Development of a radiometric uncertainty tool for the Sentinel 2 mission

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Aim of research

The design, development and implementation of techniques to estimate the radiometric uncertainty associated the TOA radiance/reflectance factor pixel measurements of EO satellite optical instruments.

Specific goals:

- End-to-end methodology: radiometric model $\rightarrow$ uncertainty contributors $\rightarrow$ uncertainty combination based on GUM (BIPM, IEC et al. 2008).

- Assessment of each one of the uncertainty contributors

- Validation of the combined standard uncertainty model vs. a MCM method, the impact of simplifications and the correlation between uncertainty contributors.

- The research for different software strategies to implement the tool and integrate as part of EO processing chain.
Publications


Sentinel-2 L1 Radiometric model

- Mathematical formulation based on the instrument and L1 processing chain.
\[ X(p, l, b, d, L(\lambda)) = \text{trunc}[G(p, b, d, L(\lambda)) \cdot V(p, l, b, d, L(\lambda))] \]

\[ Y(p, l, b, d) = X(p, l, b, d) - DS(l \mod 6, b, d) - PC_{\text{masked}}(l, b, d) \]

\[ Z(p, l, b, d) = \gamma(p, b, d, Y(p, l, b, d)) \]

\[ CN_{k, \text{NTDI}}(i, j) = B_{\text{spline}}(Z(p, l, b, d)) \]

\[ \rho_k(i, j) = \frac{\pi \cdot CN_{k, \text{NTDI}}(i, j)}{A_{k, \text{NTDI}} \cdot E_S \cdot d(t) \cdot \cos(\theta_S(i, j))} \]

\[ A(b) = \frac{1}{N_p \cdot N_l \cdot N_d} \cdot \sum_{p, l, d} K_{\text{slt}} \cdot \rho(p, \theta_{\text{sd}}(l), \varphi_{\text{sd}}(l)) \cdot E_{\text{sun}}(b) \cdot \cos(\theta_{\text{sd}}(l)) \]

\[ \rho(p, \theta_{\text{sd}}(l), \varphi_{\text{sd}}(l)) = C_{\text{spa-dir}}(p, d, b) \cdot \rho_{\text{ground}}(x_0, y_0, b, \theta_{\text{sd}}(l), \varphi_{\text{sd}}(l), \theta(p, d), \varphi(p, d)) \]

\[ C_{\text{spa-dir}}(p, d, b) = \frac{\rho_{\text{ground}}(x_0, y_0, b, \theta_{\text{sd}}(l), \varphi_{\text{sd}}(l), \theta(p, d), \varphi(p, d))}{\rho_{\text{ground}}(x_0, y_0, b, \theta_{\text{sd}}(l), \varphi_{\text{sd}}(l), \theta(p, d), \varphi(p, d))} \]
L1 Radiometric uncertainty contributors assessment

A more detailed description of each contributor can be found in [1]

Three main methods that can be identified in this research:
1. The pre-flight test documentation and Instrument Characterisation and Calibration DataBase (ICCDB).
2. Post-launch info and product information
3. Novel methodologies. Preliminary work on the spectral knowledge and orthorectification can be found in [2]

The idea is that the tool produces where possible a “dynamic” uncertainty. That is robust against model changes, optional corrections or temporal evolutions. E.g. the tool should equally work if a reprocessed product determines new noise parameters.

Showing here one example with the instrument noise and an approach to account for orthorectification uncertainty propagation.
Instrument noise

- S2 L1C product metadata, the noise model parameters $\alpha_Z$ and $\beta_Z$:

$$\text{Noise}_Z(p,l,b,d) = \sqrt{\alpha_Z(p,l,b,d)^2 + \beta_Z(p,l,b,d) \cdot Z(p,l,b,d)}$$

$$\alpha_Z(p,l,b,d) = \text{STD}_l[Z_{ds}(p,l,b,d)]$$

$$\beta_Z(p,l,b,d) = \frac{\text{STD}_l[Z_{sd}(p,l,b,d)] - \alpha_Z(p,l,b,d)^2}{A(b) \cdot K_{slit} \cdot \frac{1}{N_l} \cdot \sum_{\gamma} \rho(p, \theta_{sd}(l), \varphi_{sd}(l)) \cdot \frac{E_{\text{sun}}(b)}{d_{\text{sun}}^2} \cdot \cos \theta_{sd}(l)}$$

- The model takes the DS standard deviation ($\alpha_Z$) as the instrument noise at the absence of light and scales it by the signal measured (photon shot noise, linear to the variance ($\text{STD}^2$)).

- Strong points:
  1. Minimises the computing requirements
  2. Continuously updated during the mission lifetime and during any potential dataset re-processing.

- Weak points:
  1. One parameter per band. Assumes small noise variations across the focal plane.
  2. “Hot pixels”: Note that these are not invalid pixels. These specific cases should be flagged and potentially reported to account for in future versions of the tool.
Orthorectification: description

- 1) Earth model in UTM coordinates and DEM determine the geometric transformation that sets the position of the target point in the focal plane image.
- 2) Radiometric interpolation between the focal plane points.

- Resampling effect will generally reduce the uncertainty level (uncorrelated components) but depending on 1) interpolation method 2) correlation between interpolation grid pixels 3) position in the resampling grid.
Orthorectification: method

- Analytical approach can be done but requires 3D correlation matrices. E.g. work for spectral responsivity (2D correlation matrices):
  

- MCM resampling propagation using L1B distributions and evaluation at different grid positions.

- Separation of correlated and uncorrelated components.

- 3 resampling→ bilinear, cubic convolution and B-splines
Orthorectification: uniform scene

4x4 kernel of constant 30 Wm$^{-2}$sr$^{-1}$μm$^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uniform and full random</th>
<th>Uniform and A(b) correlated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bilinear (a)</td>
<td>Cubic (b)</td>
</tr>
<tr>
<td>Mean [%]</td>
<td>1.5631</td>
<td>1.8970</td>
</tr>
<tr>
<td>SD [%]</td>
<td>0.2603</td>
<td>0.2130</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.1491</td>
<td>1.4750</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.3165</td>
<td>2.3333</td>
</tr>
</tbody>
</table>
Orthorectification: operational implementation

- Tested a preliminary method of propagation. Highlights the importance of pixel grid correlation. It is important to produce a full spatio-temporal correlation. (studied in next slides)

- The method should minimise the data (16 pixels x radiance levels x positions in the grid). At L1B a LUT or ‘uncertainty curves’ of predefined calculated values can be obtained. Once L1C has been generated this is way more complicated.

  Potential options to explore with pros and cons:
  
  A ‘reduction factor’ that accounts for the mean reduction in uncertainty from the interpolation corners.

  This propagation will have lower impact if product is spatially binned or a ROI is calculated (see next slides). I.e. assume in further processing.

  Can we use ‘reverse engineering’ if S2 L1C product were to provide a focal plane grid position (similar to SZA)? accurate enough to the DEM?

  Can we reuse the DEM offline in SNAP to recalculate positions in the grid and apply a set of LUT and curves?

- Challenges. How to assess the interpolation accuracy and implement this for each specific scene?
Model combination and validation

- Follows the GUM (international standard) to combine the L1 rad. uncertainty.

\[
U(R_k(i, j))\% = k \cdot u(R_k(i, j)) + u_{\text{diff_temp}}(t_{\text{stamp}}) + \frac{100 \cdot A_{k,\text{NTDI}} \cdot u_{\text{stray_sys}}}{CN_{k,\text{NTDI}}(i, j)}
\]

\[
u(R_k(i, j)) = \sqrt{\left(u_{\text{ref_quant}}/\sqrt{3}\right)^2 + u_{\text{diff}}^2 + u_{\gamma}^2 + u_{\text{stray}}^2 + u_{\text{LSB}}^2}
\]

- No significant correlation between contributors simplifies the combination.

\[
u_{\text{LSB}}\% = \sqrt{\left(\frac{100 \cdot u_{\text{noise}}}{CN_{k,\text{NTDI}}(i, j)}\right)^2 + u_{\text{DS}}^2 + u_{\text{ADC}}^2}
\]

\[
u_{\text{diff}}\% = \sqrt{u_{\text{diff}_k}^2 + u_{\text{diff}_\gamma}^2 + u_{\text{diff}_\text{abs}}^2}
\]

\[
u_{\text{stray}}\% = \sqrt{u_{\text{stray}_\text{rand}}^2 + \left(\frac{100 \cdot A_{k,\text{NTDI}} \cdot u_{\text{talk}}}{CN_{k,\text{NTDI}}(i, j)}\right)^2}
\]

- Normalised counts \(CN_{k,\text{NTDI}}(i, j)\) obtained from pixel-level inversion using the L1C product metadata.

- \(u'_{\text{ADC}}\) and \(u'_{\text{DS}}\) require sensitivity coefficient \(c_y\). Negligible \(\Rightarrow\) WC of 10% error of 2 small contributors in the global L1 budget.

- Comparison to MCM method determined the validity of the central limit theorem. At low radiance values, unstable distribution due to quantisation.
Radiometric uncertainty software implementation

- Fully operational tool. Available for download as a plugin or to build it: https://github.com/senbox-org/snap-rut
- HTML help integrated as part of the tool
Radiometric uncertainty software implementation

- Refinements and new features at each release:
  - v 0.9: May 2016, preliminary version
  - v 1.0: February 2017, initial version
  - v 1.1: June 2017, issues solved (spectral band index and raising exception for no band selection)
  - v 2.0: (programmed for ~March 2018) with
    - Compatibility S2A/S2B
    - Optical crosstalk flag
    - Other minor issues…

  **Uncertainty for radiometric validation and spatial binning**
Uncertainty for radiometric validation and spatial binning

- Method is explored for using the S2-RUTv1 that can provide an uncertainty estimate of the mean of the ROI for radiometric validation purposes. Example of a 2x2 pixels’ mean:

\[ \rho_{ROI} = \frac{1}{4}(\rho_A + \rho_B + \rho_C + \rho_D) \]

- The uncertainty in vector form is:

\[
u_{ROI}^2 = C^T UC = \left(\frac{\partial \rho_{ROI}}{\partial \rho_A} \frac{\partial \rho_{ROI}}{\partial \rho_B} \frac{\partial \rho_{ROI}}{\partial \rho_C} \frac{\partial \rho_{ROI}}{\partial \rho_D}\right) = \left(\frac{1}{4} \frac{1}{4} \frac{1}{4} \frac{1}{4}\right)\]

- Or scalar

\[
u_{ROI}^2 = \frac{1}{4}\left[u_A^2 + u_B^2 + u_C^2 + u_D^2\right] + \frac{2}{4}\left[u_A u_B r_{AB} + u_A u_C r_{AC} + u_A u_D r_{AD} + u_B u_C r_{BC} + u_B u_D r_{BD} + u_C u_D r_{CD}\right] \]

- We cannot just take the average uncertainty of the 4 pixels or the standard deviation of the mean of the 4 pixels (i.e. factor of \(\sqrt{4}\))!!!
Uncertainty for radiometric validation and spatial binning

- Spectral, spatial and temporal dimensions defined by the focal plane.

- Overlap between detector modules produces different correlation structures. This will be unlikely for radiometric validation at instrumented sites but highly likely for PICS monitoring.

- Othorectification limitation: S2 L1C products do not keep the original spatial and temporal focal plane dimensions. For initial study and in the absence of other info, approximate the temporal dimension (North-South) as well as of the spatial dimension (East-West). S2A orbit is a near-polar orbit with a 98.62° inclination.
Uncertainty for radiometric validation and spatial binning

- Two methods proposed: one simple method using the RUT and another more complex for cross-validation.

Select/deselect method: select only the correlated effects, assuming that the uncorrelated effects become negligible at the scale of the ROI.

MCM propagation method: Distributions set as normal or uniform with a spread of values directly linked to the uncertainty in S2-RUTv1.
Uncertainty for radiometric validation and spatial binning

- Understanding error correlation at L1 implies a deep understanding of the instrument and processing.
- Example of Angular knowledge-cosine effect: The error is correlated in the three dimensions since any two pixels in a small ROI (e.g. 10x10) will share a large percentage of the projection over the same diffuser. That is, any tilt or deformation over the diffuser will be largely common to the pair of pixels.

Uncertainty for radiometric validation and spatial binning

- Example of results in RadCalNet Gobabeb site.

  - Uncertainty decrease ~0.2 % - 0.8 %, due to uncorrelated components. (this is a site with a relatively high radiance)
  - Correlated components dominate the uncertainty at 200m for all bands.

Evolution of the ROI uncertainty ($k = 1$) with the ROI size for the RadCalNet Gobabeb site using the MCM technique.

Evolution of the difference between the MCM and select/deselect technique as a function of the ROI size for the ROI uncertainty ($k = 1$) of the RadCalNet Gobabeb site.
Conclusions and the way forward

• The Sentinel-2 mission provides uncertainty estimates with a rigorous metrological approach and integrated in the users processing chain for their use in L1 applications. That is a full end-to-end uncertainty methodology for L1:
  • L1 uncertainty analysis and combination
  • Tool implementation and integration as part of EO processing
  • Correlation structure and application of the results.

• But this is a continuous exercise that needs:
  • Several contributors need refinement (e.g. non-linearity)
  • Stray-light and polarisation impact to be studied and implemented
  • Uncertainty embedded as part of L1C product
  • Interface with other tools, algorithms (e.g. Idepix)
  • Second byte image in support of uncertainty image (e.g. ghosting flag)
  • More quantitative correlation analysis (e.g. pre-flight experimental data?)

• Very useful lessons learnt for future approach:
  • Uncertainty considered from early mission. Pre-flight characterisation (e.g. correlation error) and product design (uncertainty and metadata info)
  • Separate strategy to train and show the usefulness to end-users
QUESTIONS?

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