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### Changes Log


Version	Date	Changes
1.0	15/09/2025	Creation of the document

### List of Changes

Version	Section	Answers to RID	Changes

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## 1 Introduction

This document describes the algorithm implemented in the Sentinel-2 Radiometric Uncertainty Tool V1.0. For the justification of the models, we refer to the S2 RUT Error Sources analysis document [RD3].

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## 2 Measurement equation

S2-MSI L1C reflectance values are obtained from L0 acquisition through several steps. A global overview of the main steps relevant for uncertainty computation are given here. More details on intermediate computation steps are available in [RD3]. In the following section, “b” represents the band index and “i” represent the pixel index.

First, total dark signal is estimated by summing all its component:

$$DS(b, i) = D_{offset}(b, i) + D_{NU}(b, i) + Xtalk_{opt}(b, i) + Xtalk_{elec}(b, i)$$

Non-linearity correction is applied on the dark corrected signal.

$$Z(b, i) = \gamma(X(b, i) - DS(b, i))$$

Reflectance is computed from the corrected digital count Z.

$$\rho(b, i) = \frac{\pi * Z(b, i)}{A(b) * Esun(b) * d(t) * \cos(\theta_{sun}(i))}$$

Where:

- DS is the total dark signal, composed of:
  - D\_offset: the residual dark offset computed using blind pixels.
  - D\_NU: the dark signal non uniformity depending on the bands.
  - X\_talk\_opt: the parasitic signal due to optical crosstalk.
  - X\_talk\_elc: the parasitic signal due to electrical crosstalk.
- X is the raw count.
- $\gamma$  represent the non-linearity correction.
- Z is the digital count corrected from dark and non-linearity.
- A is the absolute calibration coefficient, computed from diffuser acquisition.
- Esun is the extra-terrestrial solar spectrum depending on the S2 spectral response.
- d is the Earth-Sun distance factor.
- $\theta_{sun}$  is the sun zenith viewing angle.

Finally, the reflectance is resampled to the L1C grid using a cubic-spline interpolation.

## 3 Error models

### 3.1 Conversion to numerical count

First, the reflectance is converted back to numerical count using the metadata parameters read in L1C tile. From uncertainty perspective negative reflectance should not be considered. In practice several uncertainty contributors are defined in reflectance percentage and would have no physical meaning over a negative reflectance. The negative reflectances are therefore set to zero.

if  $\rho(b, i) \leq 0$ :

$$Z(b, i) = 0$$

else:

$$Z(b, i) = \rho(b, i) * \frac{A(b) * E_{sun}(b) * d(t) * \cos(SZA(i))}{\pi}$$

Variable	Description	Unit
$\rho(b,i)$	L1C reflectance for band 'b' and pixel 'i'	dl
A	Radiometric calibration	LSB/W.m-2.μm-1
E <sub>sun</sub>	Solar irradiance	W.m-2.μm-1
d(t)	Earth-Sun distance factor	dl
SZA	Sun Zenith Angle	radians
<b>Z</b>	<b>L1C digital count</b>	<b>LSB</b>

### 3.2 Geolocation uncertainty

For each contributor, the associated uncertainty term is computed from the known parameters. In the case of the geolocation uncertainty, if the tile is refined the error contribution is set to 1.5 meters, if not the contribution is set to 3 meters. Then, the gradient of the image is computed using second order accurate central differences over each pixel, and its norm is multiplied to the geolocation error divided by the band resolution.

$$u_{geoloc}(b, i) = \frac{geoloc_{error}}{band_{resolution}} * |gradient(Z(b, i))|$$

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Variable	Description	Unit
Z(b,i)	L1C digital count	LSB
Geoloc error	Geolocation error depending of the refinement of the tile, 1.5 m or 3 m.	m
Band resolution	Resolution of the band	m
<b>u_geoloc</b>	<b>Geolocation uncertainty</b>	<b>LSB</b>

### 3.3 Instrument noise model and resampling uncertainty

Uncertainty associated to the noise is computed by applying the noise model to the radiometry and accounting for the resampling factor.

$$u_{noise}(b, i) = resampling_{factor} * \sqrt{\alpha^2 + \beta * Z(b, i)}$$

Variable	Description	Unit
Z(b,i)	L1C digital count	LSB
resampling factor	Resampling factor associated to the projection from L1B to L1C.	dl
$\alpha$	Alpha parameter of the noise model	
$\beta$	Beta parameter of the noise model	
<b>u_noise</b>	<b>Noise uncertainty</b>	<b>LSB</b>


### 3.4 Out-of-field straylight

The out of field straylight systematic contribution has been estimated at 0.3% of the mean radiance of the scene, as we assume that the mean level of the scene is representative of the mean level outside the scene. This term is the same for pixels of the tiles

The out of field straylight random contribution has been estimated for each band during pre-flight analysis. this term is computed per pixels.

$$u_{stray_{sys}}(b) = \frac{0.3 * \frac{1}{N} \sum_{i=0}^N Z(b, i)}{100}$$

$$u_{stray_{rand}}(b, i) = \frac{stray_{random}(b) * Z(b, i)}{100}$$

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Variable	Description	Unit
Z(b,i)	L1C digital count	LSB
stray_random	Random straylight factor per band	dl
<b>u_stray_sys</b>	<b>Out of field straylight systematic uncertainty</b>	LSB
<b>u_stray_rand</b>	<b>Out of field straylight random uncertainty</b>	LSB

### 3.5 Electronic cross-talk

The uncertainty term associated to the residual correction of cross talk has been shown negligible, and it is therefore disabled in the default configuration. However, users can choose to enable this contribution. An early estimation of the residual was made at  $0.01 \text{ W.m}^{-2}.\mu\text{m}^{-1}$ , the uncertainty contributor account for the conversion to LSB thank to the radiometric absolute gain coefficient.

$$u_{\text{crosstalk}}(b) = A(b) * \text{Residual}_{\text{crosstalk}}(b)$$

Variable	Description	Unit
A	Radiometric calibration	LSB/W.m <sup>-2</sup> .μm <sup>-1</sup>
Residual_crosstalk	crosstalk residual value, estimated at 0.01.	W.m <sup>-2</sup> .μm <sup>-1</sup>
<b>u_crosstalk</b>	<b>electrical crosstalk uncertainty</b>	<b>LSB</b>

### 3.6 Dark signal stability

The dark signal residual contribution has been estimated per band during the preflight temperature characterization for both VNIR and SWIR channel. The uncertainty accounting for the dark signal stability is assumed to be identical for all pixel of the tiles, it has been directly measured in LSB per band.

$$u_{DS}(b) = \text{DarkSignal}_{\text{stability}}(b)$$

Variable	Description	Unit
Dark signal stability	preflight uncertainty model	LSB
<b>u_DS</b>	<b>dark signal uncertainty</b>	<b>LSB</b>

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### 3.7 Non linearity

The gamma correction in the measurement equation accounts for non-linearity and non-uniformity effects. The preflight characterization residual was measured per band as a percentage of Lref. The uncertainty is directly computed on the LSB radiometry.

$$U_{non\_linearity}(b, i) = NonLinearity_{error}(b) * \frac{Z(b, i)}{100}$$

Variable	Description	Unit
Non-linearity error	preflight uncertainty model: 0.4% in VNIR. 0.6% in SWIR	%
<b>u_non_linearity</b>	<b>Non-linearity uncertainty</b>	<b>LSB</b>

### 3.8 Radiometric calibration error

The uncertainty associated to the radiometric calibration error is formed by 3 components :

- Diffuser absolute knowledge, estimated during preflight characterisation for each band and expressed as percentage.
- diffuser cosine effect estimated during preflight at 0.4% for all bands.
- Straylight in calibration mode, accounting for the knowledge of the correction factor of the straylight, estimated at 0.3%

$$U_{diff\_abs}(b, i) = Diffuser_{abs}(b) * \frac{Z(b, i)}{100}$$


$$U_{diff\_cosine}(b, i) = Diffuser_{cosine} * \frac{Z(b, i)}{100}$$

$$U_{diff\_sl}(b, i) = Diffuser_{SL} * \frac{Z(b, i)}{100}$$

The 3 components are then summed quadratically.

$$u_{diffuser}(b, i) = \sqrt{u_{diff\_abs}^2(b, i) + u_{diff\_cosine}^2(b, i) + u_{diff\_sl}^2(b, i)}$$

Variable	Description	Unit
diffuser_absolute	Diffuser Reflectance absolute knowledge error in percentage.	%
diffuser_cosine	diffuser cosine effect.	%
diffuser_SL	Straylight in calibration mode, knowledge of correction.	%

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u_diff_abs	diffuser absolute knowledge uncertainty	LSB
u_diff_cosine	diffuser cosine effect uncertainty	LSB
u_diff_sl	diffuser straylight uncertainty	LSB
<b>u_diffuser</b>	<b>diffuser uncertainty</b>	<b>LSB</b>

### 3.9 Diffuser ageing

This term account for the ageing of the diffuser, it has been shown negligible for S2, and it is therefore disabled in the by configuration. Users can still choose to enable it for investigation purpose

$$U_{diff\_ageing}(b, i) = Diffuser_{ageing}(b) * \frac{Z(b, i)}{100}$$


Variable	Description	Unit
diffuser_agein	Diffuser ageing error in percentage.	%
<b>u_diff_ageing</b>	<b>ageing uncertainty of the diffuser</b>	<b>LSB</b>

### 3.10 Quantisation

The uncertainty term associated to the L1C quantisation is computed based on the quantisation value used to encode image on 16 bits. In practice this term is negligible in comparison to the other terms.

$$U_{quant} = \frac{0.5}{quantisation * \sqrt{3}}$$

Variable	Description	Unit
quantisation	S2 quantisation = 10000	
<b>u_quantisation</b>	<b>quantisation uncertainty</b>	<b>LSB</b>

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## 4 Summation


All different components are summed together to compute the expended term: systematic parts are summed linearly, and all random components are summed up quadratically and then multiply by the expansion factor 'k'. The absolute uncertainty obtained is then multiplied by the reflectance factor to obtained per-pixel uncertainties in reflectance dimension.

$$u_S(b, i) = [u_{\text{stray\_sys}} + u_{\text{diff\_ageing}}]$$

$$u_R(b, i) = \sqrt{u_{\text{geoloc}}^2 + u_{\text{noise}}^2 + u_{\text{strayrand}}^2 + u_{\text{crosstalk}}^2 + u_{\text{DS}}^2 + u_{\text{nonlinearity}}^2 + u_{\text{diff}}^2 + u_{\text{quant}}^2}$$

$$\mathbf{u}(b, i) = [\mathbf{u}_S(b, i) + k * \mathbf{u}_R(b, i)] * C_{\text{factor}}$$

Variable	Description	Unit
k	Expanded uncertainty factor, set to 1	dl
C <sub>factor</sub>	conversion factor from LSB to reflectance	
u <sub>s</sub>	systematic uncertainty	LSB
u <sub>r</sub>	random uncertainty	LSB
<b>u</b>	<b>expanded uncertainty in reflectance dimension</b>	<b>dl</b>

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## 5 References

[RD1]	<p>Gorroño, J.; Fomferra, N.; Peters, M.; Gascon, F.; Underwood, C.I.; Fox, N.P.; Kirches, G.; Brockmann, C. <b>A Radiometric Uncertainty Tool for the Sentinel 2 Mission</b>. Remote Sens. 2017, 9, 178. <a href="https://doi.org/10.3390/rs9020178">https://doi.org/10.3390/rs9020178</a></p>
[RD2]	<p>Gorroño, J.; Banks, A.; Gascon, F.; Fox, N.P.; Underwood, C.I. <b>Novel techniques for the analysis of the TOA radiometric uncertainty</b>. Proc. SPIE 2016. <a href="https://doi.org/10.1117/12.2240391">https://doi.org/10.1117/12.2240391</a></p>
[RD3]	<p>Alexis Deru, Sebastien Clerc, Emmanuel Hillairet, Bruno Lafrance, Rémi Bellouard, <b>OMPC.ACR.MEM.41 - i1r0 - RUT Error sources analysis</b>, 2025</p>

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