Landsat 8 L1T Product Radiometric Pixel Uncertainty Approach and Algorithm Overview

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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
Gorrono et al. 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

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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
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:

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

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

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L1T Radiometric Resampling Uncertainty

L1R SCA/Band → Inherent per pixel L1R Radiometric Uncertainty (SI Traceability + Noise) → L1T Resampling Algorithm

Transfers SI Uncertainty

Propagates Noise Uncertainty

Introduces Intrinsic Interpolation Uncertainty

Resampled per pixel Radiometric Uncertainty

Coupled Geometric and Radiometric Uncertainty Algorithm

L1T Resampled Radiometric Uncertainty

Geometric Uncertainty from L1T
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)

Surface Reflectance p22r39 December 21, 2020

Lake Pontchartrain P22/R39

Surface Reflectance p43r33, October 5, 2020

Lake Tahoe P43/R33
Landsat 8 Test Imagery (RGB)

TOA Reflectance

North of Alaska P71/R10
L1R (Inherent) Radiometric Uncertainty

SI Radiometric Uncertainty
Sensor Noise
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

### SI Radiance/Reflectance Uncertainty Values

<table>
<thead>
<tr>
<th>Band</th>
<th>TOA Radiance</th>
<th>TOA Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Radiance ($L_{typ} - 0.9L_{max}$)</td>
<td>Low Radiance ($0.3L_{typ} - L_{typ}$)</td>
</tr>
<tr>
<td>Coastal Aerosol</td>
<td>3.4 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Blue</td>
<td>3.1 %</td>
<td>3.4 %</td>
</tr>
<tr>
<td>Green</td>
<td>3.0 %</td>
<td>3.3 %</td>
</tr>
<tr>
<td>Red</td>
<td>2.9 %</td>
<td>3.2 %</td>
</tr>
<tr>
<td>NIR</td>
<td>3.0 %</td>
<td>3.3 %</td>
</tr>
<tr>
<td>SWIR1</td>
<td>3.3 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>SWIR2</td>
<td>3.2 %</td>
<td>3.6 %</td>
</tr>
<tr>
<td>Pan</td>
<td>3.4 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Cirrus</td>
<td>4.1 %</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>

Ball Aerospace provided uncertainties
### Initial Algorithm SI Radiance/Reflectance Uncertainty Values

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

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

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

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

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

where,
- \( u \) = relative radiometric uncertainty
- \( i, j \) = L1R pixel position
- \( \rho, L \) = input reflectance or radiance
- \( \rho_{\text{noise}}, L_{\text{noise}} \) = reflectance or radiance noise
- \( \rho_{\text{SI}}, L_{\text{SI}} \) = reflectance or radiance SI gain uncertainty
Band 4 L_{typical} = 22 \text{ Wm}^{-2}\text{sr}^{-1}\text{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, Radiance [W m$^{-2}$ sr$^{-1}$ $\mu$m$^{-1}$]

Radiance Uncertainty [W m$^{-2}$ sr$^{-1}$ $\mu$m$^{-1}$]

Relative Uncertainty (Percent)

Band 7 $L_{\text{typical}}$ 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
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
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.

\[
(d_{y1}, d_{y2}, d_{y3}) = \frac{\text{sign}(d_{y1})}{\max_i |d_{yi}|}
\]

LUT coordinate: 

Interpolation zone divided into 10 segments.
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:

\[
m_i = \frac{dy_i}{dx_i}
\]

\[
\hat{m}_i = \frac{\text{sign}(m_i)}{\max_j(|m_j|)} \cdot m_i
\]
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*
The blue ‘x’ marks the root mean square residuals for the feature shown. The black line shows a 4\textsuperscript{th} order fit of these points. The 4\textsuperscript{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\textsuperscript{nd} and 3\textsuperscript{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
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
Uncertainty in pixel position knowledge can produce uncertainty in radiance.
A geometric uncertainty algorithm was developed that uses GCP’s directly from the Image Assessment System (IAS)
- Produces absolute and relative geometric uncertainty
Two curves represent an edge on the ground imaged on different days
- $\Delta y$ is the radiometric uncertainty due to geometric uncertainty ($\Delta x$)

- 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,
  $$\Delta y \approx \frac{\partial y}{\partial x} \Delta x$$
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.

$$u_{coupled} = \sqrt{(\frac{\partial \rho}{\partial x} dx)^2 + (\frac{\partial \rho}{\partial y} dy)^2}$$
Combined L1T Radiometric Uncertainty
The final radiometric uncertainty is the combination (root sum of the squares) of the uncertainty from all sources.

\[ \sigma_{total} = \sqrt{\sigma^2_{SI\, uncertainty} + \sigma^2_{noise} + \sigma^2_{intrinsic} + \sigma^2_{coupled}} \]

where,
- \( \sigma_{SI\, uncertainty} \) = SI uncertainty
- \( \sigma_{noise} \) = Resampled sensor noise
- \( \sigma_{intrinsic} \) = Intrinsic interpolation uncertainty
- \( \sigma_{coupled} \) = Coupled geometric and radiometric uncertainty
Uncertainty Component Magnitudes
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

- SI Uncertainty
- Radiometric Noise Uncertainty
- Intrinsic Interp. Uncertainty
- Coupled Geo–Rad Uncertainty

P43/R33
October 21, 2020
Red (Band 4)
Uncertainty Component Histograms

- SI Uncertainty
- Radiometric Noise Uncertainty
- Intrinsic Interp. Uncertainty
- Coupled Geo–Rad Uncertainty
- Total Uncertainty
L1T Radiometric Pixel Uncertainty
Summary and Next Steps

GUI-based Uncertainty Tool
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