and NIR Band 5 (right)

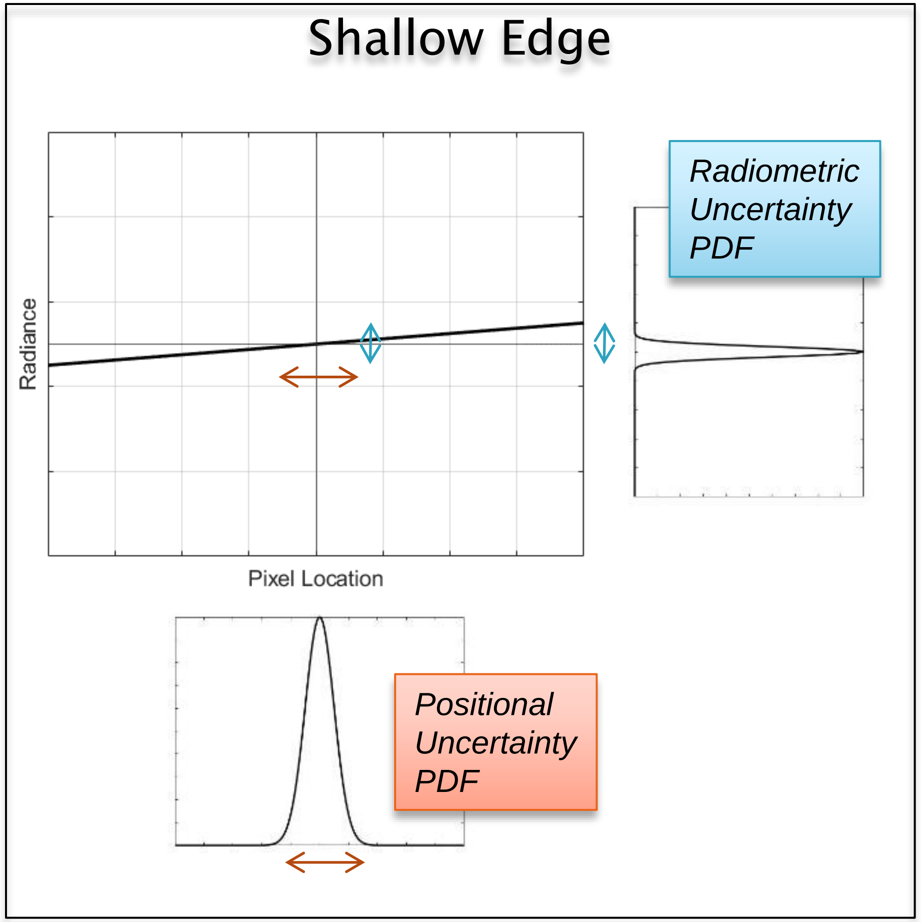
Coupled Geometric and Radiometric Uncertainty

Coupled Geometric and Radiometric Uncertainty

- Although each image is orthorectified, there are differences between different acquisitions of the same path/row
  - Estimated by L1T geometric uncertainty
- Geometric differences affect the interpolation of the L1R data and the estimation of radiometric uncertainty
  - Expect larger effect around features such as edges
- The coupled geometric and radiometric uncertainty is what geometric uncertainty introduces to the radiometric uncertainty during interpolation
  - Combines geometric uncertainty with the gradient of L1T image

Radiometric and Geometric Uncertainty Relationship Example



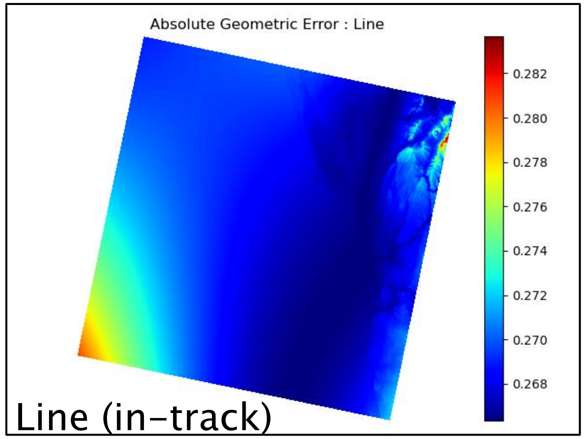


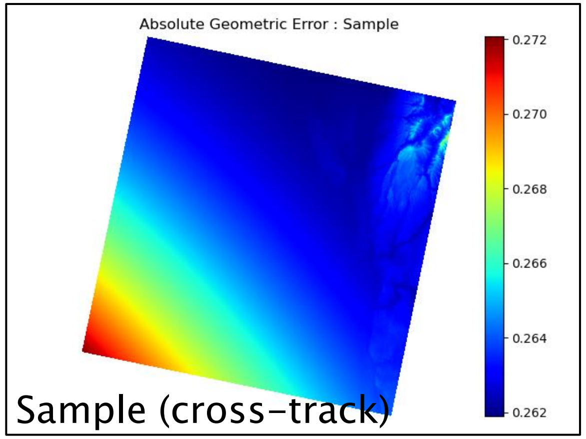
Uncertainty in pixel position knowledge can produce uncertainty in radiance

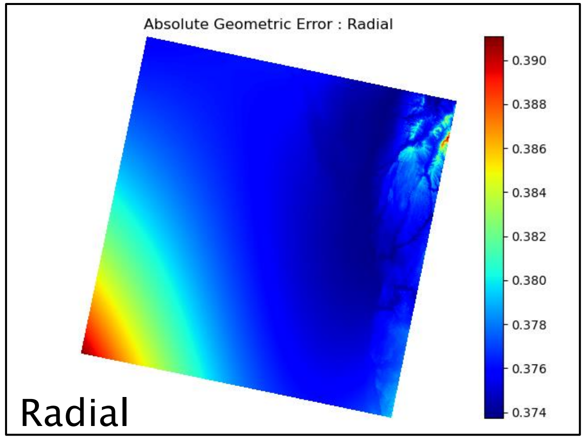
Geometric Uncertainty

- A geometric uncertainty algorithm was developed that uses GCP's directly from the Image Assessment System (IAS)
  - Produces absolute and relative geometric uncertainty

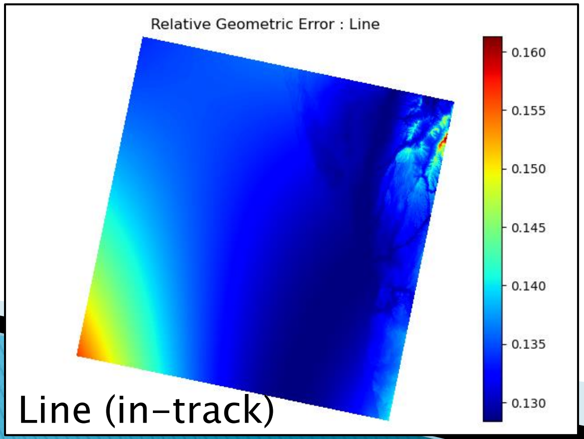
Absolute Geometric Uncertainty

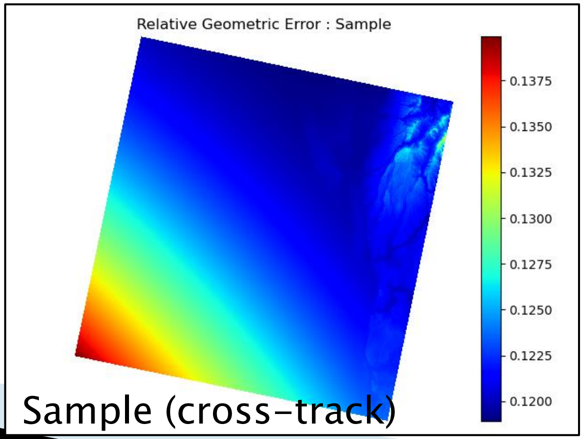


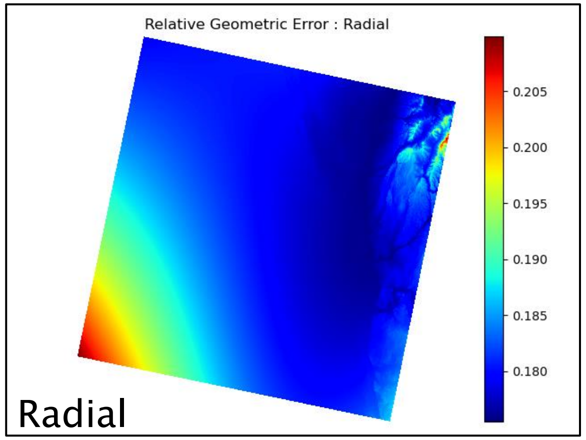




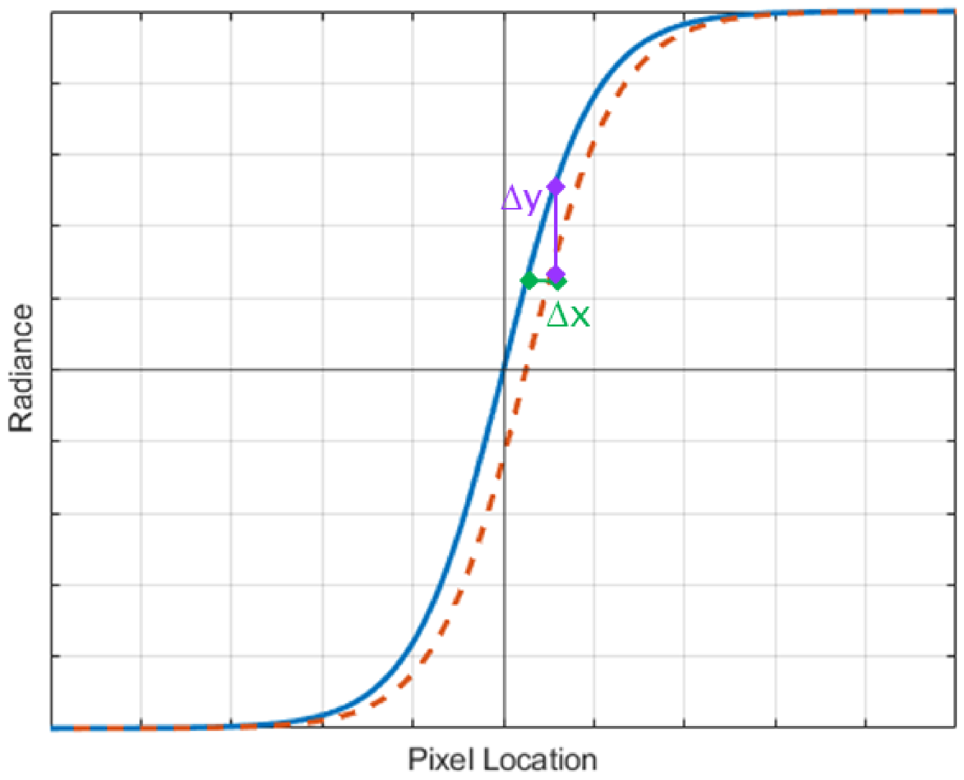
Relative Geometric Uncertainty







Coupled Uncertainty of an Edge



- Two curves represent an edge on the ground imaged on different days
  - Δy is the radiometric uncertainty due to geometric uncertainty (Δx)
- Gradient of the edge $= \frac{\partial y}{\partial x}$
- By generalizing, $\partial y = \frac{\partial y}{\partial x}\partial x$,

  we can estimate coupled geometric and radiometric uncertainty as,

$$\Delta y \approx \frac{\partial y}{\partial x}\Delta x$$

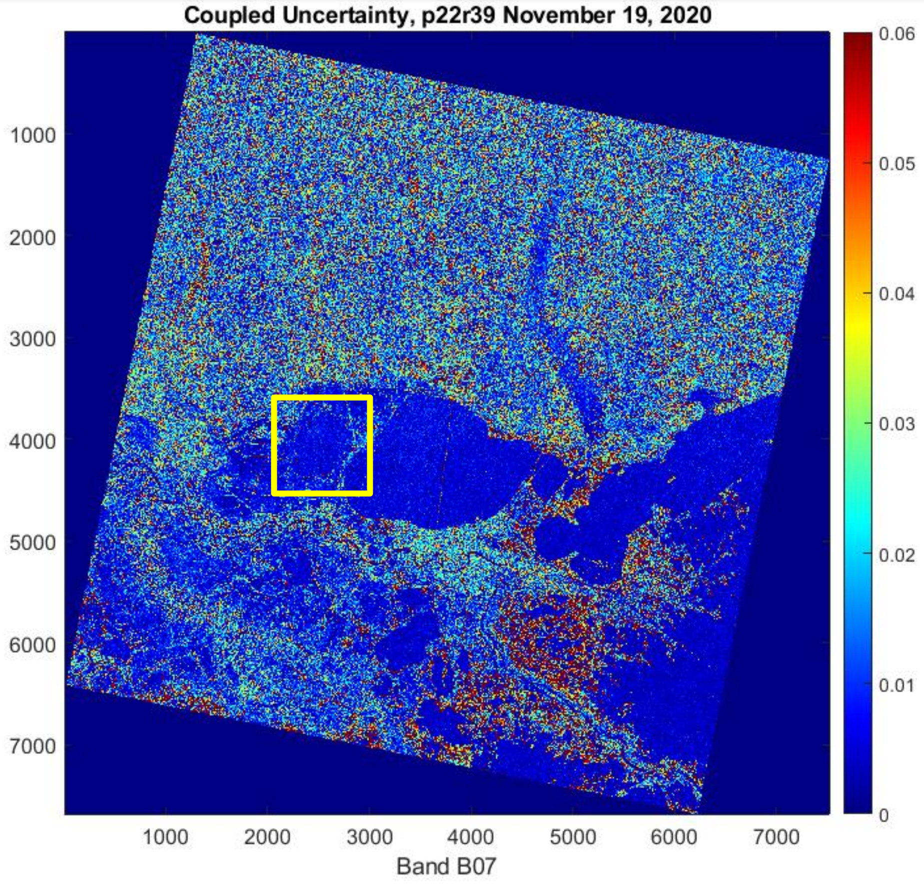
Coupled Geometric And Radiometric Uncertainty

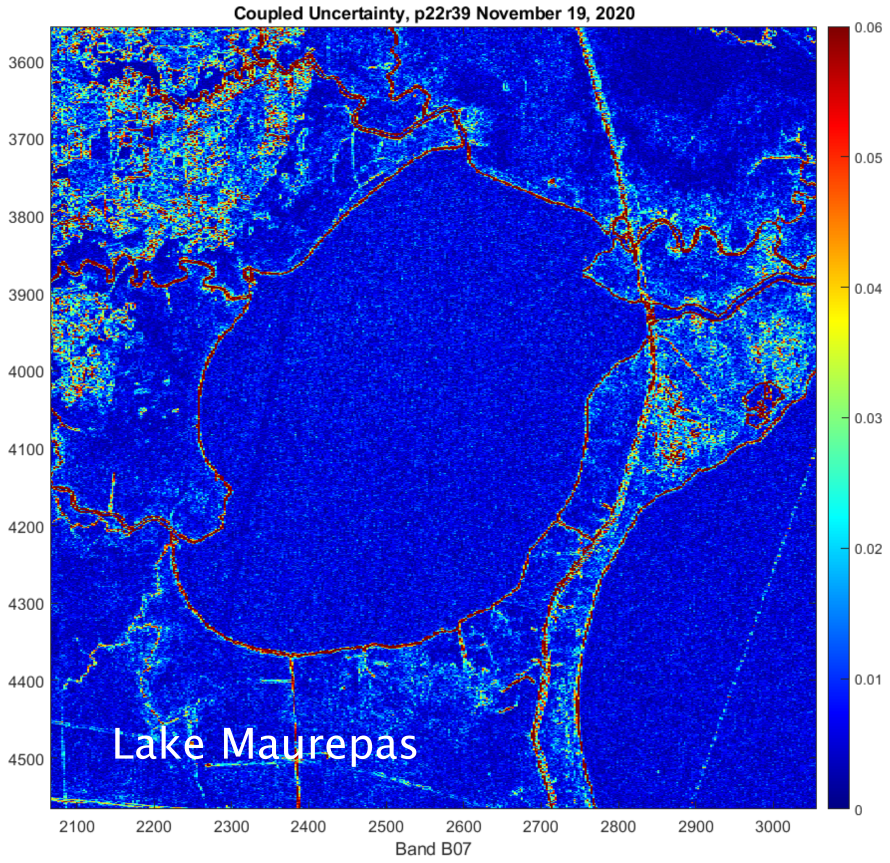
- The radiometric uncertainty due to positional variation is estimated as the product of the geometric uncertainty and the slope of the data (the gradient of the image)
  - There are two directional terms for positional displacement, dx and dy, and two directional terms in the gradient, $(\partial\rho/\partial x)$ and $(\partial\rho/\partial y)$
  - Each directional displacement has an associated uncertainty estimate
  - Uncertainties are combined to estimate the coupled geometric and radiometric uncertainty

$$u_{coupled} = \sqrt{\left(\frac{\partial\rho}{\partial x}dx\right)^2 + \left(\frac{\partial\rho}{\partial y}dy\right)^2}$$

Coupled Geometric and Radiometric Uncertainty

Lake Pontchartrain P22/R39; SWIR 2 (Band 7)





Combined L1T Radiometric Uncertainty

Combined L1T Radiometric Uncertainty

- The final radiometric uncertainty is the combination (root sum of the squares) of the uncertainty from all sources

$$\sigma_{total} = \sqrt{\sigma_{SI\ uncertainty}^2 + \sigma_{noise}^2 + \sigma_{intrinsic}^2 + \sigma_{coupled}^2}$$

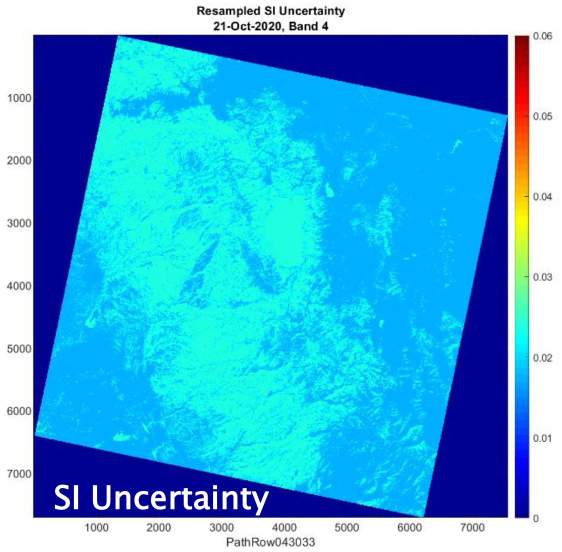
where, $\sigma_{SI\ uncertainty}$ = SI uncertainty
σ_{noise} = Resampled sensor noise
$\sigma_{intinstic}$ = Intrinsic interpolation uncertainty
$\sigma_{coupled}$ = Coupled geometric and radiometric uncertainty

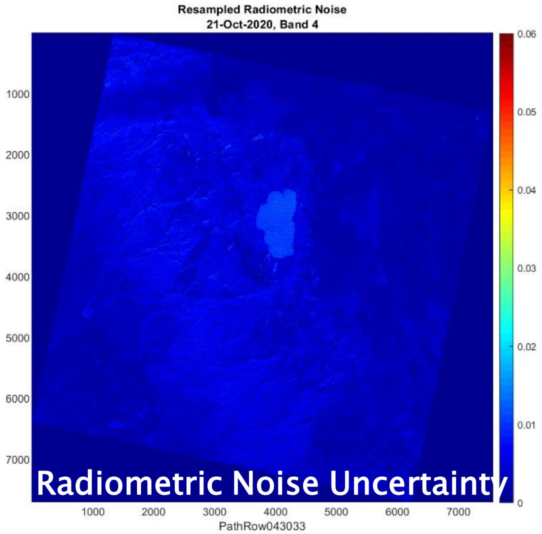
Uncertainty Component Magnitudes

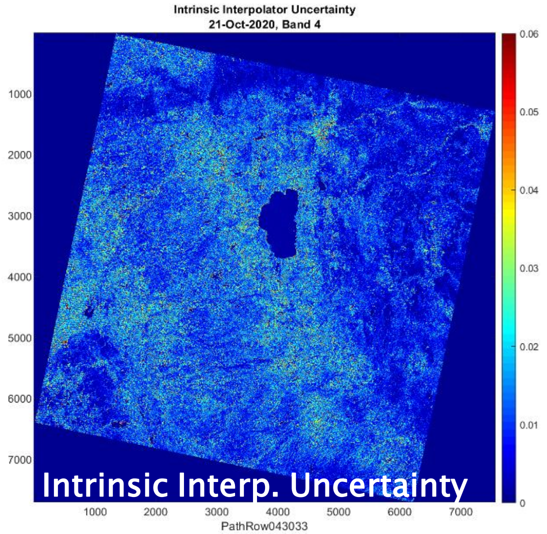
Uncertainty Magnitude

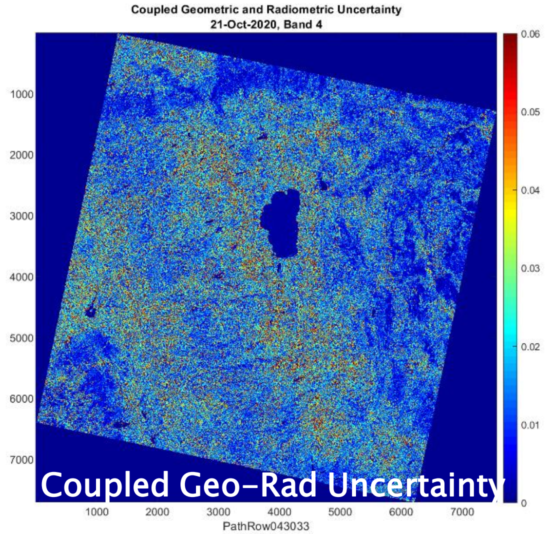
- Estimated uncertainty budget for L1 components computed
  - Radiometric SI uncertainty
  - Resampled Radiometric Noise
  - Intrinsic Interpolation Uncertainty
  - Coupled Geometric and Radiometric Uncertainty
- Each component was computed separately and compared to the total uncertainty

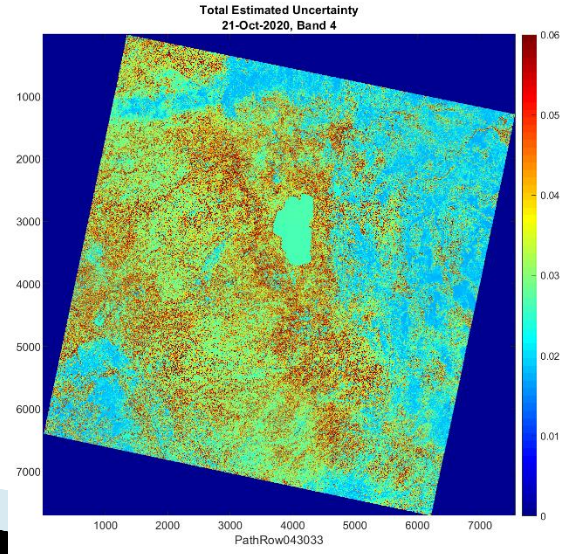
Uncertainty Component Images











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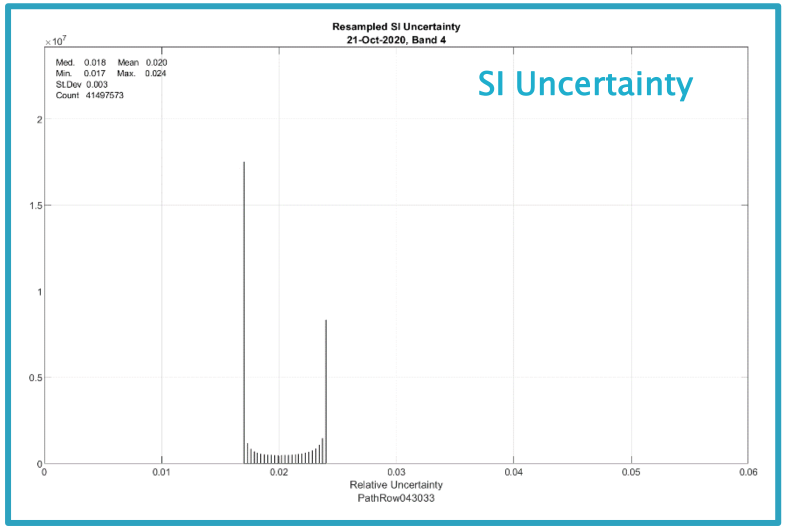
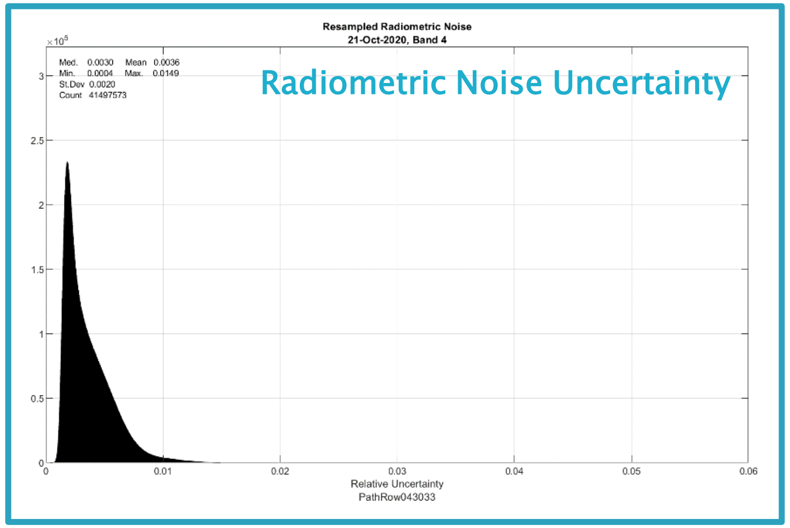
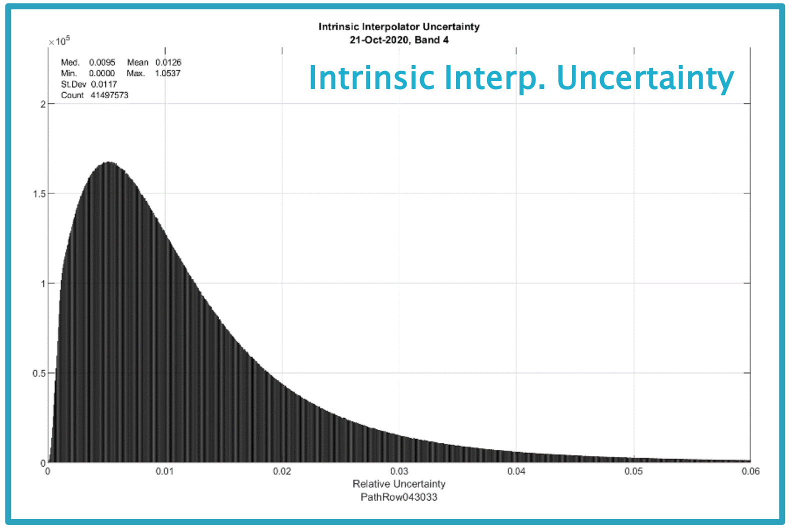
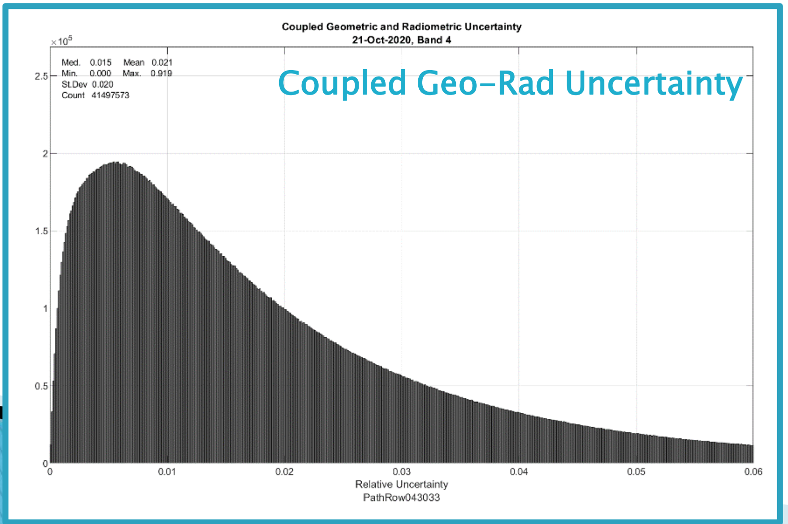
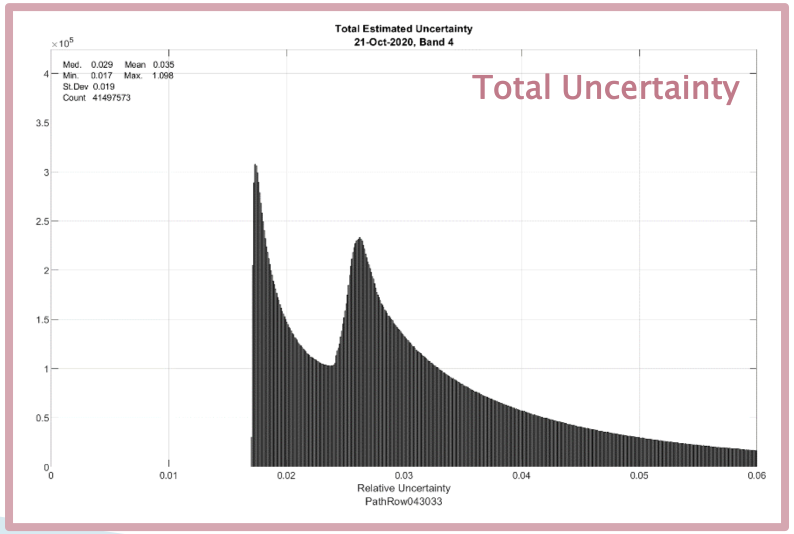
Uncertainty Component Histograms











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L1T Radiometric Pixel Uncertainty Summary and Next Steps

GUI-based Uncertainty Tool

L1T Radiometric Pixel Uncertainty Summary

- An initial L1T radiometric pixel uncertainty algorithm is being developed with a goal to help users better understand uncertainties
  - Algorithms being developed for OLI and TIRS L1T products
  - Validation is underway, but not complete
  - Aliasing has not been considered, but should be in future versions
    - OLI simulations using high resolution imagery such as WorldView can be used to understand impact of aliasing for different feature types
  - Algorithm would benefit from additional insight into SI uncertainty
- The algorithm is being expanded to address L2 processing
- A GUI is being developed to enable a group of users to execute the algorithms and provide feedback

Initial Landsat 8 Radiometric Uncertainty Tool