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Sentinel-2 MSI level-1 Radiometric Uncertainty Tool, status and perspective

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Context and status

The S2 Radiometric Uncertainty Tool (RUT) has been initially developed by Javier Gorrono. It is an offline tool, developed as a SNAP plugin, to assess the level-1 uncertainty directly from the level-1 product. First, L1-RUT reconstructs the level-0 quantities and then estimates their uncertainty level.

Unfortunately, the current code is not maintained and need to be revised.

The OPT-MPC, with the help of Javier, performed an assessment of the tool and issued several recommendations presented today.

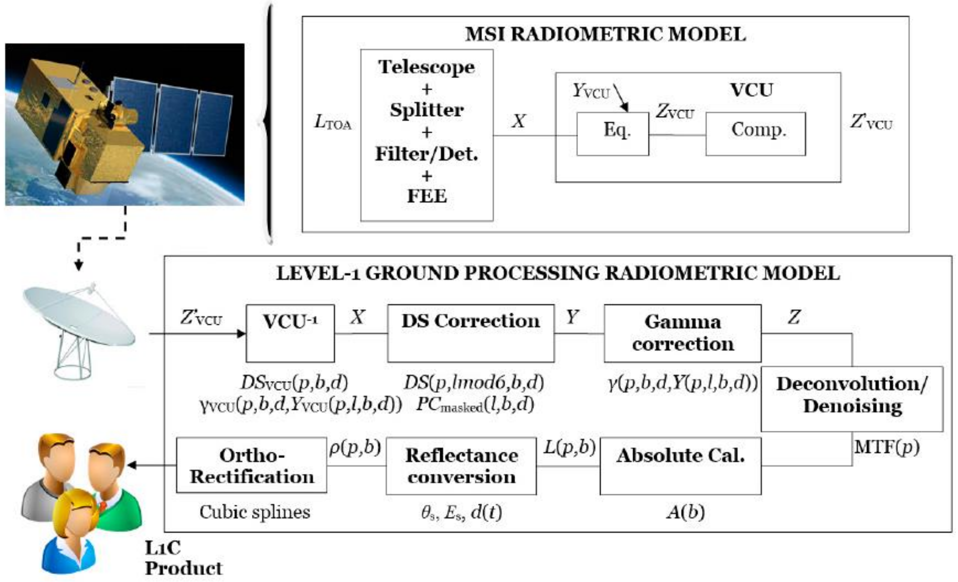
Outline:

1. Assessment of current tool
2. Contributors to be revised
3. Missing contributors
4. Software evolution

Assessment of current tool

S2 uncertainty estimation follow the L1c radiometric model of MSI. The following table gives the status of each uncertainty contributor in the RUT-V1. Many are already included, some are negligeable, and some are not yet included.

L1B contributor	status		L1C contributor	status
instrument noise	y		Diffuser reflectance abs knowledge	y
systematic out of field straylight	y		Diffuser reflectance temporal knowledge	y
random out of field straylight	y		Angular diffuser knowledge BRF effect	<0.1%
Crosstalk	y		Instrument noise and dark signal in calibration	<0.1%
Deconvolution residual	n		Solar irradiance model	<0.1%
Polarisation Error	n		Angular diffuser knowledge cosine effect	y
ADC quantisation	y		Straylight in calibration mode	y
Compression noise	<0.1%		sun to satellite distance knowledge	<0.1%
Dark signal knowledge	<0.1%		Angular observation knowledge—cosine effect	<0.1%
Dak signal stability	y		Orthorectification	n
Non linearity knowledge	y		Spectral knowledge	n
Non uniformity spectral residual	n		Geometric knowledge	n
L1B Image quantisation	<0.1%		L1C Image quantisation	y



y	Computed in RUT-V1
n	May be include in next version
<0.1%	Negligeable

Assessment of current tool

First, we can compare to the L1 uncertainty analysis made on S3-OLCI.

Major similarities with OLCI L1 uncertainty:

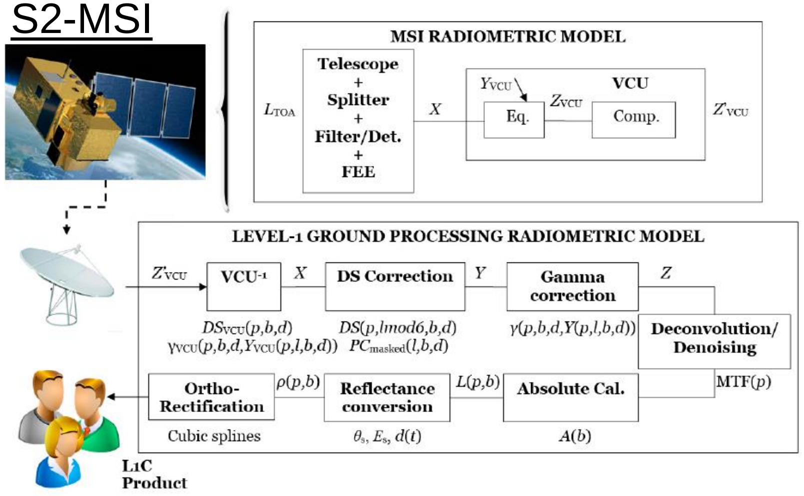
- Propagation is focused on radiometric terms.
- Spectral and Geometric knowledge are not included.
- Overall same negligeable contributors.

Major differences with OLCI L1 uncertainties:

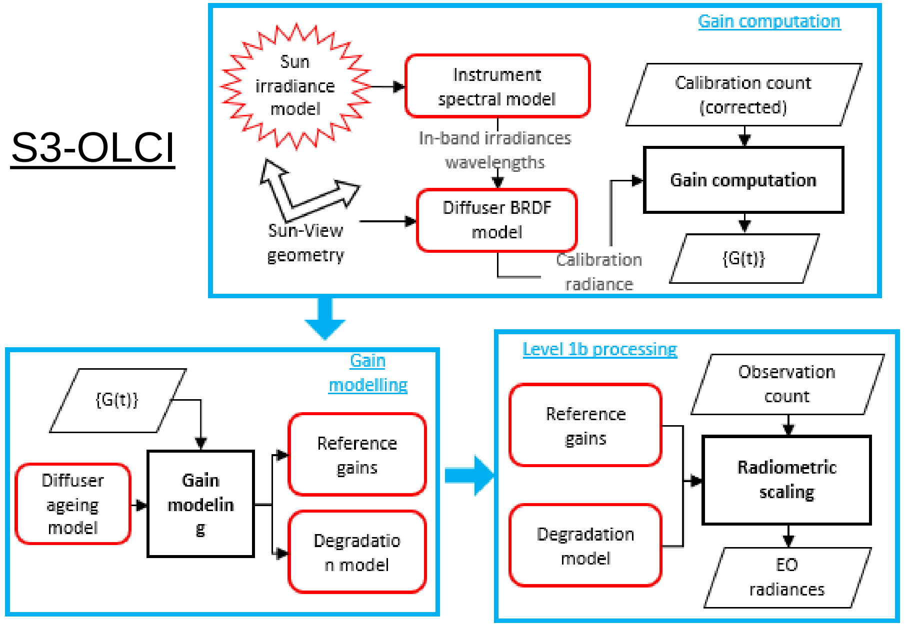
- Straylight systematic component are accounted for, while no systematic part is included in OLCI uncertainties.

➔ The both propagation analysis appears coherent within each other.

S2-MSI



S3-OLCI

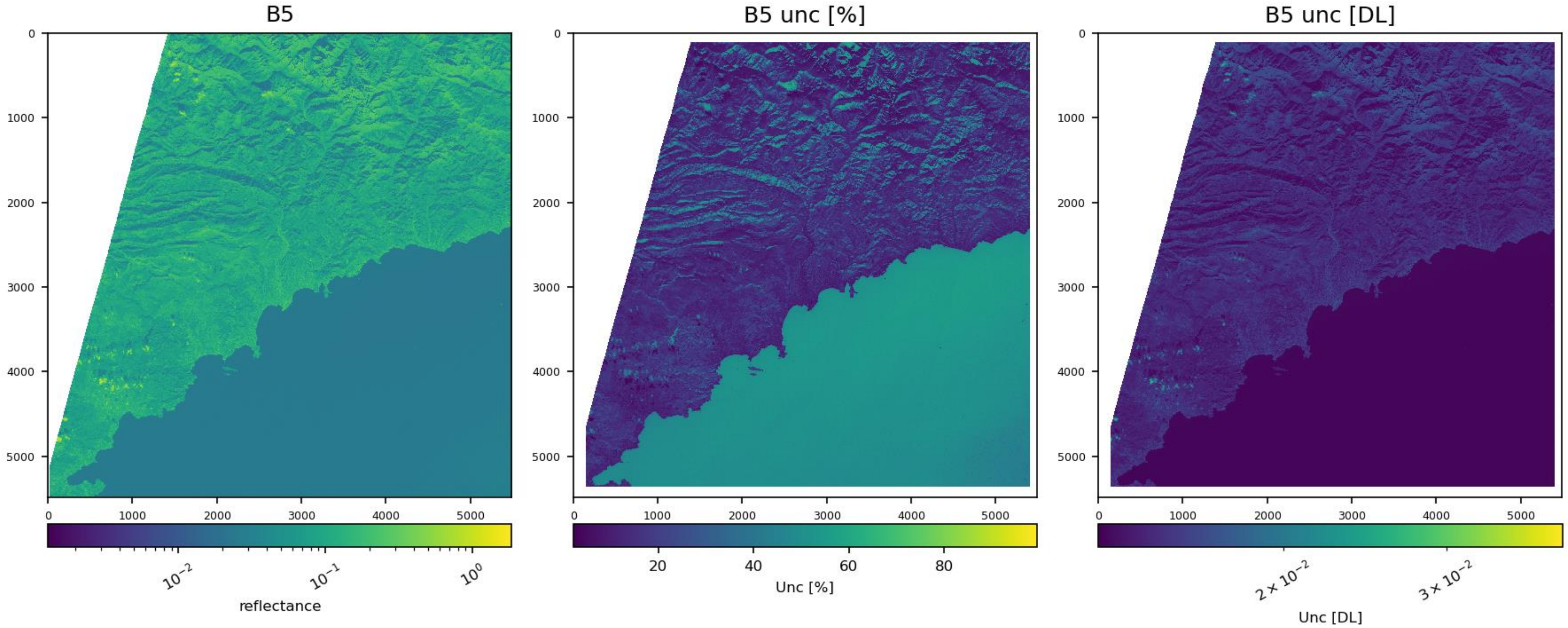


Assessment of current tool

S2 L1-RUT (V1) results for band 5:

The tool computes uncertainties per pixel for a L1C granule.

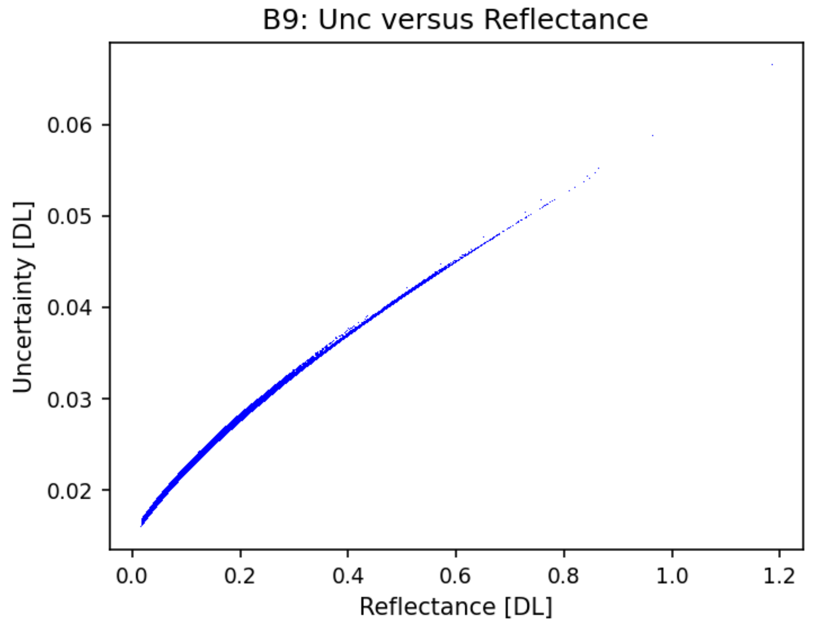
Percentage uncertainty are high over region without signal, but absolute values remains the lowest in the same region.



Reflectance (unitless - logscale) **Uncertainty (%)** **Uncertainty (unitless - logscale)**

Assessment of current tool

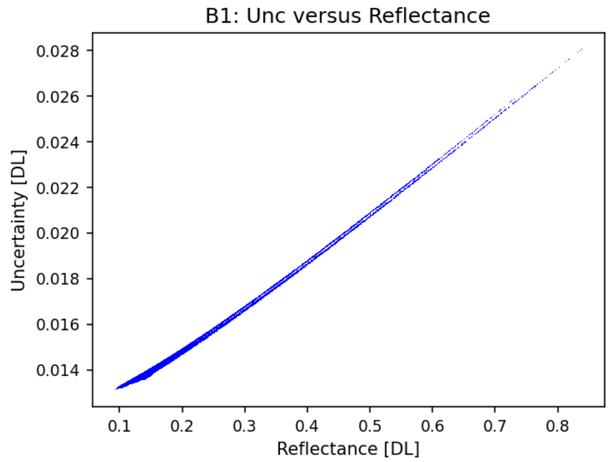
For most bands, the scatterplot between the uncertainty and the reflectance follows a well-known shape (between linear and square root shape). See B9 example.

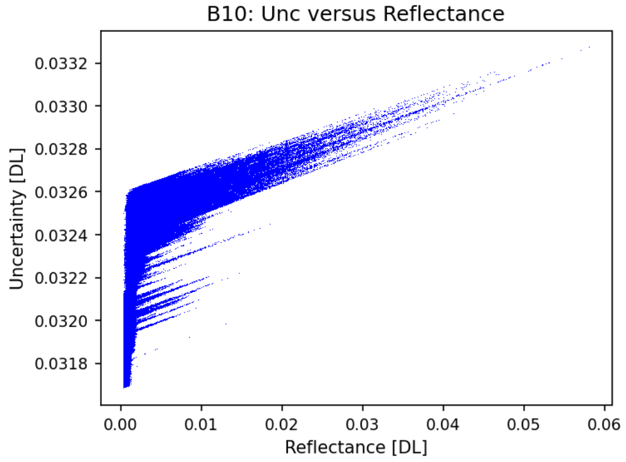


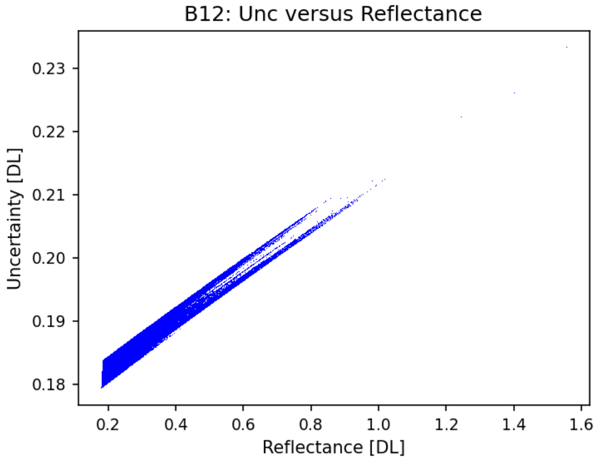
3 bands seem to have a different behaviour B1, B10, B12:

- B1 is almost fully linear which come from the systematic part.
- B10 is expressed in thousands of %
- B12 is almost above 100% everywhere

➔ Not a big issue for B1, but B10 and B12 appears non-usable in this state.







Contributors to be revised

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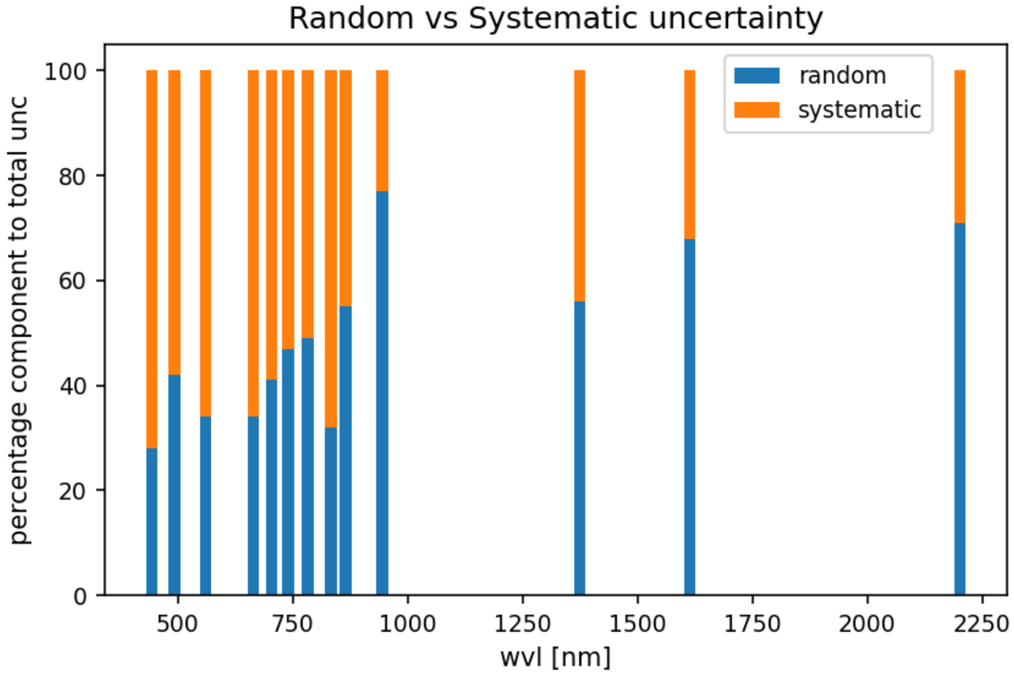
Straylight

The plot presents the Random and Systematic contribution to the total uncertainty:

- For VIS: systematic part represent the main contributor
- For SWIR: systematic part is lower but still significant

The systematic component is coming from the **out of field straylight**, estimated at 0.3% of Lref. As a systematic effect it is applied uniformly to whole field of view and summed linearly to other random contributors

The overall impact is very severe. But since providing a full straylight correction is not feasible, the effort must focus on estimating the impact of the contributor as accurately as possible.



- **Random contribution to total unc**
- **Systematic contribution to total unc, coming from out-of-field straylight**

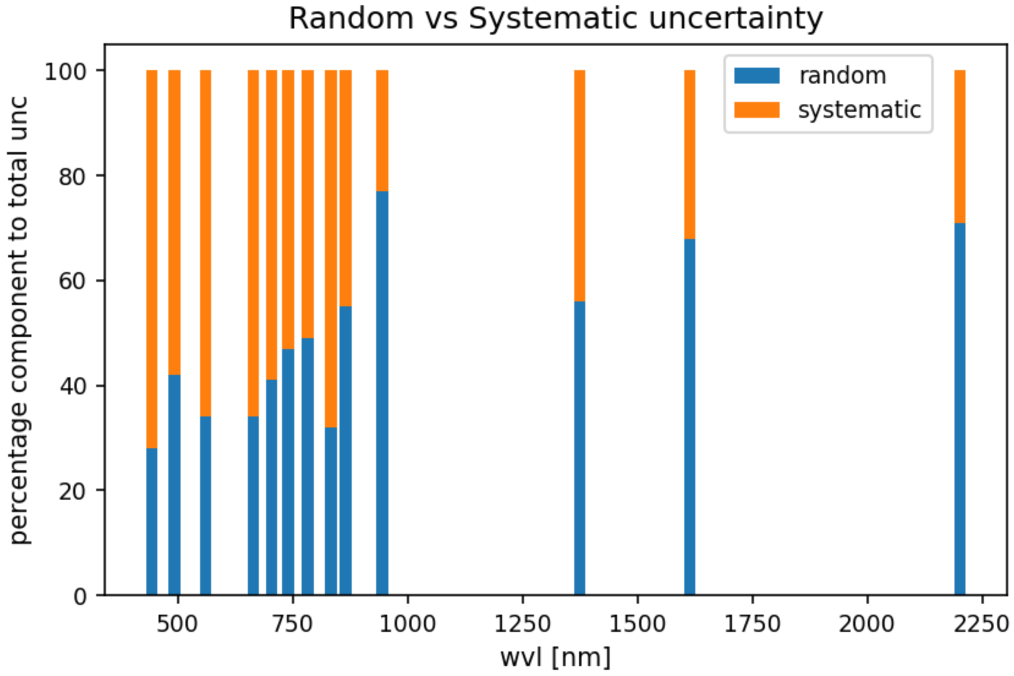
Contributors to be revised

3 straylight sub-contributors need to be distinguished:

- **Straylight in calibration mode**: a correction factor is considered in the calibration chain. The residual error is modelled as a constant bias and summed quadratically to other error terms.

- **Out-of-field straylight in observation mode**: this impact can be assimilated as constant bias affecting all pixels. A systematic term of 0.3% Lref is considered, which corresponds to a typical value. The straylight error will depend on the (unknown) radiance levels surrounding the scene. To account for the variability of this term, another constant value is added quadratically.

- **In-field straylight**: this term is currently not modelled.



- Random contribution to total unc
- Systematic contribution to total unc, coming from out-of-field straylight

Foreseen action:

➔ Review the Airbus documentation on straylight characterization.

➔ Analyse straylight impact to assess the estimate and the variability with different type of scenes. Scene-dependent estimates/correction will be investigated.

Contributors to be revised

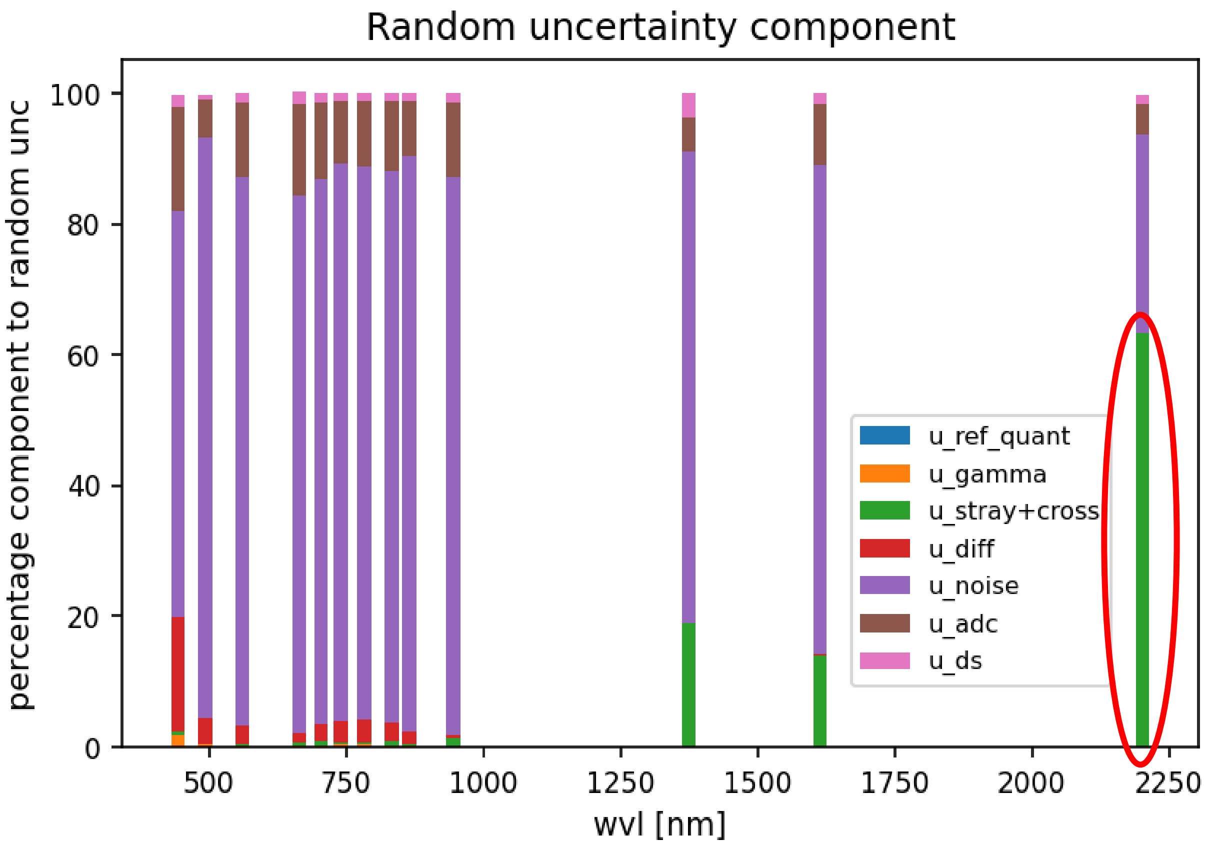
Cross-talk

Random contributors can be decomposed in several main contributors, some of them include multiple terms but cannot be decomposed easily.

The green contributor is coming from both random part of straylight and cross-talk. But since the random straylight contribution is null in SWIR bands, only cross talk is considered in SWIR.

Cross talk is estimated at 1% of the radiometry and we see that it largely impact the SWIR bands, especially B12.

Otherwise, the main contributor is the radiometric noise which is coherent with S3-OLCI results.



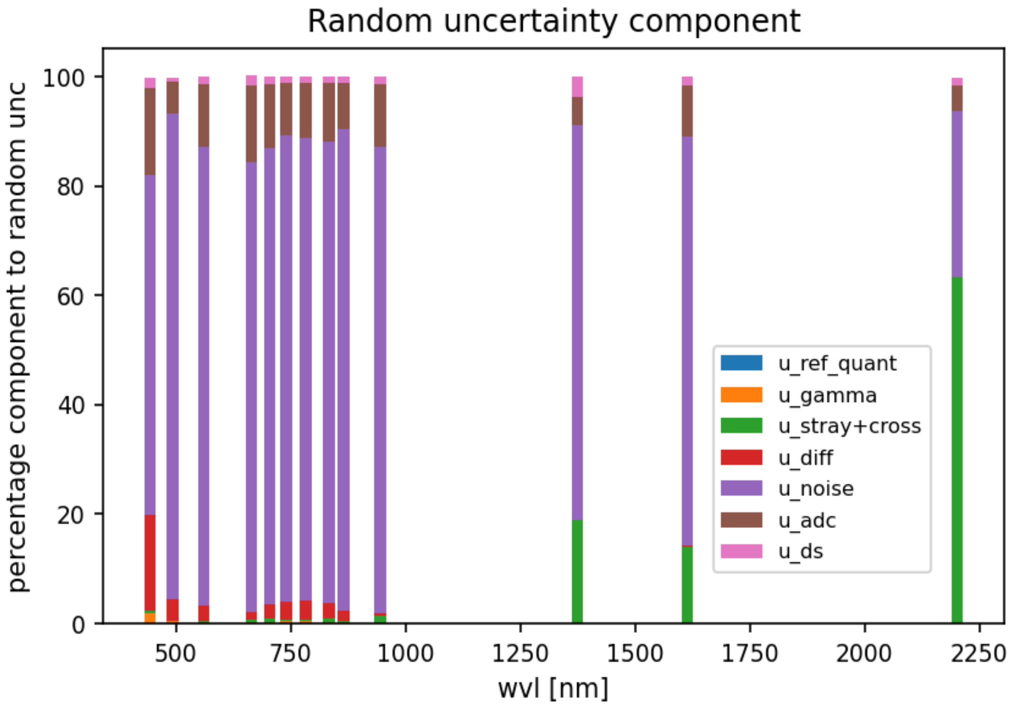
Cross-talk

The cross-talk is estimated from a worst-case scenario on a single band and then generalised to all the bands. The model should consider the correction residual to be a fraction of the actual correction (worst case 10^{-5} for the B11-> B10 pair). Cross-talk is not significant for VNIR bands.

Accounting for the correction residual is not straightforward since the crosstalk is proportional to the image with an along-track shift corresponding to the time delay between bands.

We will analyse in more detail the impact of this effect, considering issues discovered after the launch of S2A:

- Term proportional to the image gradient
- Bevel-effect near detector edges
- Non-linear cross-talk affecting some S2D detectors



➔ **It seems likely that the cross-talk effects should be negligible in most cases.**

Missing contributors

Currently missing contributors

1. **Geometric knowledge**
2. Spectral knowledge
3. Ortho-rectification error

The geometric errors have a direct impact on the knowledge of the pixel content. For high spatial resolution bands, this can lead to an error on the radiometry of the pixel, especially in the case of a non-uniform region. For band with a lower spatial resolution, the impact should be minimum.

➔ To estimate the impact of this effect, a first idea would be to project the geometric error on a map of the radiometric gradient of the image to evaluate the impact on the pixel radiometric content. This contributor will largely depend on the context of the observed scene.

Missing contributors

Currently missing contributors

1. Geometric knowledge
2. **Spectral knowledge**
3. Ortho-rectification error

The spectral calibration knowledge is limited by the pre-flight calibration and their variations in the lifetime of the spacecraft, due to temperature change or ageing of components. While the spectral response is typically associated with the mean for all the pixels across the focal plane, the residual of this effect is accounted in non-uniformity spectral residual.

➔ Preliminary work has been conducted by J. Gorrono, it should be assessed to be included in the next version of the tool.

Missing contributors

Currently missing contributors

1. Geometric knowledge
2. Spectral knowledge
3. **Ortho-rectification error**

This contributor is link to the interpolation required to reproject the MSI focal plane in the orthorectified grid on Earth. A preliminary study of the propagation of the uncertainty through the resampling process has been proposed.

The interpolation introduces two effects:

- Low-pass filtering of the L1B noise – this effect is present on uniform scenes. This term can be analysed mathematically and depends on the interpolation scheme.
- Additional interpolation error, only present in case of image gradient. For this term, an empirical approach based on experiments on synthetic Sentinel-2 images is envisaged. A similar approach was followed by the Landsat team.

➔ OPT-MPC will analyse the proposed models and consider a potential implementation in the L1C RUT.

Software evolution

Other software evolution, independent of the uncertainty propagation, are foreseen:

- **Adaptation of the code to new MSI product format (done)**
- **Uncertainty output format:**
  - Remove limitation of the maximal uncertainty at 25%.
  - Switching from relative to absolute unit.
  - Switch from short integers to 16-bit integer.
- **Automatic processing:**
  - Change to support automatic processing of full products. While current tool only process ROI specified by user.
- **Software interface:**
  - Current tool is a SNAP plugin, making its installation quite complex.
  - We recommend switching to a simpler python tool to support batch processing. This would allow us to remove the dependence to SNAPPY, the SNAP python module that requires specific python version.

Outlook for L2 uncertainties

Recent work (Graf et al. 2023) showed that correlation between spectral bands strongly impact the (non-linear) error propagation to L2 surface radiances

- **J. Gorrono proposed a Monte-Carlo approach to rigorously propagate correlated uncertainties**
  - Applicable only to a limited number of individual pixels
- **Extension to larger AOIs or full images will require massive parallel processing capabilities**
- **Alternative empirical approaches could be investigated**
  - Macroscopic model to predict correlation between spectral bands ?

Conclusion

The current S2 RUT is a powerful tool including many uncertainty contributors. Update and maintenance of this tool is the best way to provide a complete uncertainty budget of the S2-MSI data. Several axis of improvement are foreseen:

- **Existing contributors to be revised :**
  - Straylight: confirm the current estimation and impact.
  - Cross-talk: totally review the estimation as it is probably over-estimated.

- **Missing contributor to be considered:**
  - Geometric knowledge
  - Spectral knowledge
  - Ortho-rectification error

  } Review/adapt the existing preliminary work

- **Software evolution:**
  - Future tools to be designed as a python tool instead of SNAP plugin.
  - Uncertainty outputted in absolute unit instead of relative.

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