Impact of varying SNR in L1C data on Sentinel-2 L2A products

Sebastien Clerc[a], Bringfried Pflug[*b], Louis Rivoire[a], Avi Putri Pertiwi[b], Silvia Enache[c], Rosario Quirino Iannone[d], Marco Celesti[e], Roberto Camarero[e], Francisco Reina[e], Constantin Mavrocordatos[e]

[a]ACRI-ST, Email: sebastien.clerc@acri-st.fr; louis.rivoire@acri-st.fr, [b]German Aerospace Centre (Germany), Email: bringfried.pflug@dlr.de, Avi.Pertiwi@dlr.de; [c]CS Group, France, Email: silvia.enache@csgroup.eu; [d]Rhea spa, Italy, Rosario.Quirino.Iannone@ext.esa.int, [e]European Space Agency, ESTEC, Netherlands, Email: Marco.Celesti@ext.esa.int, Roberto.Camarero@esa.int, Francisco.Reina@esa.int, Constantin.Mavrocordatos@esa.int

ABSTRACT

In the frame of the Copernicus program, ESA launched the Copernicus Sentinel- 2 optical imaging satellites, which are fully operational since June 2017. Sentinel-2C- and -2D satellites will be launched following Sentinel-2A and -2B units with identical sensors.

This paper reports on a sensitivity analysis of Sentinel-2 atmospheric correction / cloud masking vs Signal-to Noise Ratio (SNR) in specific spectral bands. Some Sentinel-2 L1C products are selected to study this effect. Noisy products are simulated adding noise to original L1C-data applying different Gaussian noise models. Finally, both original and noisy L1C-products are processed with Level-2A processor Sen2Cor and resulting L2A-products are compared. Results showed, that added noise to B10 is most critical due to performance reduction of cloud masking. Added noise to B01 is less critical because it does not lead to systematic changes of average surface reflectance. It results in increased scatter of surface reflectance. Added noise to B09 is found to be uncritical because the impact on water vapor retrieval is within uncertainty of validation method.

Keywords: Sentinel-2, Atmospheric correction, cloud masking, additional noise

1. INTRODUCTION

The Copernicus program is a European initiative for the implementation of information services dealing with environment and security, mainly based on observation data received from Earth Observation (EO) satellites. In the frame of this program, ESA launched the Copernicus Sentinel- 2A and Sentinel-2B optical imaging satellites [1], which are fully operational since June 2017. They are equipped with optical imaging sensor MSI (Multi-Spectral Instrument) acquiring optical data products with spatial resolution up to 10 m in 13 spectral bands from the VIS to the SWIR spectral domains. Sentinel-2C- and -2D satellites will be launched following Sentinel-2A and -2B units with identical sensors.

Many satellites with new features and observation capabilities are in development or in preparation. Sometimes the realization of new features requires a reasonable compromise with specified instrument requirements. Special investigations are necessary to estimate, what a reasonable compromise is. The objective of the present paper is to investigate the impact of higher noise and consequently reduced Signal-to-Noise-Ratio (SNR) in L1C data on L2A-products. Sentinel-2 units have an excellent radiometric performance [2] and can be considered as a flagship mission. Therefore, Sentinel-2 data will be used as reference for the present study. The present paper reports on a sensitivity analysis of Sentinel-2 atmospheric correction / cloud masking vs Signal-to Noise Ratio (SNR) in specific spectral bands.

2. METHODOLOGY

Noisy products are simulated adding noise to original L1C-data applying Gaussian noise models (see Figure 1). However, noise can only be added to radiances. Therefore, original reflectances have to be converted to radiances for adding noise and then back to reflectances. Finally, both original and noisy L1C-products (reflectances) are processed with Level-2A processor Sen2Cor [3] and resulting L2A-products are compared.

*bringfried.pflug@dlr.de

Sensors, Systems, and Next-Generation Satellites XXVIII, edited by Sachidananda R. Babu, Arnaud Hélière, Toshiyoshi Kimura, Proc. of SPIE Vol. 13192, 1319216

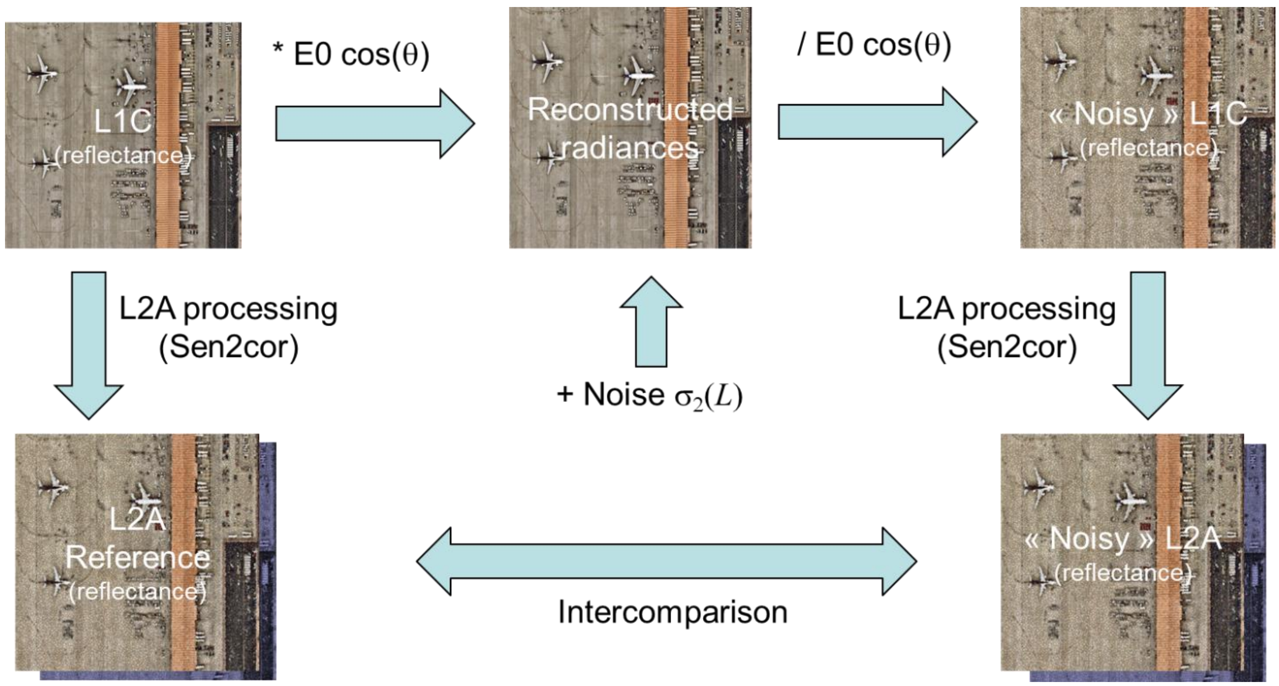

Figure 1: Methodology adding noise to Sentinel-2 L1C products

Gaussian noise models with two different hypotheses on noise level have been used adding noise to bands B01, B09 and B10 of Sentinel-2 products (Figure 2). Noise hypothesis 1 represents the stronger noise level reducing SNR to about 600, 120 and 240 at B01 (443 nm), B09 (945 nm) and B10 (1374 nm) at reference radiance L_{ref}. Noise hypothesis 2 leads to SNR of about 1100, 175 and 300 (Figure 3). Both original and noisy L1C products are processed with Sen2Cor 2.11 user processing with Copernicus DEM at 30 m spatial resolution and default configuration.

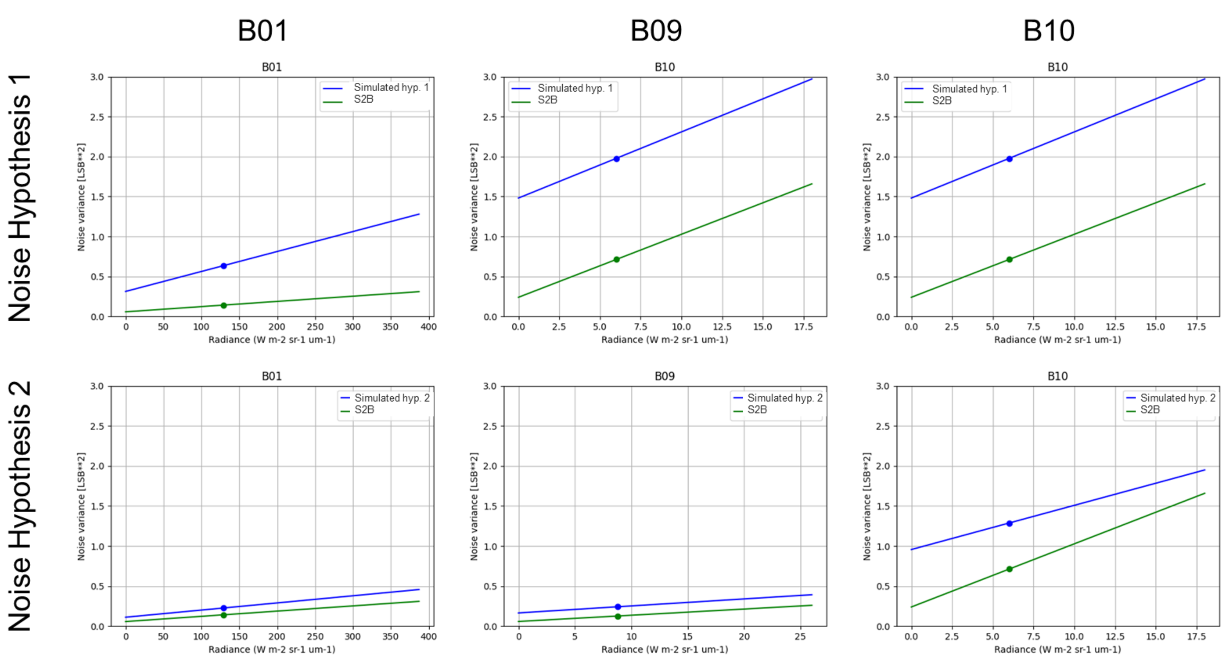

Figure 2: Noise variance [lsb] of two different hypothesis on noise level.
Added noise = (Blue - Green) = (simulated noise – MPC S2 noise model)

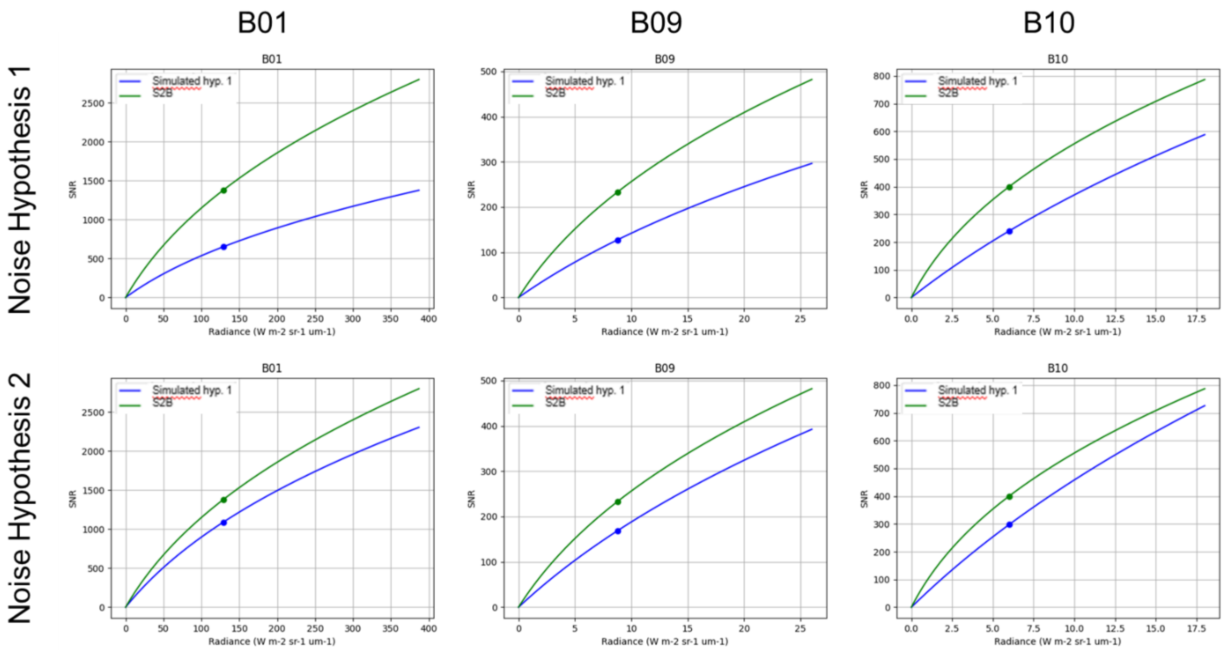

Figure 3: Signal to Noise ratio resulting from noise variance of two different hypothesis on noise level.

3. DATA

Some Sentinel-2 L1C products were selected to study this effect covering summer and winter seasons, different cloudiness and different types of land cover including inland and coastal water, dark African equatorial forest and snow.

Table 1: Sentinel-2 products selected.

Site	Granule	Date	Climate zone	Season	Inland water	Coastal water	Snow	Clouds over land	Cirrus
Rimrock	T11TMM	2023-02-08	Boreal	Winter			6%	22%	0.3%
Yakutsk	T52VEP	2023-05-01	Polar	Summer			84%	14%	11%
Potsdam	T33UUU	2023-06-12	Boreal	Summer	yes		0%	19%	5%
Rimrock	T11TMM	2023-07-25	Boreal	Summer			0%	26%	2.5%
Rimrock	T11TMM	2023-12-25	Boreal	Winter			3%	40%	9%
Murcia	T30SXH	2023-03-11	Midlatitude N	Winter		yes	0%	30%	27%
Bandung	T48MZT	2023-04-06	Tropical		yes	yes	0%	50%	17%
Congo	T35MNU	2023-05-05	Tropical				0%	14%	13%
Murcia	T30SXH	2023-08-08	Midlatitude N	summer		yes	0%	11%	6%
Congo	T35MNU	2023-10-02	Tropical				0%	10%	10%

4. RESULTS

Level-2A processor Sen2Cor [3] performs atmospheric correction of L1C data providing Level-2A Bottom-of-Atmosphere (BOA) Surface Directional Reflectance product (SDR) together with Aerosol Optical Thickness (AOT), Integrated Water Vapour (WVP) and Scene Classification (SCL) maps. The following subsections show the impact of added noise on all these products.

Impact of added noise on SCL performance

The spider plots in Figure 4 show the difference between percentage of SCL classes provided by Sen2Cor applied to original and noisy products. Noisy products give up to 1.25% less thin cirrus and consequently less clouds than original products. These in reality cloudy pixels are classified as cloudless. It can be assumed, that this difference in thin cirrus detection comes from the added noise in B10 which is the cirrus band. As expectable, noisy data for hypothesis 1 give worse results than data for hypothesis 2.

Even if the commission of cirrus pixels to clear is only about 1% it is very critical for downstream applications. Users require confidence that pixels masked as clear are really clear. Therefore, advancement of SCL performance is fighting for every percent less commission to clear pixels. Consequently, it is recommended to limit additional noise to B10 in order to keep similar performances for cirrus detection as achieved with Sentinel-2.

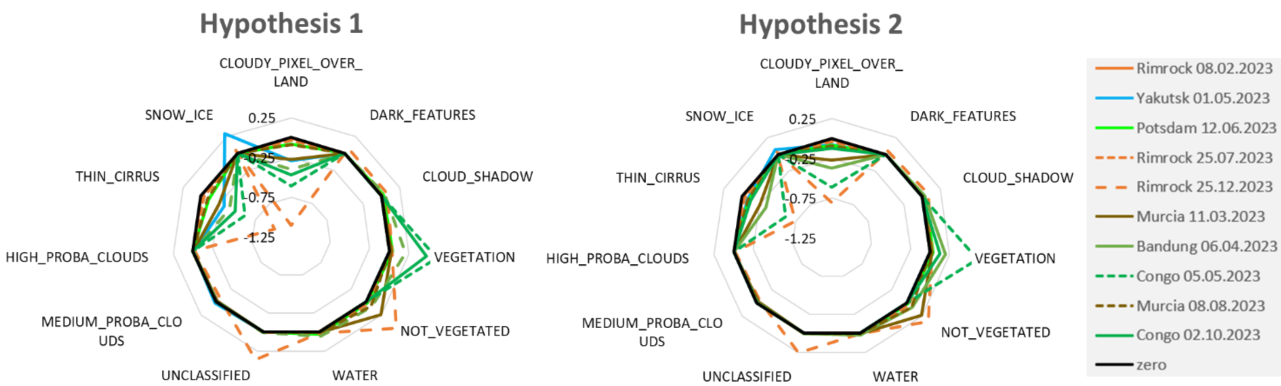

Figure 4: Difference (noisy – original) between percentage of SCL-classes. The black line points to no difference.

Impact of added noise on AOT estimation

Sen2Cor processor relies on Dense Dark Vegetation (DDV) pixels for estimation of AOT and uses AOT from Copernicus Atmospheric Monitoring Service (CAMS) as fall-back option in case there are not enough DDV-pixels in the image [3]. The 10 test images listed in Table *1* contain 5 images estimating AOT based on DDV algorithm and 5 images processed with fall-back option. Average AOT values per granule agree within 3 digits for all 10 test images and all of the original S2-data and noisy data. Added noise to B01, B09 and B10 has no influence on AOT estimation.

Impact of added noise on WVP retrieval

WVP retrieval is based on B09 of Sentinel-2. Results in Table *2* show granule average differences of retrieved WVP in the third digit, up to 0.2%, with noisy data giving more WVP than original data. There is no difference within 3 digits between both different hypothesis on noise level except for one test data image. Per pixel differences are up to (0.1 ±0.5)%. These differences are more than one magnitude smaller than the current average WVP retrieval uncertainty of 0.20 cm respectively around 9% [4]. More, the WVP retrieval differences found are smaller than uncertainties of WVP reference data and thus within uncertainty of validation methods. Therefore, B09 SNR requirements can be relaxed for retrieval of WVP.

Table 2: Average WVP per granule depending on noise hypothesis.

Site	Date	Climate zone	Season	L2A ref	L2A noisy Hyp1	L2A noisy Hyp2	Percent diff. Hyp1	Percent diff. Hyp2
Rimrock	2023-02-08	Boreal	Winter	0.528 cm	0.529 cm	0.529 cm	0.2%	0.2%
Yakutsk	2023-05-01	Polar	Summer	0.715 cm	0.716 cm	0.716 cm	0.1%	0.1%
Potsdam	2023-06-12	Boreal	Summer	1.044 cm	1.044 cm	1.045 cm	0.1%	0.1%
Rimrock	2023-07-25	Boreal	Summer	1.555 cm	1.556 cm	1.556 cm	0.1%	0.1%
Rimrock	2023-12-25	Boreal	Winter	0.675 cm	0.675 cm	0.675 cm	0.0%	0.0%
Murcia	2023-03-11	Midlatitude N	Winter	0.876 cm	0.877 cm	0.877 cm	0.1%	0.1%
Bandung	2023-04-06	Tropical		4.000 cm	4.005 cm	4.005 cm	0.1%	0.1%
Congo	2023-05-05	Tropical		3.451 cm	3.452 cm	3.452 cm	0.0%	0.0%
Murcia	2023-08-08	Midlatitude N	summer	2.291 cm	2.293 cm	2.293 cm	0.1%	0.1%
Congo	2023-10-02	Tropical		3.283 cm	3.285 cm	3.286 cm	0.1%	0.1%

Impact of added noise on SDR retrieval

Figure *5* gives a typical example for the impact of added noise in B01, B09 and B10 on SDR retrieval. B01 and the WVP image show larger noise than the other bands due to the direct impact of the added noise in these bands. Per pixel differences in B01 are up to (-0.1 ±0.8)% and per pixel differences of WVP are up to (0.1 ± 0.4)% for the given example. B05 to B12 are more or less influenced by absorption bands of WVP. Therefore, an indirect effect of WVP retrieval variance due to the noise is visible like in the example of B07. B02 to B04 don't overlap with WVP absorption bands and therefore they don't show scatter of SDR in distance of clouds. However, they show differences around the clouds. This can be interpreted to be caused by the observed commission error from cloudy to clear pixels which obviously mostly occurs at the boarder of clouds. The indirect effect of WVP retrieval noise and masking difference together leads to differences of up to (0.01 ±0.04)% for the given example, which is one magnitude lower than the direct effect on B01 and WVP.

Generally, over all 10 test images, results show that adding noise leads more to increased scatter of SDR than to changes in average SDR. The direct influence of added noise to B01 leads to up to 0.4% average relative difference and up to 5% variation of SDR for data of noise hypothesis 1. The mean average difference is (0.2 ±0.1)% and the average variation (1.5±1.2)%. As expectable, data for noise hypothesis 1 are more influenced than data for noise hypothesis 2. Noise hypothesis 2 gives up to 2.4% variation of SDR and a mean variation of (0.7 ±0.6)%.

The indirect influence on B02 to B12 due to masking difference and WVP retrieval noise can reach in few cases average relative differences up to 0.1% and variation up to 1.6% for hypothesis 1, but is mostly much smaller with average relative difference (0.0 ±0.02)% and (0.2 ±0.5)% variation. Results for hypothesis 2 are again about half of these values.

The observed 1-2% impact of added noise to B01, B09 and B10 on SDR is negligible compared to the current retrieval uncertainty of about 5% and to the SDR retrieval performance specification of 5% [4]. The impact of that noise cannot be recognized with the current reference data for validation which have uncertainties of more than 3%. However, with regard to B01, the added noise can reduce the applicability of B01 for aquatic applications which have stronger requirements.

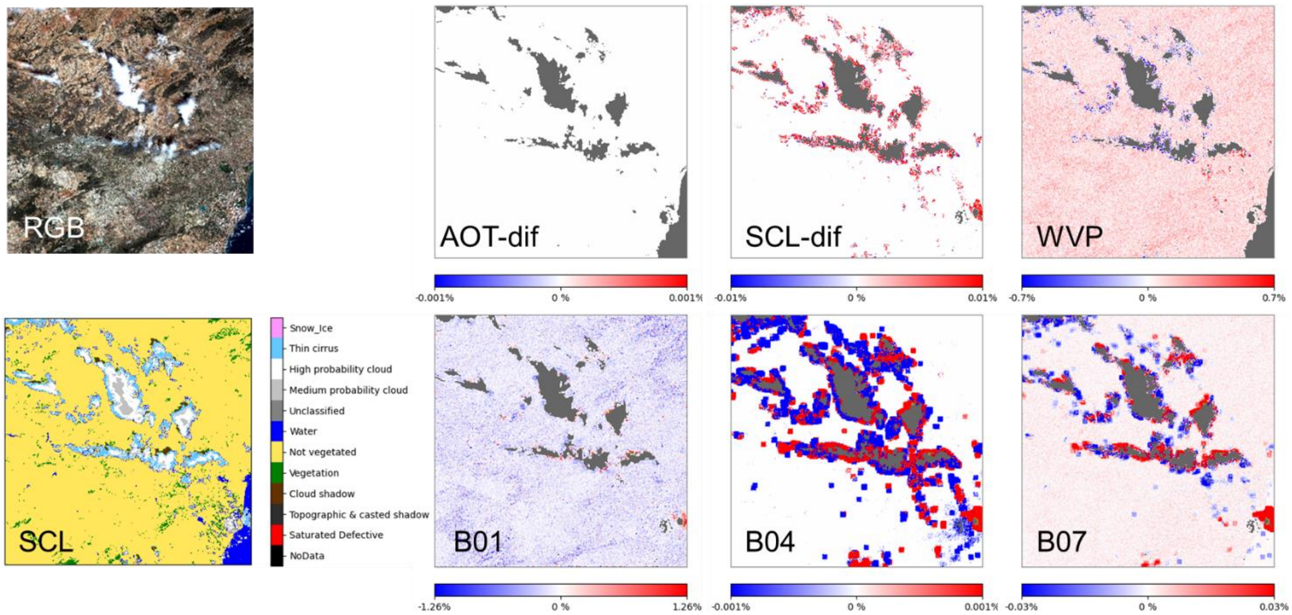

Figure 5: SDR retrieval difference per pixel for hypothesis 1 on example of image over test site Murcia acquired on 2023-08-08 (retrieved AOT=0.3 and WVP=2.3cm). The color scale for difference images goes from -2σ difference (blue) over zero difference (white) to +2σ difference (red).

5. CONCLUSIONS

Results showed, that added noise to B10 is most critical due to performance reduction of cloud masking. It increases the commission of cirrus pixels to clear pixels by up to 1%. Therefore, it is recommended to limit additional noise to B10 for future sensors in order to keep similar performances for cirrus detection as achieved with Sentinel-2.

Added noise to B01 leads more to increased scatter of SDR than to systematic changes of average SDR. It has a direct influence of 1-2% variation of SDR in B01. This variation is smaller than current retrieval uncertainty (~ 5%), SDR specification (~ 5%) and uncertainty of reference data for validation (> 3%). Therefore, as far as surface reflectance over land is concerned, B01 requirements can be relaxed for future sensors without major impact. Noise like for hypothesis 2 would be ok. Other applications (e.g. aquatic) may have other requirements.

Among the B01, B09 and B10 SNR requirements, B09 SNR requirement is the one that can be the most relaxed for future sensors because the impact of added noise on WV retrieval is 0.2% only. This is more than 1 magnitude lower than current systematic WVP retrieval uncertainty (~9%). Both the changes in masking and WVP retrieval noise have an influence on SDR retrieval on other bands giving 0.2% more variation of SDR

ACKNOWLEDGEMENTS

This work was funded by EU and ESA. The views expressed herein can in no way be taken to reflect the official opinion of the European Space Agency or the European Union.

REFERENCES

1. Drusch, M., et al., *Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services.* Remote Sensing of Environment, 2012. **120**: p. 25-36.

2. Sentinel-2 MPC Team. *Sentinel-2 L1C Data Quality Report (S2-PDGS-MPC-L1CDQR)*. 11 June 2020]; Available from: https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi/document-library/.
3. *Sentinel-2 Level-2A Algorithm Theoretical Basis Document (ATBD)*, *S2-PDGS-MPC-ATBD-L2A*. 2020.
4. Sentinel-2 MPC Team. *Sentinel-2 L2A Data Quality Report (S2-PDGS-MPC-L2ADQR)*. 18 August 2020]; Available from: https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi/document-library/.