European Commission

# JRC TECHNICAL REPORT

# SPOT TrueSharp 4m

## *Comparison with Sentinel-2, PlanetScope, SPOT, and Pleiades - a preliminary quality assessment*

2021

Pär Johan Åstrand, Slavko Lemajic, Csaba Wirnhardt

*Figure 1 - SPOT TrueSharp 4m (11/05/2019, extract from area A East in Puglia, IT); © Airbus*

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Joint Research Centre

Contact information
Name: Pär Johan Åstrand
par-johan.astrand@ec.europa.eu

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https://ec.europa.eu/jrc

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**Contents:**

## Acknowledgements

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## Authors

Pär Johan Åstrand, Slavko Lemajic, and Csaba Wirnhardt.

# Abstract

Earlier results [ref i] show that there is little to no evidence that there is a wealth of “extra” processing-ready information for use in Checks by Monitoring within the HHR Time Stacks compared to those of the Sentinel-2, even for small narrow parcels (typically < 0.3ha). However, this analysis continues, and the possible need for HHR data for other lanes of the new CAP monitoring scenarios (Checks by Monitoring, Area Monitoring System) justifies further investigation.

This report addresses SPOT TrueSharp processed imagery and aims to assess whether such imagery can be considered another regulatory option (Article 40a of the implementing regulation (EU) 746/2018 of 18 May 2018 amending the Implementing Regulation (EU) No. 809/2014) for data requiring qualities "equivalent or better than Sentinel". It is of interest to conclude whether SPOT TrueSharp imagery is comparable and can be used equally as the native HHR data with an inherent better Ground Sample Distance (range between 2.5-5.0 m).

The analysis includes visual and radiometric quality assessment of the SPOT TrueSharp product by comparison with available Sentinel-2, PlanetScope Classic Dove, SPOT 6/7, and Pleiades 1A/1B data sets. The test should be considered as preliminary since limited to a single acquisition date (or the closest possible date) for only two restricted geographic areas (Italy and Belgium). The study sites were selected to have “small” or elongated agricultural parcels where SPOT and Pleiades imagery were made available by Airbus, and where JRC has ground truth data.

Visual comparison of the extracts of true colour rendering or nIR false colour composites does not show the radiometric difference between TrueSharp and the standard SPOT product, or the difference is very small. TrueSharp also shows comparable or better radiometry cf. PlanetScope for visual interpretation. The exercise performed by the JRC, in addition shows that there is clear visible enhancement of the spatial resolution in the TrueSharp 4m product compared to PlanetScope (and obviously S2). This brings on the conclusion from the visual comparison that the product (TrueSharp) makes the visual interpretation just as feasible as with the other products.

Comparison of the radiometric Bottom of Atmosphere (or surface reflectance) values of TrueSharp with the other products (Sentinel-2 and PlanetScope) shows that the NDVI values of Sentinel-2, and TrueSharp 4m are very much aligned, while PlanetScope most often was found lower (‘damped’). It can, however, be concluded that the dependency between the image sets are strong, the $R^2$ goodness-of-fit values are high overall, and the measurements from the different sensors are well represented with a linear relationship, as could be expected over this mainly agricultural landscape. This also brings the conclusion that all three products can supplement each other.

This is confirmed also in the application of Pearson’s correlation coefficient, when used as an estimator of similarity, where results tell us that the NDVI profiles for the three sensor products are comparable. Of interest, in the last JRC test, is the heterogeneity test which tells that heterogeneity is not more evident in either of the HHR data sets (PlanetScope, TrueSharp) compared to Sentinel-2. But such tests need to be done on a larger population of parcels, with smaller sizes.

Regards to determining whether the HHR Time Stacks specification can be revised permitting the use of SPOT TrueSharp equally as the source HHR data with an inherent better Ground Sample Distance, the answer is positive with respect to spatial resolution and radiometric BOA reflectance. However, to conclude on the real complementarity of TrueSharp to the other products, a test of the time series frequency should be made. It is also suggested to extend tests to include more sites, and more imagery to make final conclusions on the TrueSharp 4m product.

The report concludes discussing the need of HHR imagery within the frame of the new CAP. It suggests that Time Stacks products could be of use in regions with almost exclusively small arable land parcels. Other hypothetical use cases could lie in the potential for the discrimination of landscape elements not discernible on Sentinel data. While additional tests are required to prove the added value of HHR products to detect more reliably the heterogeneity conditions, a second use case of HHR products is the conclusion on parcel maintenance activities or abandonment when intra-parcel heterogeneity is accounted for. In both these latter cases, however, there is probably competition from more cost-effective and accurate solutions. Other fields of research may arise depending on the detailed settings currently under discussion for the new CAP.

# 1 Context and Objectives

The Common Agricultural Policy (CAP) Checks by Monitoring (CbM) replaces the on-the-spot-checks presently used to verify that area-based direct aid is granted correctly to EU farmers. This alternative control method is implemented through Article 40a of the implementing regulation (EU) 809/2014, and is used since 2018 by some Member States (MS).

CbM primarily relies on automatic methods to conclude on the CAP eligibility criteria, commitments and obligations from regular and systematic Copernicus Sentinel imagery. For some agricultural parcels, the spatial resolution of the Sentinel imagery (10m) could be insufficient to conclude on the support (eligibility, compliance). For this reason, the use of High High Resolution (HHR) image data as source to the Time Stacks (TSs) has been considered to verify and possibly complement the results obtained using Sentinel data.

Earlier results [ref i] show that there is little to no evidence that there is a wealth of "extra" processing-ready information for use within CbM inside the HHR TSs compared to those of the Sentinel-2 (S2), even for small and narrow parcels (typically < 0.3ha). However, this analysis continues, and the possible need for HHR data in other lanes of the future CAP 2020+ monitoring scenarios (CbM, Area Monitoring System (AMS)) justifies further investigation.

This report introduces SPOT TrueSharp processing and assesses whether such imagery can be considered another regulatory option (Article 40a of the implementing regulation (EU) 746/2018 of 18 May 2018 amending the Implementing Regulation (EU) No. 809/2014) for data requiring qualities "equivalent or better than Sentinel", and therefore whether such data is comparable and can be used equally as a source of HHR data with an inherent better Ground Sample Distance (GSD).

Indeed, in earlier specifications, the spatial resolution of the product used for the extraction of the HHR TS should be derived from sensor data acquired in the GSD range between 2.5-5.0 m, inclusive of effects of elevation angle and earth curvature. For the radiometry the product used should have spectral bands corresponding to the S2 bands B2, B3, B4, and B8 (nota. a minimum of 70% spectral range overlap for the B4, B8), and in addition have a minimum bandwidth of 40nm. The S2 spectral bands are shown in Figure 2 below.

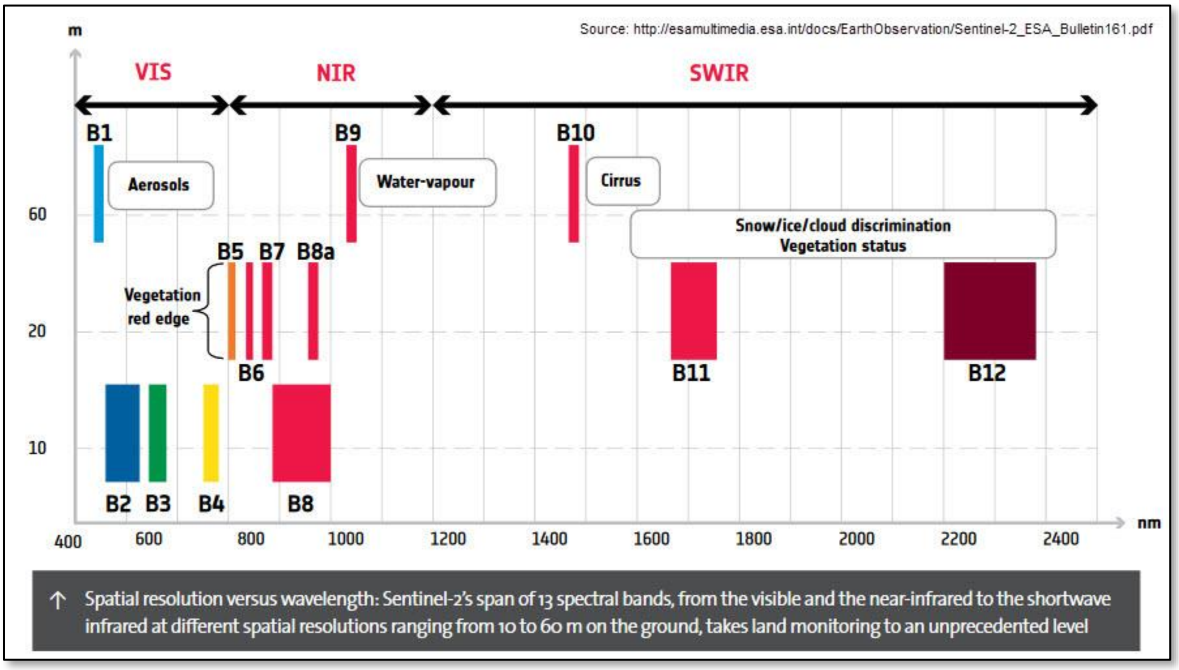



*Figure 2 - Sentinel-2 spectral bands [ref ii].*

The aim is therefore to determine whether SPOT TrueSharp (TSHP) can be used as source imagery for the HHR TS and therefore whether above specification should be revised. Our test performs visual and radiometric quality assessment of this product by comparison mainly with S2, and PlanetScope, but also with the TSHP source imagery SPOT-6/7 itself, and in a few cases with VHR resolution Pleiades 1A/1B imagery. The test was limited to a single acquisition date (or to the closest possible date) for two restricted geographic areas (Italy and Belgium, with suitable arable land (AL) containing both some “small” (<0.3 ha) and some elongated agricultural parcels), where Airbus had SPOT and Pleiades imagery, and JRC could couple with parcel crop type ground truth.

The JRC test was divided into four parts and concerns:

- Visual comparison - Computer Aided Photo-Interpretation (CAPI);
- Numerical comparison and linear regression of Digital Number (DN) and NDVI values;
- Comparison of some spatial profiles (visual, and similarity index [ii]);
- Parcel heterogeneity.

# 2 Areas of interest (AOIs)

## 2.1 Puglia, Italy and Eeklo, Belgium, Flanders

As mentioned above, the study areas, both of them situated in suitable AL, were chosen to fit to some “small” (<0.3ha) and to some elongated agricultural parcels (APs) landscape, where Airbus had SPOT 6/7 and Pleiades 1A/1B imagery. Also in these study areas the JRC could couple with ground truth obtained from the IT Paying Agency, Agenzia per le Erogazioni in Agricoltura (AGEA) [ref i]:

1. Puglia, close to Bari (Italy) contained two Areas of Interest (AOIs) both along the coast: the first East (A) and the other (B) further North West. See Figure 3.
2. Eeklo (Belgium Flanders) instead with intense AL, containing many elongated APs. See Figure 4.

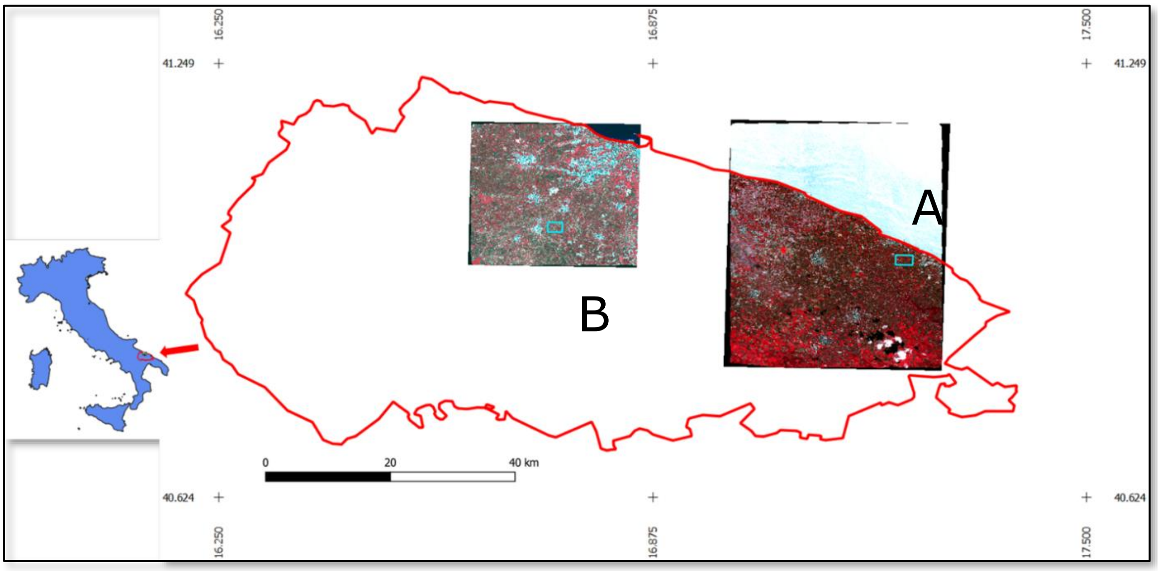



*Figure 3 - Puglia, AOI in Italy (A-East size 2.0 x 1.5km lat/long LL 17.2244, 40.9589; UR 17.2496,40.9733; and B-West 1.8 x 1.5km lat/long LL 16.7235, 41.0064; UR 16.7449, 41.0206 )*

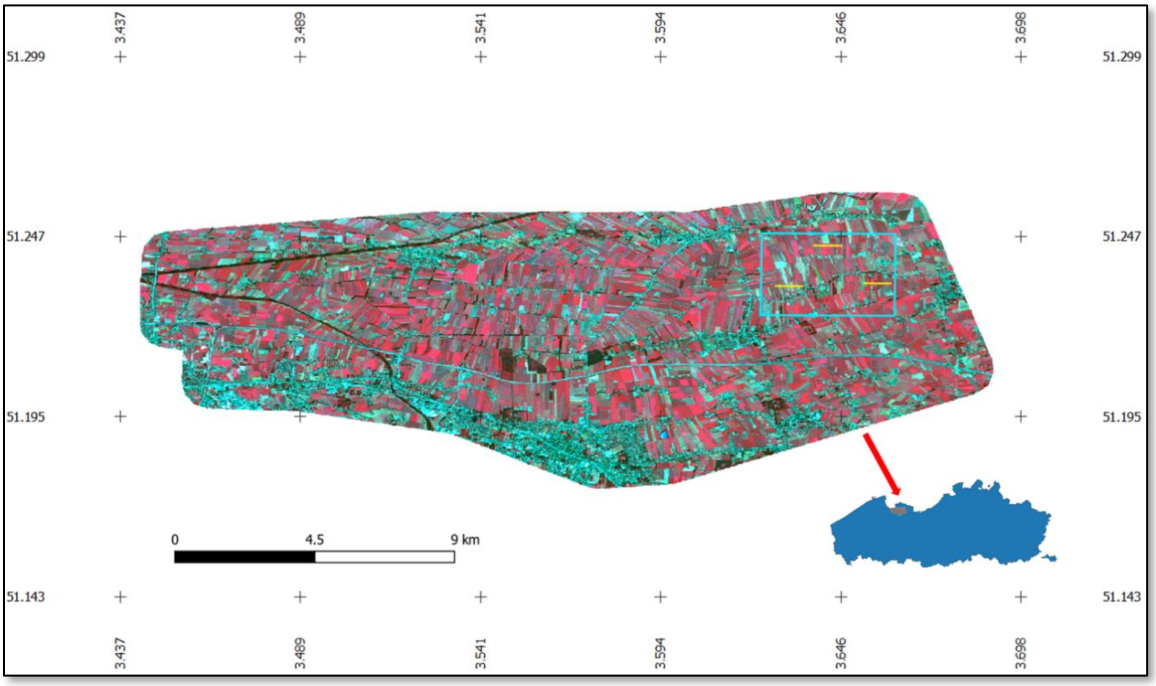



*Figure 4 - Eeklo, AOI in Belgium (size. 2.7 x 2.7 km, lat/long LL 3.6224, 51.2187; UR 3.6617, 51.2480), Flanders*

# 3 Data Scope

## 3.1 SPOT TrueSharp

For the purposes of use within the CAP of any specifically processed/produced imagery, maintaining the spectral information is essential. The SPOT TrueSharp (TSHP) processing patented by Airbus places special care on making a resolution improvement with a physical meaning, ultimately found in the NDVI values after the TSHP processed image (see Fig 5). At time of writing this report, there is no publically available publication on the TSHP processing yet.

The method is based on a physical modelling of the reflectance signal and aims to determine optimal translation of the local variation of the Panchromatic (PAN) band (referred as PAN 'modulation') into the Multispectral (MSP) bands, for any point in the MSP spectral domain.

Modelling of the scene reflectance integrates several sub-models, e.g. SAIL-PROSPECT for the vegetation and a Case-2 Waters model to simulate various water bodies' conditions. Atmospheric modelling is based on Lowtran 7 and uses a dedicated turbid medium model for clouds and cloud veils.
The overall model is obtained by coupling both the scene and atmospheric models, and so is driven by a set of variables ($v$ = ($vk$), $k$ = 1… $N$) that describe both the pixel composition (soil, plant cover, water) and associated characteristics (e.g. brightness, shade, pigmentation, etc.), and the atmospheric conditions. The model allows calculation of reflectance in the MSP bands $\rho model\text{–}(v)$, and the PAN band $\rho model\text{–}PAN(v)$.

The method includes the following steps:

i. Model inversion of the MSP bands to determine local values of the set of variables

ii. Model inversion of the PAN band in these local conditions to determine how a local variation in the PAN band should translate into local variation of the model variables, then into the MSP bands, providing the so called PAN "injection coefficients" (i.e. from PAN to MSP)

iii. Application of a Gaussian convolution filter to the PAN band in order to simulate a PAN image with an actual resolution similar to the MSP image, named PAN-lowRes

iv. Application of the PAN local injection coefficient to the PAN modulation = (PAN - PAN-lowRes) to determine the additional signal that will sharpen the MSP bands

Indeed, the SPOT TSHP was proposed and used in Copernicus VHR 2018 [ref iv] as a MSP product (@4m resolution), for part of the coverage provided at this resolution.

In this report special interest has been placed on the 4m spatial resolution product since this seems to be an HHR resolution appropriate for the CAP uses, referred to as TSHP4 throughout the report. Sometimes the TSHP2.5 is included as comparison term, since the output spatial sampling distance is arbitrary in the TSHP processing.

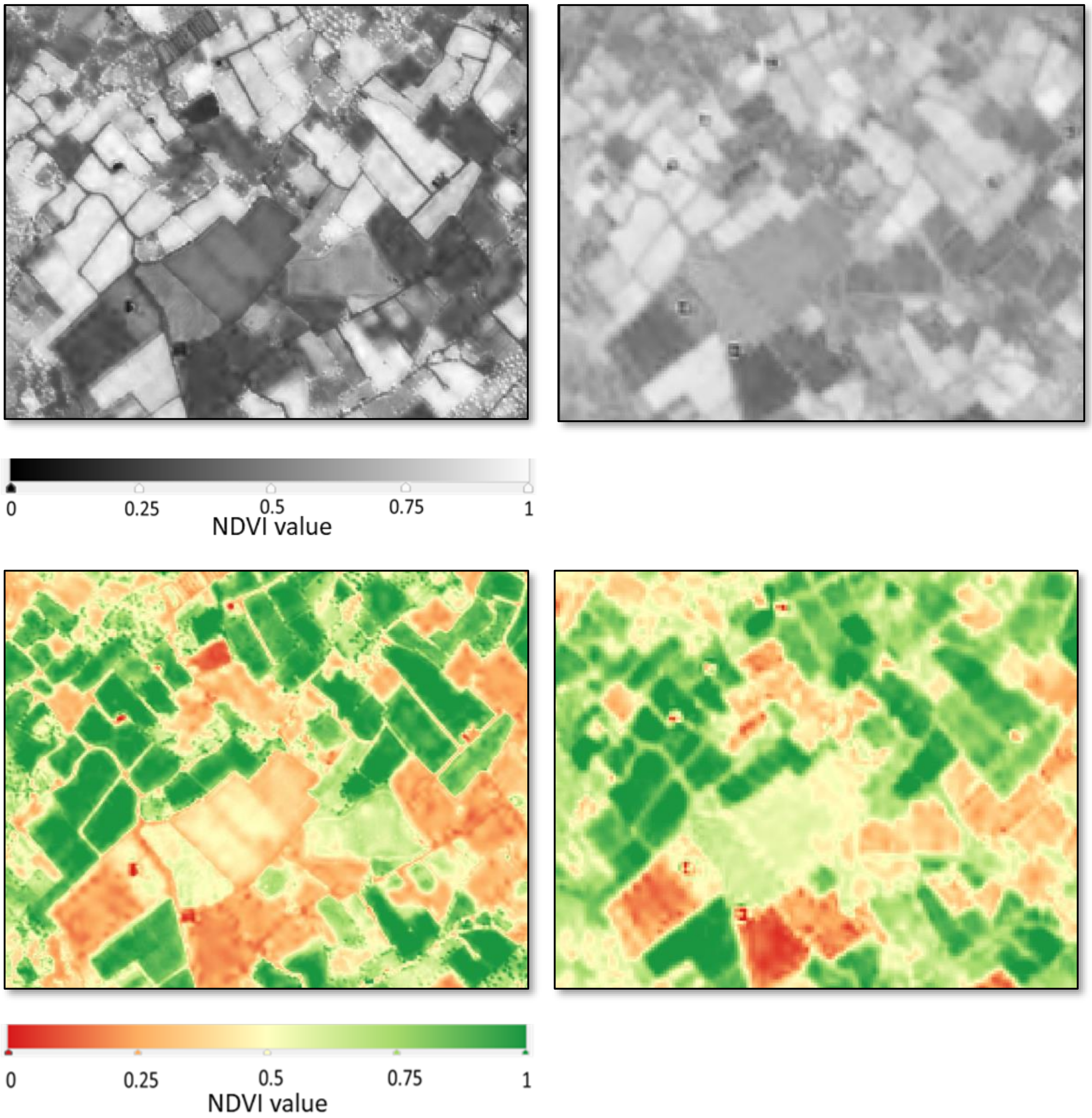



*Figure 5 - Orthorectified NDVI map showing the difference between TrueSharp SPOT (left) and its source SPOT6 (right), extract from area A East (Puglia, IT); image date 11/05/2019;*

## 3.2 Data sets provided / downloaded

The figure below summarizes the sensors, products, and acquisition dates used in the tests.

| Sensor/Product | GSD (m) | Output pixel size (m) | Processing level | Ortho rectified | Acquisition date | |
|---|---|---|---|---|---|---|
| | | | | | Puglia (IT) | Eeklo (BE) |
| **SPOT-6 MSP** | 2.2, 8.8 | 1.5, 6.0 | BOA Reflectance | Y | 11/05/2019 | 30/06/2018 |
| **SPOT-7 MSP** | 2.2, 8.8 | 1.5, 6.0 | BOA Reflectance | Y | 16/04/2019 | |
| **Pleiades 1A** | 0.7, 2.8 | 0.5, 2.0 | BOA Reflectance | Y | 16/04/2019 | |
| **Pleiades 1B** | 0.7, 2.8 | 0.5, 2.0 | BOA Reflectance | Y | 11/05/2019 | 30/06/2018 |
| **TSHP4 (source SPOT) delivery I** | n/a | 4 | TSHP processing | Y | 16/04/2019, 11/05/2019 | 30/06/2018 |
| **TSHP4 (source SPOT) delivery II** | n/a | 4 | TSHP processing | Y | 16/04/2019, 11/05/2019 | 30/06/2018 |
| **TSHP2.5 (source SPOT)** | n/a | 2,5 | TSHP processing | Y | 16/04/2019, 11/05/2019 | 30/06/2018 |
| **Planet Scope (classic)** | 3,74 | 3 | L3B Analytics Surface Reflectance | Y | 16/04/2019, 18/04/2019, 11/05/2019 | 29/06/2018, 01/07/2018 |
| **Sentinel-2A** | 10 (B2,3,4,8); 20 (B5,6,7,8a,11,12); 60 (B1,9,10) | (always resampled to 10m in our | L2A BOA Reflectance | Y | 25/05/2019 | 30/06/2018 |

*Table 1 - Sensors, products, and acquisition dates used in JRC tests*

### 3.2.1 SPOT, Pleiades and TSHP data

The subject of analysis was the TSHP4 product as a Bottom of Atmosphere (BOA) reflectance (also known as surface reflectance) This is the satellite derived Top Of Atmosphere (TOA) reflectance corrected for the scattering and absorbing effects of atmospheric gases and aerosols in this case derived from SPOT-6/7 image acquisitions. The AOIs where, as mentioned above in Chapter 2, located in Puglia, close to Bari (Italy) and Eeklo (Belgium, Flanders).

- Puglia; two acquisitions of SPOT and two of Pleiades
- Flanders; one acquisition of SPOT and one of Pleiades

For the AOIs the following data was provided by Airbus:

- Source SPOT data bundled product; Puglia dates: 16/04/2019, 11/05/2019; Eeklo date: 30/06/2018
- Source Pleiades data bundled product; Puglia dates: 16/04/2019, 11/05/2019; Eeklo date: 30/06/2018
- TrueSharp product 4m derived from SPOT; BOA (scaling factor of 10000) of the 4 VNIR bands (in natural order: B-G-R-NIR); delivery (I) March 2020, delivery (II) re-processed July 2020
- TrueSharp product 2.5m derived from SPOT; BOA (scaling factor of 10000) of the 4 VNIR bands (in natural order: B-G-R-NIR); delivery (I) March 2020
- NDVI computed from the BOA reflectances of above TSHP products with ad-hoc colour table (i.e. same used for a given site, but different between Puglia and Flanders).

The two images below show the difference between the source SPOT (only MSP shown here and not the PAN) and the resulting TSHP4m.

*Figure 6 - SPOT-6 MSP 6m over extract from area A East (Puglia, IT); image date 11/05/2019 [MSP original GSD 8.8m]*

*Figure 7 - TSHP4 over extract from area A East (Puglia, IT); image date 11/05/2019; [Delivery I, see Chapters 3.2.1, Table 1, and Chapter 4 for details on delivery I and II]*

### 3.2.2 PlanetScope data

PlanetScope Surface reflectance processed data [ref. v] was provided by Planet Labs as follows.

Puglia:

- 20190416_093816_89_105c_3B_AnalyticMS_SR.tif - a scene captured on 16/04/2019 with appropriate metadata, and SR (Surface reflectance processed).
- 20190418_082218_104b_3B_AnalyticMS_SR – a scene captured on 18/04/2019 with appropriate metadata, and SR (Surface reflectance processed).
- 20190511_091612_1004_3B_AnalyticMS_SR.tif – a scene captured on 11/05/2019 with appropriate metadata, and SR (Surface reflectance processed).

Eeklo:

- 20180629_101418_0f43_3B_AnalyticMS_SR.tif - a scene captured on 29/06/2019 with appropriate metadata, and SR (Surface reflectance processed).
- 20180701_101401_102c_3B_AnalyticMS_SR.tif - a scene captured on 01/07/2019 with appropriate metadata, and SR (Surface reflectance processed).

The PlanetScope satellite constellation consists of multiple launches of groups of individual cubesats (DOVEs). Comparisons are made using the classic DOVE, since the next generation Dove-R, and the SuperDove [ref vi] were not available at time of this study. We can see in **Error! Reference source not found.Error! Reference source not found.**Figure 8 below that for PlanetScope, the RED band has a significant contribution from the GREEN domain, and the NIR band from some RED-edge.

### 3.2.3 Copernicus Sentinel-2 data

Copernicus S2 L2A Level-2A (BOA reflectance) products [ref.vii], freely available, were downloaded from the ESA archives as needed. The following products were used since best cloud cover conditions over the AOIs:

Puglia:

- S2A_MSIL2A_20190525T094031_N0212_R036_T33TXF_20190525T123044 (25/05/2019)

Eeklo:

- S2A_MSIL2A_20180630T105031_N0208_R051_T31UES_20180630T144133 (30/06/2018)

Figure 2 above gave an overview of all S2 bands, while the comparison with the SPOT/Pleiades, and PlanetScope is shown more in detail in Figure 8 below. In all visual and digital analysis, the S2 bands were resampled to 10m output pixel size (i.e. the SWIR band B11 which is native 20m was resampled to 10m).

### 3.2.4 Spectral bands comparison

A schematic comparison of the spectral bands of SPOT/TSHP/Pleiades, compared to PlanetScope, and compared to S2 is shown in figures below.

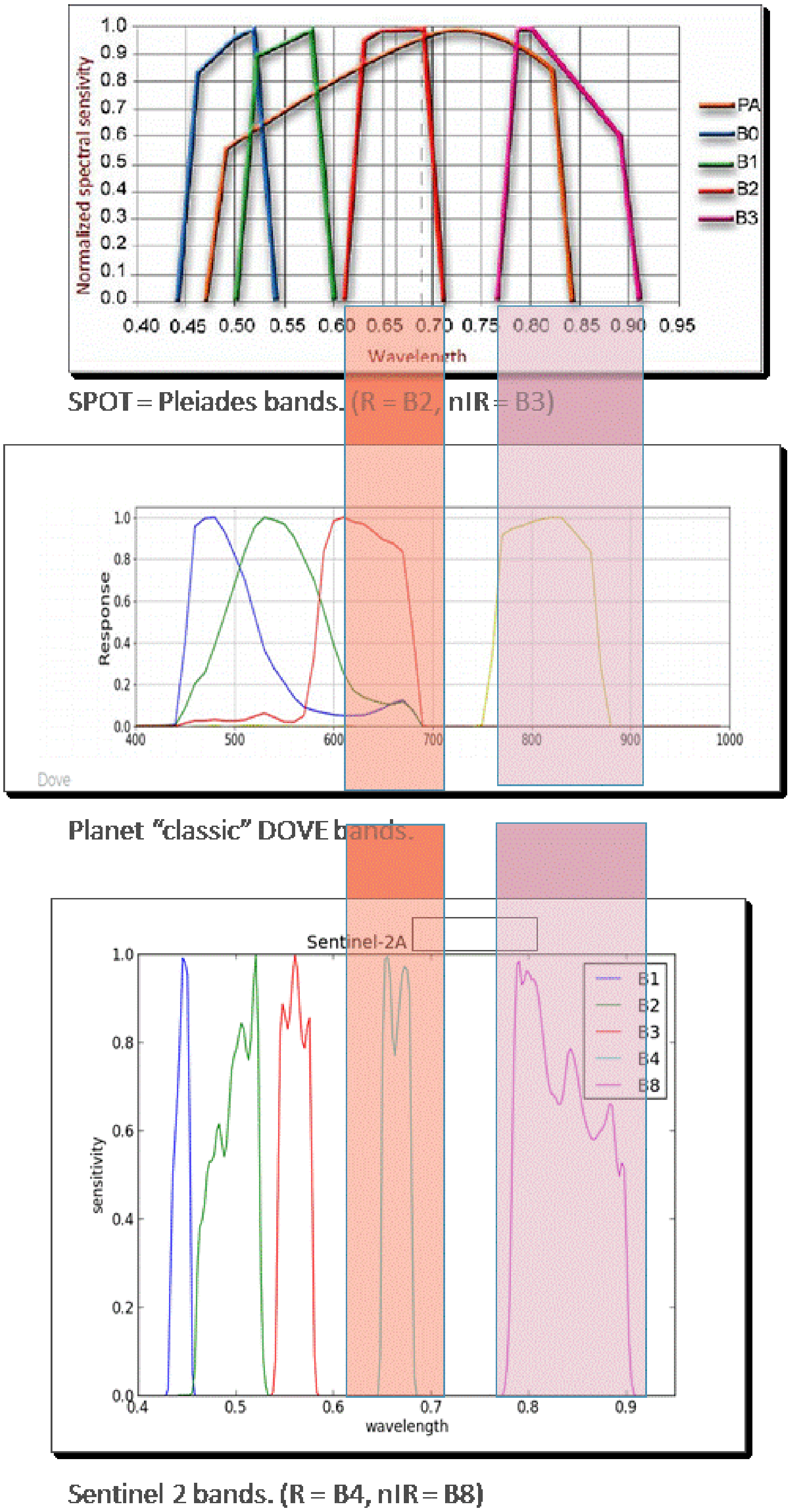



*Figure 8 - Spectral bands comparison*

# 4 JRC testing

As mentioned above, the test was divided into four parts,

- Visual comparison - CAPI over the AOIs selected
- Numerical comparison and linear regression of DN and NDVI values over some selected parcels, and over the whole AOIs
- Comparison of some spatial profiles within the AOIs (visual, and similarity index [ii]);
- Parcel heterogeneity.

These are further detailed in the chapters below. It needs to be mentioned that these visual comparisons were started on the TSHP Delivery (I) provided to the JRC in March 2020 and then re-iterated on the Delivery (II) delivered to the JRC in July 2020, since Airbus corrected some issues brought forth by the JRC. These issues concerned a 'zig-zag' pattern (aliasing), higher signal variation (spatial frequency noise in the TSHP profiles examined), and some blurring at the edges of the TSHP imagery. Examples of Delivery (I) TSHP imagery and Delivery (II) imagery, after applying appropriate filtering to the SPOT imagery prior to TSHP processing and after proper clipping of the image extent,  are given in below figures.

Re-processing produced a less crispy and more homogeneous image. The visual interpretation on a large scale image (features, roads, etc.) appeared better on Delivery (I), while interpretation at a smaller scale was more favourable on Delivery (II) with a reduced aliasing (zig-zag) and in addition importantly a higher $R^2$ goodness-of-fit measure vis-a-vis S2 as we will see in the analysis favouring the NDVI linear regression, and the profiles discussed in Chapters 4.2 and 4.2.4 below.

*Figure 9 - TSHP4 nIR; Delivery (I) left, Delivery (II) right. Extract from area A East (Puglia), IT; date 11/05/2019;*

*Figure 10 - TSHP4 true colour; Delivery (I) left, Delivery (II) right. Extract from area A East (Puglia), IT; date 11/05/2019;*

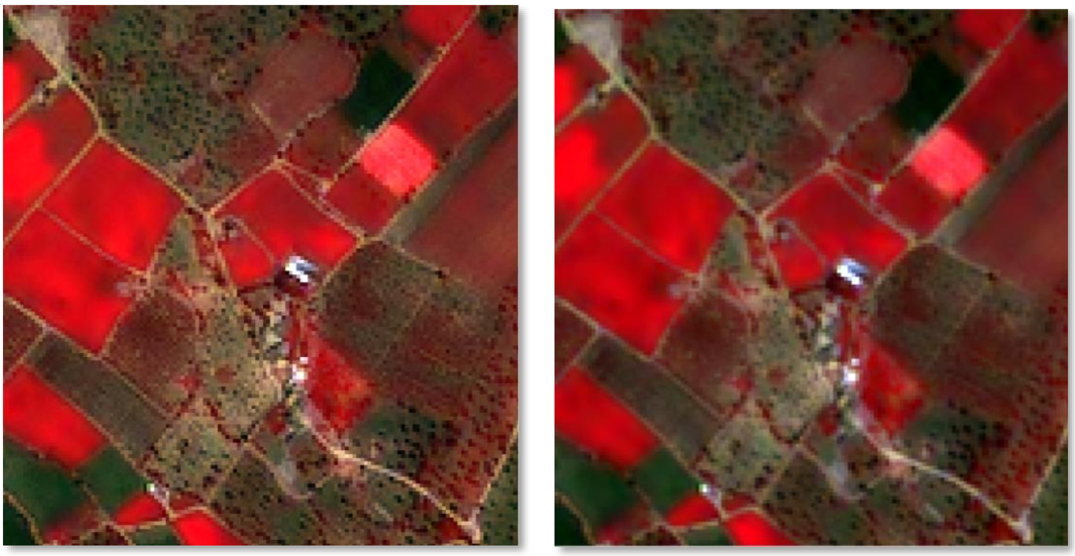


*Figure 11 - TSHP4 nIR; Delivery (I) left, Delivery (II) right. Extract from area A East (Puglia), IT; date 11/05/2019;*

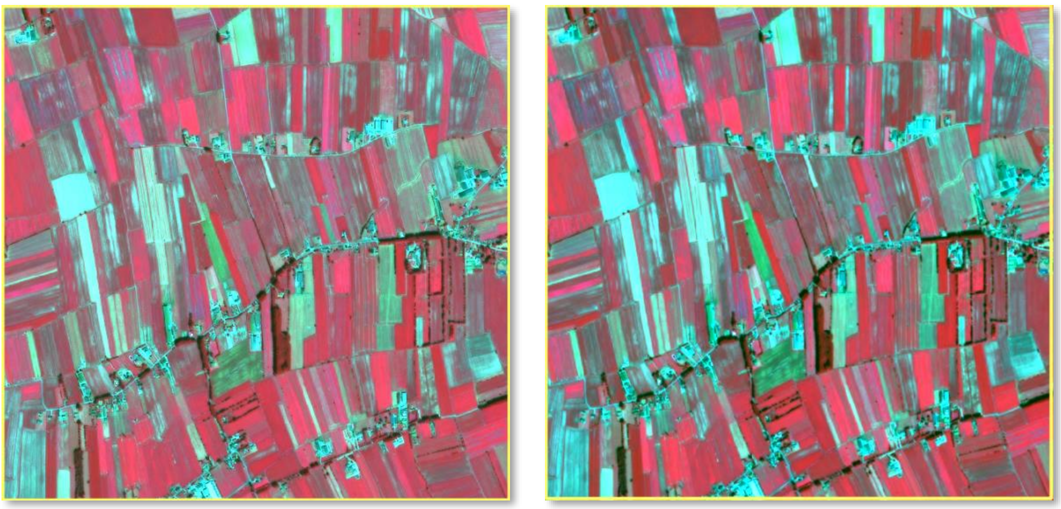


*Figure 12 - TSHP4m nIR; Delivery (I) left, Delivery (II) right. Extract from area Eeklo BE_FL; date 30/06/2018;*

## 4.1 Visual comparison

### 4.1.1 Puglia

Visual assessment (CAPI) tends to be highly subjective. However, by visual assessment the intention was to compare one image to another looking at the same object (agriculture land, parcel, or feature) on both images. The following visual tests were performed on the images on hand with emphasis on our chosen AOIs. Some screenshots are shown in the figures below:

- TrueSharp 4m vs TrueSharp 2.5m
- TrueSharp 4m vs PlanetScope 3m
- TrueSharp 4m vs. S2

*Figure 13 - TSHP4 vs TSHP2.5 nIR. Extract from area A East (Puglia), IT; date 11/05/2019; Delivery (I)*

*Figure 14 - PlanetScope 3m vs TSHP4 nIR. Extract from area A East (Puglia), IT; date 11/05/2019; Delivery (I)*

*Figure 15 - PlanetScope 3m vs TSHP4; RGB true colour. Extract from area A East (Puglia), IT; date 11/05/2019; Delivery (I)*

Visual interpretation shows that TSHP 4m and 2.5m are very similar. The roads/boundaries with sharp radiometry change to adjacent object shows the effect of resampling of pixels on the coarser TSHP4. The comparison with PlanetScope instead clearly gives the impression of a resolution improvement (i.e. a better spatial resolution) of the TSHP4. Some blurriness can be detected at the borders of the homogeneous parcel (or part of a parcel) in the TSHP4 (some examples are marked in yellow in Figure 14 above).

### 4.1.2 **Visual comparison – Flanders**

*Figure 16 - True colour; PlanetScope 3m (29/06/2018) vs. TSHP4 (30/06/2018), Delivery (I). Extract from area Eeklo BE_FL;*

Very similar results were achieved interpreting the Eeklo dataset. In the screenshot above the clear resolution improvement can be seen in the TSHP4 true colour on the right. The blurriness on the TSHP was experienced less than in Puglia.

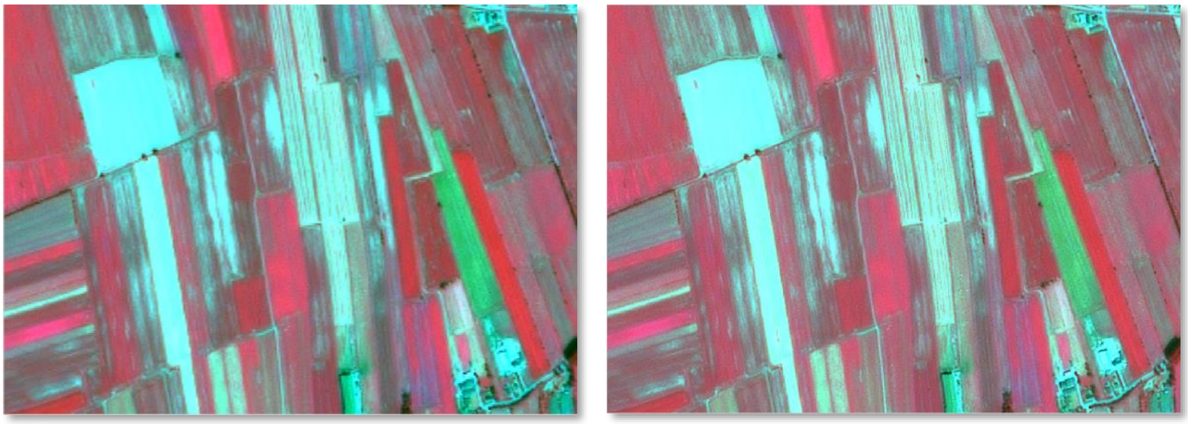


*Figure 17 - nIR; TSHP4 vs TSHP2.5, Delivery (I). Extract from area Eeklo BE_FL; date 30/06/2018;*

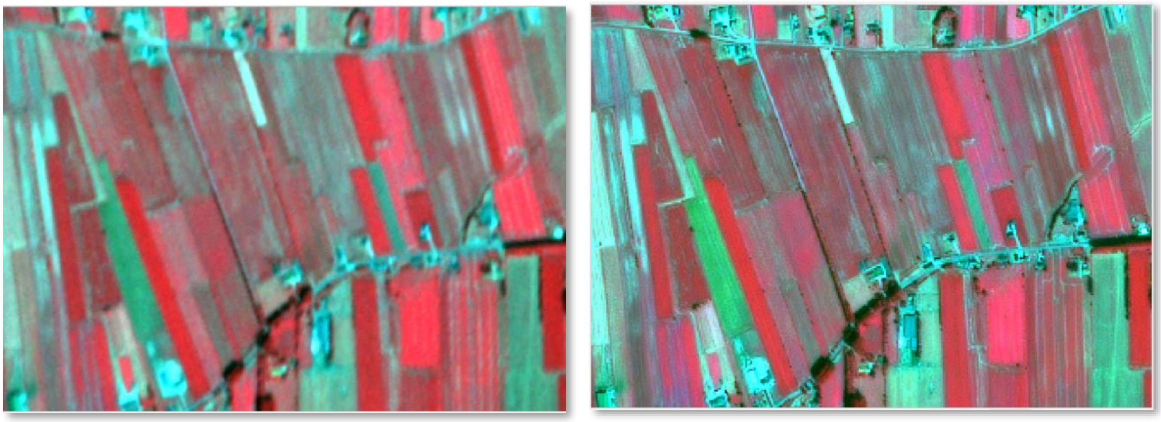


*Figure 18 - nIR, PlanetScope 3m (29/06/2018) vs TSHP4 (30/06/2018), Delivery (I). Extract from area Eeklo BE_FL;*

## 4.2 Numerical comparison and linear regression of BOA DN and NDVI values

### 4.2.1 Selection of pixels within a parcel

The HHR TS project [ref i] proposed a statistical method for selection of an ordered series of eight point coordinates uniformly distributed within a parcel including a proper buffer management to exclude narrow spikes, corridors etc. from the parcel (see fig below). Each of these eight points were then used to select the BOA value of the nearest cloud free image pixel, located through nearest neighbour search. The mean of all the eight values constituted the mean parcel BOA value used in many parcel NDVI profile plots.

Since these time stacks coordinates were readily available and ancillary data on them on hand, it was suitable to use this selection approach also for our study even if the parcels available were not numerous. Since five parcels were considered, forty pixels were present in each of our AOIs over Puglia, and Flanders. The eight pixels (numbered 0-7) in each of the parcels are thus the closest BOA values in our respective images (TSHP4, PlanetScope or S2) in our analysis.

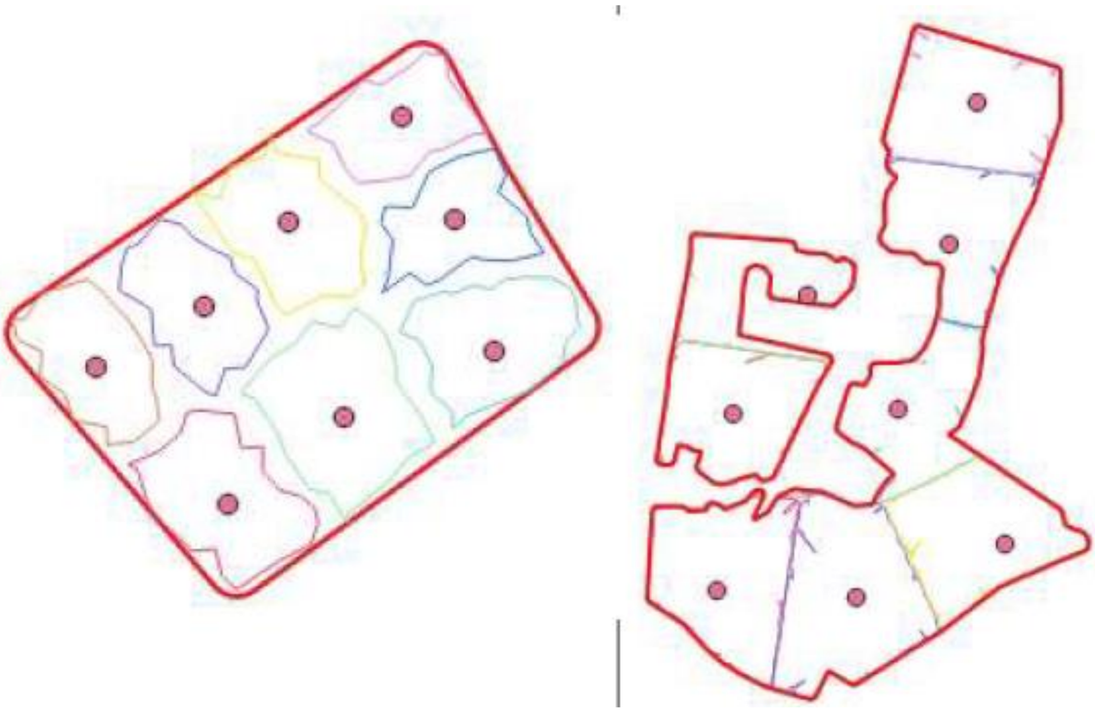


*Figure 19 - Method for pixel selection from ordered, uniformly distributed point coordinates*

### 4.2.2 **Puglia**

For the radiometric part of the testing, DN and the NVDI values have been compared. The ground truth is stemming from the HHR TS project [ref. i]. In area A, five parcels of known crop type and fully covered by image products were chosen. Crop types were 'Agricultural land not in production' and 'Aneto (dill)'. The 'cleanest' pixels where used in analysis of the DNs and NDVI values.

All values in the graphics shown below are taken from the enhanced Delivery (II) batch of TSHP data. The figure below shows the location of the five parcels and one of the profiles used later in Chapter 4.3.14.2.3.


*Figure 20 - Extract from Area A East (Puglia), IT showing the 5 parcels chosen for comparison ((1) of 'Agricultural land not in production', and four (2, 3, 4, 5) of Aneto (dill)); nIR TSHP4 image date 11/05/2019;*

#### 4.2.2.1 Numerical comparison of BOA DN and NDVI values

The first parcel (Agricultural land not in production (parcel # 572634529)) is shown below where out of the eight chosen pixels within the parcel, the three cleanest ones, i.e. the visually most homogeneous (# 1, 4, and 6) are best followed in the comparisons.

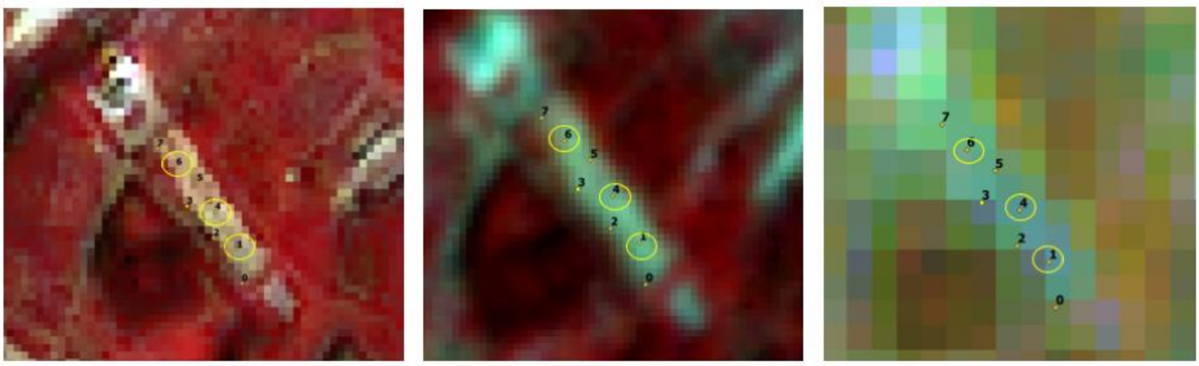


*Figure 21 - Zoom of 'Clean' pixels; from left to the right: TSHP4 (11/05/2019), PlanetScope 3m (11/05/2019) and S2 10m bands (8,11 (20m),4 (25/5/2019). Extracts from Area A East (Puglia), IT;*

Similarly for the next sample parcel (Aneto (dill), (parcel # 568054643)), out of the eight chosen pixels, the two cleanest ones within the parcel (numbered 4, and 5) are best followed in the comparisons. The figure below shows the pixel locations.

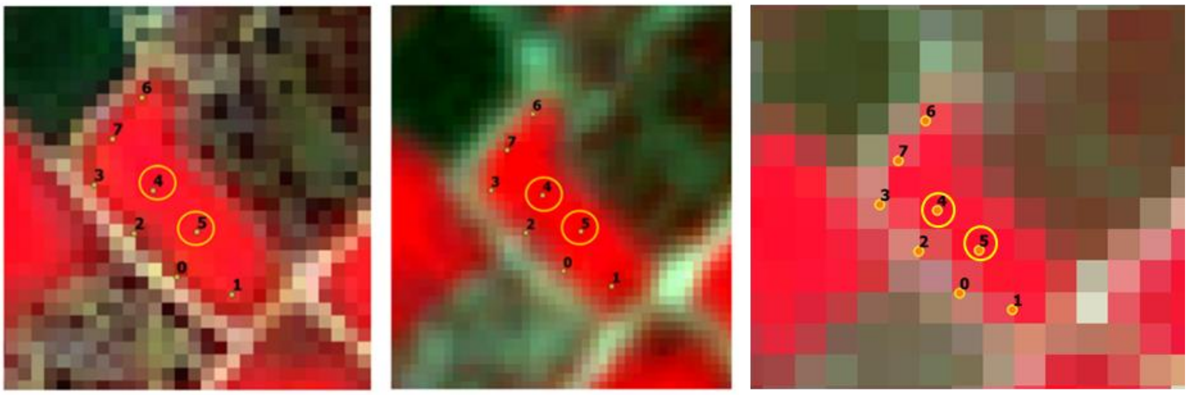
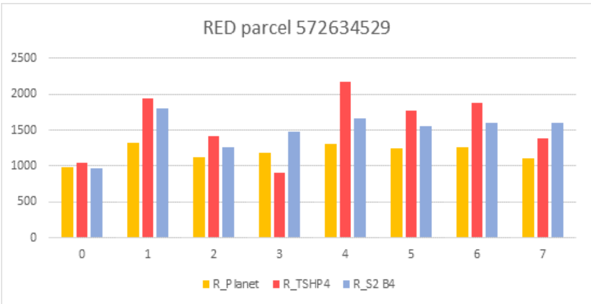
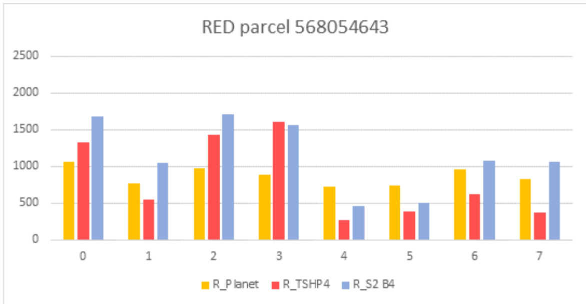


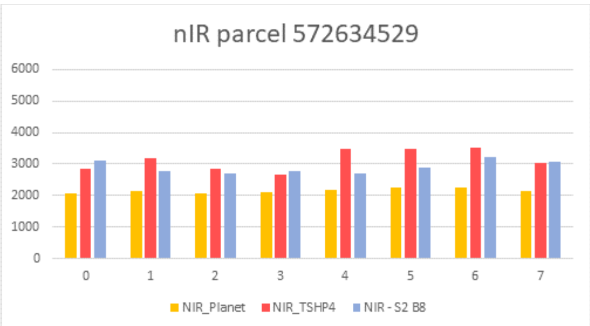
*Figure 22 – Zoom of 'Clean' pixels from left to the right, nIR composite: TSHP4 (11/05/2019), PlanetScope 3m (11/05/2019) and S2 (25/5/2019); extracts from Area A East (Puglia), IT;*

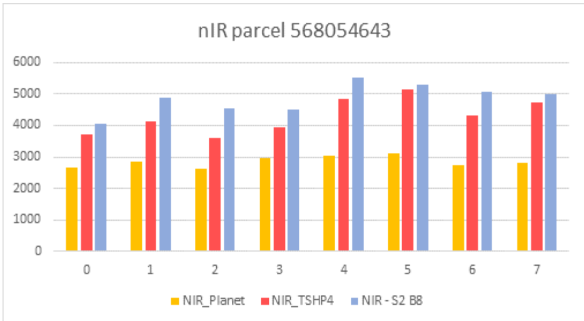
The BOA DN values and NDVI values (y-axis) for the 8 pixels (x-axis) are shown below. The two parcel figures are placed adjacent to each other, and with the same scale for better comparison. The NDVI was calculated as follows:

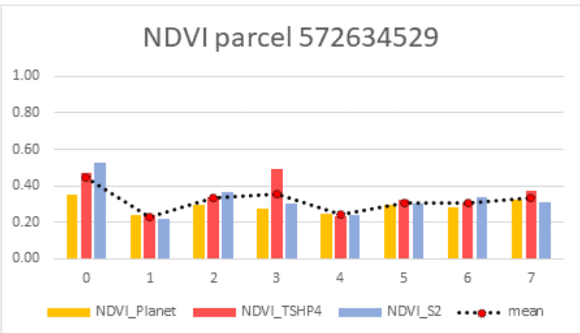
$$NDVI = \frac{(nIR - R)}{(nIR + R)}$$



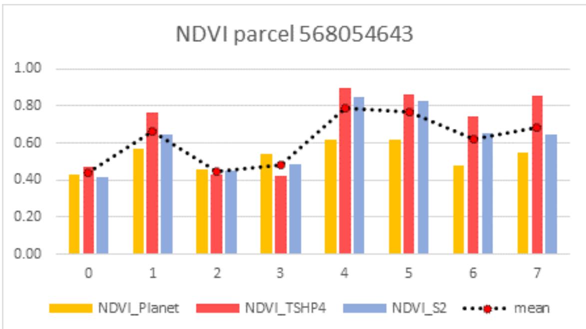



*Figure 23 - BOA DN and NDVI comparison (parcels # 572634529 'agricultural land not in production', and # 568054643 'dill');*

First of all it can be seen (maybe obvious) that the NDVI values for the Dill (at right) are higher throughout than those in the Agricultural land not in production (left) which is correct for all sensors considering the two crop types. The Dill reflects higher (nIR) values due to its higher chlorophyll content at the acquisition date compared. The NDVI mean is more similar for all pixels of the left parcel and this may indicate that the parcel is more homogeneous.

Then, we can see that the PlanetScope values in nIR are lower which results in a lower NDVI. This is a finding throughout, that the PlanetScope NDVI shows a somehow 'damped' NDVI value. The NDVI values of especially the 'clean pixels' (1, 4, 6 left, and 4, 5 right) are quite similar for TSHP4 and S2. These seem aligned.

A number of factors can be mentioned as cause to the BOA reflectance values variations between the sensors:

(1) the spectral profile of the system (see chapter 3.2.2 and 3.2.33.2),

(2) the respective characteristics of the sensor system where each one follows a different method to achieve the target resolution,

(3) the atmospheric correction method (L2A for S2, SR for PlanetScope, and use of Lowtran for SPOT).

One generic explanation of somewhat higher R, nIR values of SPOT TSHP, can be traced back to the fact that SPOT is an agile sensor, the viewing angle has wider variations than PlanetScope or S2. This will result in reduced or enhanced canopy self-cast shadows depending on its across-track pointing. This is less sensitive on the NDVI and in fact the NDVI values are aligned i.e. TSHP ≈ S2 especially for the clean pixels. To avoid these problems the best way to make these comparisons would probably be to use biophysical parameters retrieved from models that take full account of the Bidirectional Reflectance Distribution Function (BRDF), being independent from the viewing angle, the sensor, and the light conditions.

#### 4.2.2.2 Linear regression of NDVI values

By making use of all the 8 pixel values in the 5 parcels on hand (i.e. 40 points) the extent of linear dependency is evaluated using linear regression and calculation of the $R^2$ goodness-of-fit measure[1]. For example, an $R^2$ of 90% can be defined as "good". It basically means that 10% of the variability cannot be explained by the model. The NDVI $R^2$ between TSHP4 and S2 of Delivery (I) was 0.8925, which became 0.9122 after the reprocessed in Delivery (II). Figures below show the NDVI scatterplots with relative $R^2$. The best $R^2$ value was obtained between S2 and TSHP4.

[1] The R-squared value measures the proportion of variation in the dependent variable that can be attributed to the independent variable. It measures the strength of the relationship between your model and the dependent variable on a convenient 0 - 100% scale. An $R^2$ of 1 (100%) indicates that the regression predictions perfectly fit the data.

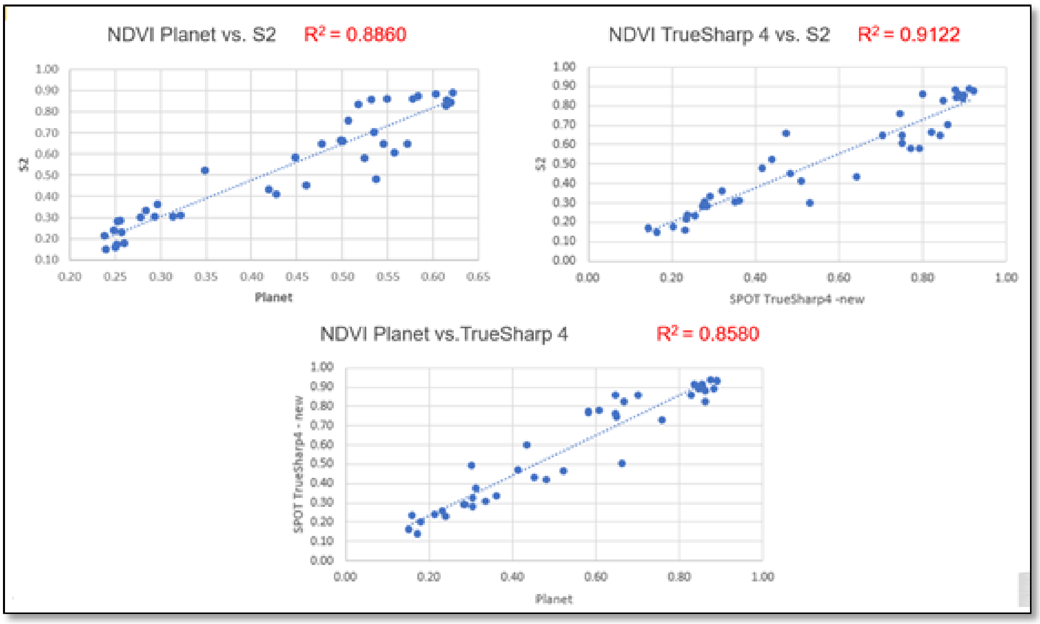



*Figure 24 - NDVI scatterplots all 5 parcels 8 pixels each;*

### 4.2.3 **Flanders**

Similarly as in Puglia, for the radiometric part of the testing, the DN and the NVDI values have been compared. Five parcels with unknown crop type were chosen arbitrarily. All values in the graphics shown below are taken from the enhanced Delivery (II) batch of TSHP data. The figure below shows the location of the five parcels.

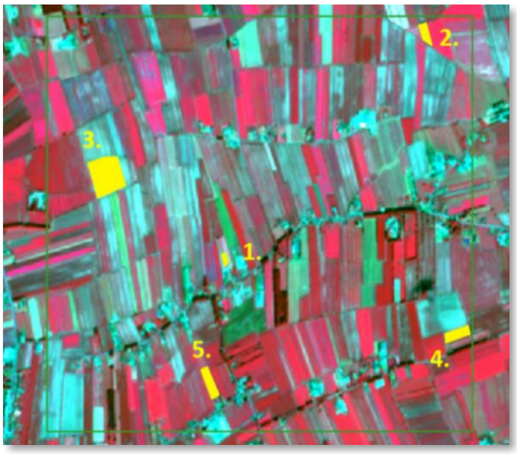



*Figure 25 - Extract from area Eeklo BE_FL showing the 5 parcels chosen for comparison; nIR TSHP4 image date 30/06/2018;*

#### **4.2.3.1 Numerical comparison of BOA DN and NDVI values**

In the case of Flanders, all five agricultural parcels were chosen arbitrarily as well as the eight points within the parcels. Data on declared crops were not known.

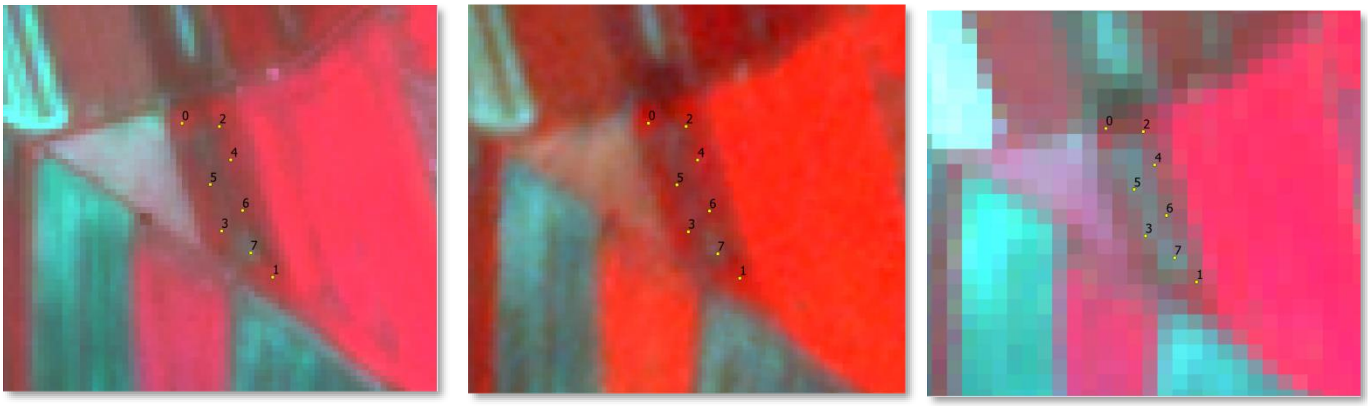


*Figure 26 - 8 pixels (from left to right nIR composite of TSHP4 (30/06/2018), PlanetScope 3m (29/06/2018) and S2 (30/06/2018) - Parcel 1. Zoomed extract from area Eeklo BE_FL;*

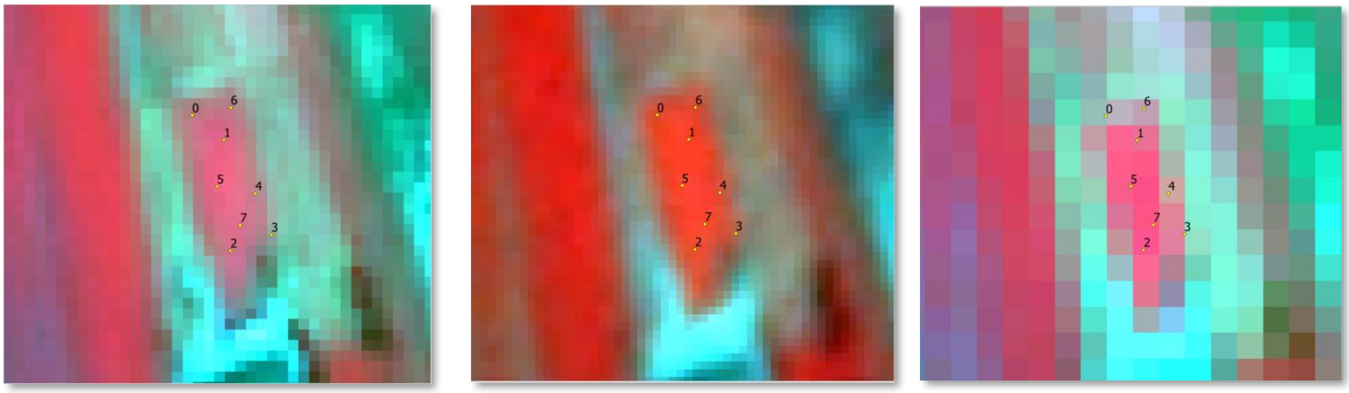


*Figure 27 - 8 pixels (from left to right nIR composite: TSHP4 (30/06/2018), PlanetScope 3m (29/06/2018) and S2 (30/06/2018) - Parcel 2. Zoomed extract from area Eeklo BE_FL;*

Similarly to the Puglia case above, the BOA DN values and NDVI values (y-axis) for the 8 pixels (x-axis) are shown below. The two parcel figures are placed adjacent to each other, and with the same scale for better comparison.

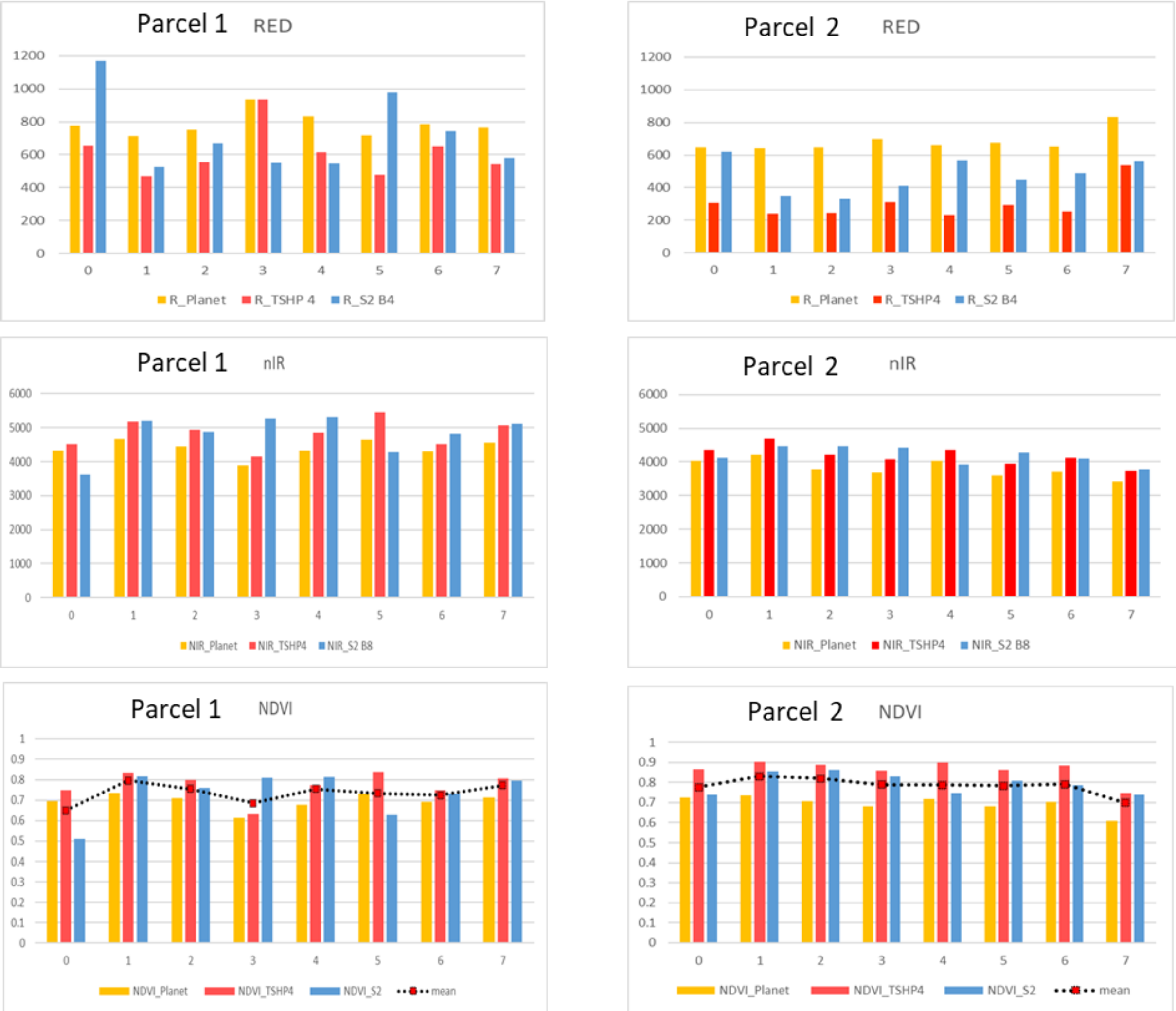



*Figure 28 - BOA DN and NDVI comparison (parcels 1 and 2);*

We can see like in the case of Puglia that the PlanetScope values in nIR are lower, and in R higher which results in a lower NDVI. This is a finding throughout, that the PlanetScope NDVI shows a somehow 'damped' NDVI value.

#### 4.2.3.2 Linear regression of NDVI values

By making use of all the 8 pixel values in the 5 parcels on hand (i.e. 40 points) the extent of linear dependency is evaluated using linear regression and the calculation of the $R^2$ goodness-of-fit measure. The NDVI $R^2$ between TSHP4 and S2 of Delivery (II) is 0.83837 and between TSHP4 and PlanetScope is higher and equal to 0.96804. Due to the arbitrary selection of parcels, $R^2$ values (TSHP4 vs. S2) are lower compared to those in Puglia. Figures below show the NDVI scatterplots with relative $R^2$.

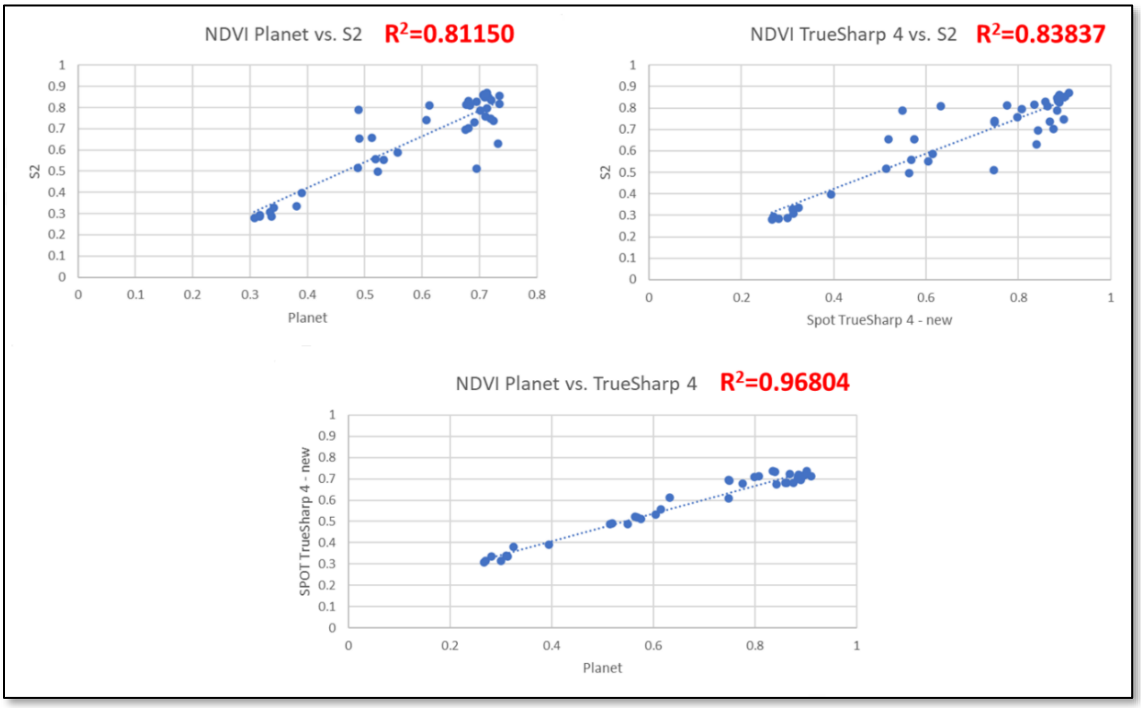



*Figure 29 - NDVI scatterplots all 5 parcels 8 pixels each;*

### 4.2.4 **Linear regression over a larger overlapping area - Flanders**

Since above analysis was made only on a few selected parcels within our AOIs, a further test to include all parcels was made. Figure 30 below shows the largest overlap area (approximately 10x5 km) between our input imagery (TSHP4, PlanetScope, and S2) over Eeklo BE_FL. It has to be noted that this area, however depicting a largely agricultural landscape, is heterogeneous, and including different land cover types and different features. Moreover all imagery was resampled to the TSHP 4m pixel size making use of nearest neighbour approach. While necessary for the comparison, resampling introduces artefacts that affects the quality of linear regression.

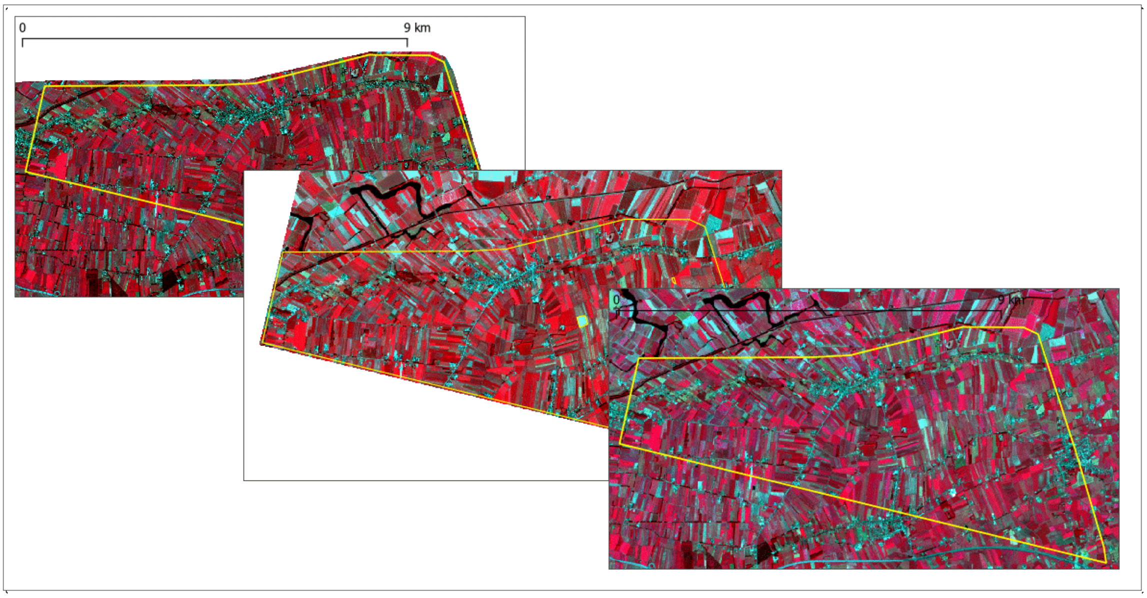



*Figure 30 - TSHP4 (30/06/2018; nIR), PlanetScope (29/06/2018; nIR), and S2 (30/06/2018; nIR); subset of area AOI Eeklo BE_FL*

A python script extracting the BOA, and the NDVI values from the datasets, within the overlap area, was used to compare extracted information and their relationship. Two types of scatterplots were produced:

- One, where for each sensor, the x-axis represents its RED band and the Y-axis its nIR band. The cloud of points are shown in Figure 31 below.
- The other type (Figure 32, Figure 34, Figure 35 below) which shows 2D scatterplots including linear regression and $R^2$ values, where the same bands of the three sensors are plotted against each other i.e. on the X axis the BOA value of the pixel from one sensor, on the Y axis the value of the same pixel from the other sensor for the given band, or NDVI. In order to improve the readability of the images, scatterplots have been represented as 2D histograms were the density of points has been encoded using different colors. Each point represents a pixel in the overlapping imagery.

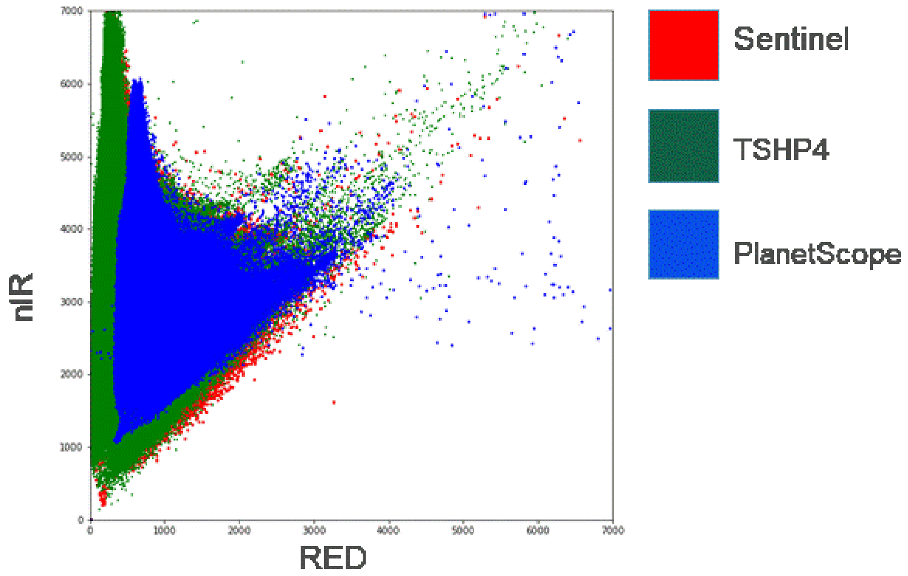



*Figure 31 - Scatterplots of bands Red (horizontal axis) and Near Infrared (vertical axis) calculated from the pixels within the overlap area*

From Figure 31 above (which is the same methodological approach we used in Chapter 4.4 on parcel heterogeneity) we can already see the corridor of no values in the Planet dataset indicating that the RED response practically never assumes values below about 300. There is also some indication that the nIR response is always above 1000 and below 6000 for Planet. In the other cases, higher nIR values are observed. While the three scatterplots assume similar shapes, the Planet response results shifted and compressed with respect to the other two cases. This scale and bias, that will be further analysed below, are likely the reason for the overall damped NDVI value (higher RED and lower nIR gives lower NDVI) seen throughout the study.

The linear regression shown in Figure 32 below was performed excluding points around (0,0) since these points were biasing the estimation of the scale and bias parameters. From the figure, it is clearly seen that the measurements from the different sensors can be effectively related trough a linear relationship as confirmed by the high $R^2$ values.

Of interest are some high values in S2 (indicated in cyan colour lower left plot on Figure 33 below) which are considered outliers not fitting the model. An example is given in Figure 33 below of a large barn house roofing and bare soil around it giving extremely high surface reflectance in S2.

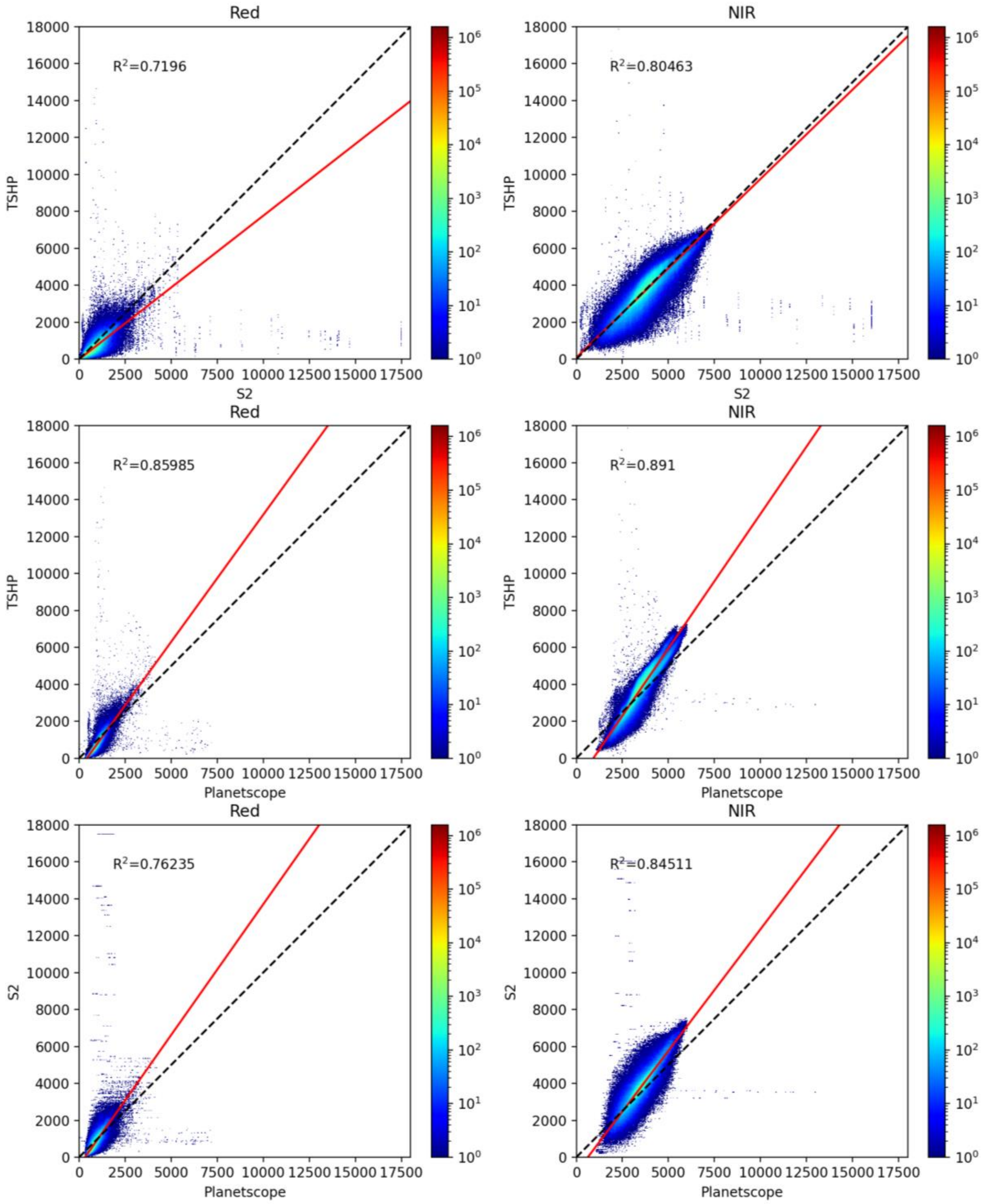



*Figure 32 - 2D scatterplots including linear regression and $R^2$ values, where the same bands of the three sensors are plotted against each other. The scatter plots are provided as 2D histograms where different colors indicate the density of points. The red line is the interpolating curve, whereas the black dotted line is the diagonal line, y = x.*

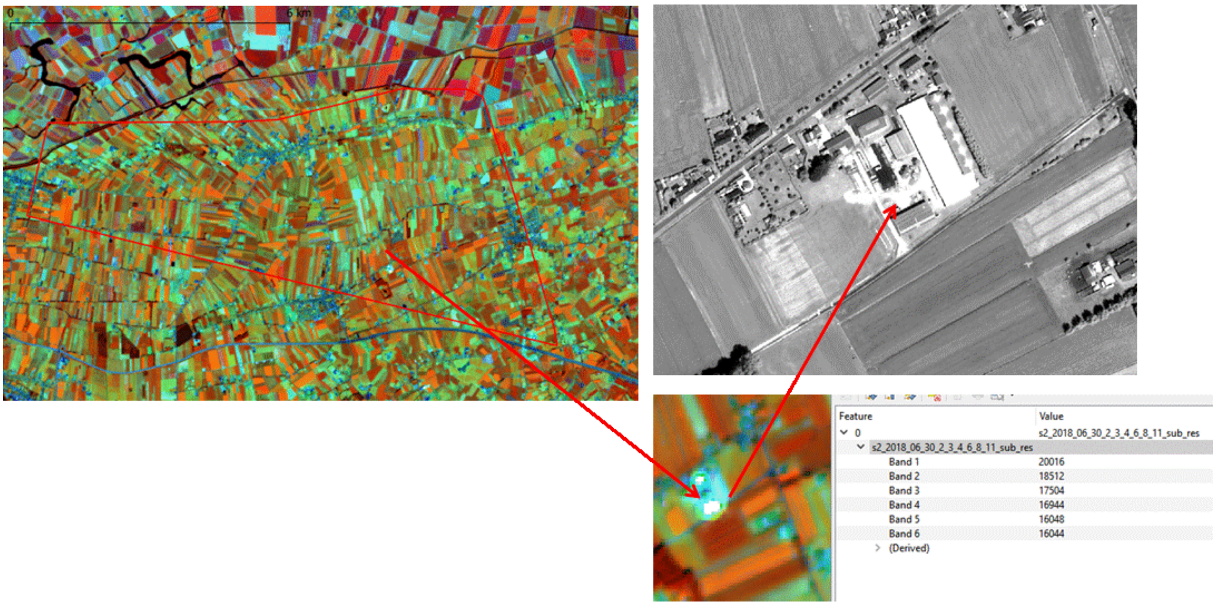



*Figure 33 - Example of outlier - a large barn house roofing and bare soil around it giving extremely high surface reflectance in S2;*

The above scatterplots are viewed better by zooming around [0-8.000] x [0-8.000] BOA value region as shown in Figure 34 below where the linear relationship between measurements from different sensors can be better appreciated: the bulk of observations, as highlighted by lighter colors in the 2D histograms, are well aligned along the regression line. Residual variations and deviations from the regression line can be explained by the presence of artefacts, as indicated in Figure AB, and by effects related to resampling.

The scale and bias parameters along with the $R^2$ value are reported in Table 2 for the different sensors and the RED and nIR components. In all case, a $R^2$ higher than 0.71 was found. From the table, it emerges that Planet measurements are affected by a significant bias (b) as compared to the other sensors. This is in agreement with the results discussed above. The S2 and TSHP values are the most similar with a scale factor close to 1 and a reduced bias.

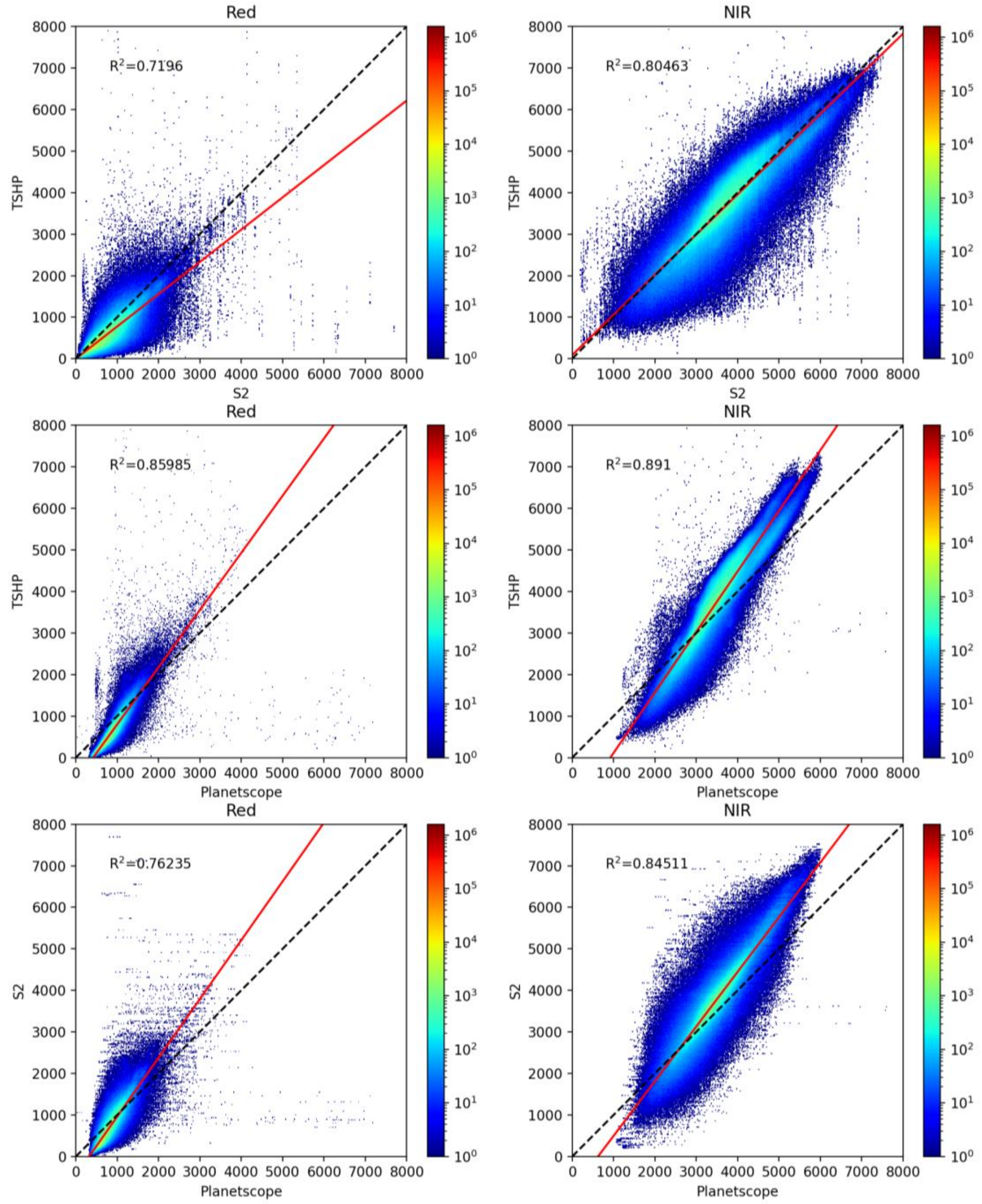



*Figure 34 - 2D scatterplots including linear regression and $R^2$ values, where the same bands of the three sensors are plotted against each other. The scatter plots are provided as 2D histograms where different colors indicate the density of points. The red line is the interpolating curve, whereas the black dotted line is the diagonal line, y = x.*

| Case | a (scale factor) | b (bias) | R2 |
|---|---|---|---|
| S2-TSHP-R | 0.7769 | 0.0415 | 0.7196 |
| S2-TSHP-nIR | 0.967 | 88.585 | 0.8046 |
| Planet-TSHP-R | 1.376 | -576.4 | 0.8598 |
| Planet-TSHP-nIR | 1.457 | -1345.25 | 0.891 |
| Planet-S2-R | 1.415 | -453.6 | 0.7623 |
| Planet-S2-nIR | 1.316 | -820.13 | 0.8451 |

*Table 2 - Summary results of parameters (scale, bias, R2)*

The same analysis has been repeated for the NDVI that is analysed in Figure 35 and Table 3 below. The NDVI scatterplots are performed considering only values in the [0-1] range.

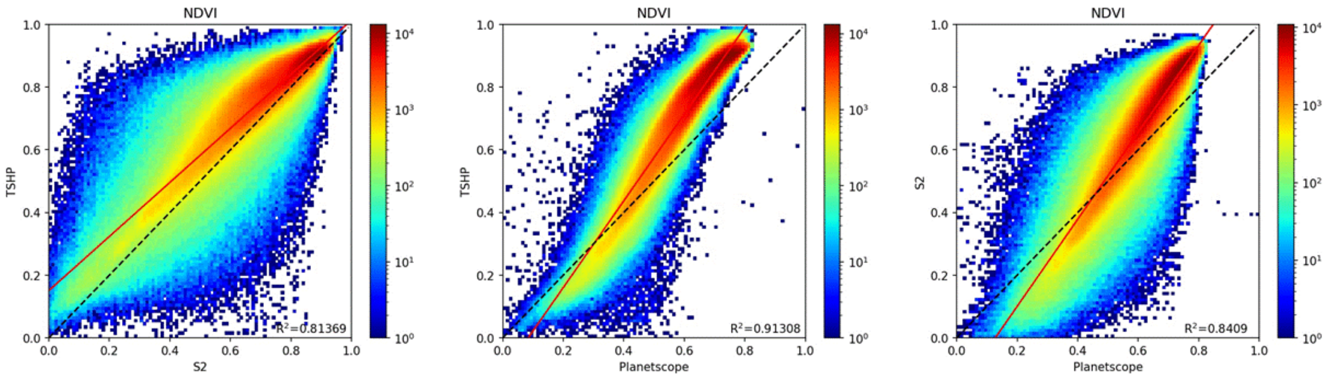



*Figure 35 - 2D scatterplots for the NDVI including linear regression and $R^2$ values, where the same bands of the three sensors are plotted against each other. The scatter plots are provided as 2D histograms where different colors indicate the density of points. The red line is the interpolating curve, whereas the black dotted line is the diagonal line, y = x.*

| Case | a (scale factor) | b (bias) | R2 |
|---|---|---|---|
| S2-TSHP-R | 0.7769 | 0.0415 | 0.7196 |
| S2-TSHP-nIR | 0.967 | 88.585 | 0.8046 |
| Planet-TSHP-R | 1.376 | -576.4 | 0.8598 |
| Planet-TSHP-nIR | 1.457 | -1345.25 | 0.891 |
| Planet-S2-R | 1.415 | -453.6 | 0.7623 |
| Planet-S2-nIR | 1.316 | -820.13 | 0.8451 |

*Table 3 - Summary results of parameters (scale, bias, R2)*

In summary, it can be said that the dependency between the image sets are strong, $R^2$ values are high, and the measurements from the different sensors over the whole overlapping area are well represented with a linear relationship. This is what was expected for this area composed mainly of agricultural parcels. The dependency between S2 and TSHP is mainly explained with a scale parameter, while for Planet there is also a strong bias component.

## 4.3 Comparison of some spatial profiles (visual, and similarity index)

### 4.3.1 Profile - Puglia

Two profiles where drawn and assessed over Puglia. The first one, shown here, stretching diagonally some 300m across a somewhat larger parcel can be seen in Figure 36 below. The same parcel can also be seen with its surroundings in Figure 20 above. Moving from west to east PlanetScope has a lower NDVI throughout which again confirms our findings from radiometry test (I) reported above and which tells us of a somehow 'damped' NDVI value. The lower NDVI of S2 in the west is explained by the later date of the image 25/05 cf. 11/05. TSHP is however higher than both PlanetScope and S2 over the second parcel, which is explained by the presence of solar panels (Photovoltaic, PV) with quite specific bidirectional reflectance where apparently the SPOT image with quite a large incidence angle 26.9°, and azimuth 316° gives a higher NDVI value than the other two (Figure 36).

It needs to be mentioned that in the figure below it is clear how the TSHP4 Delivery (II) shows a more homogeneous profile, with less variability (less high spatial frequency noise than delivery (I)). This was due to Airbus suitable filtering before the TSHP process.

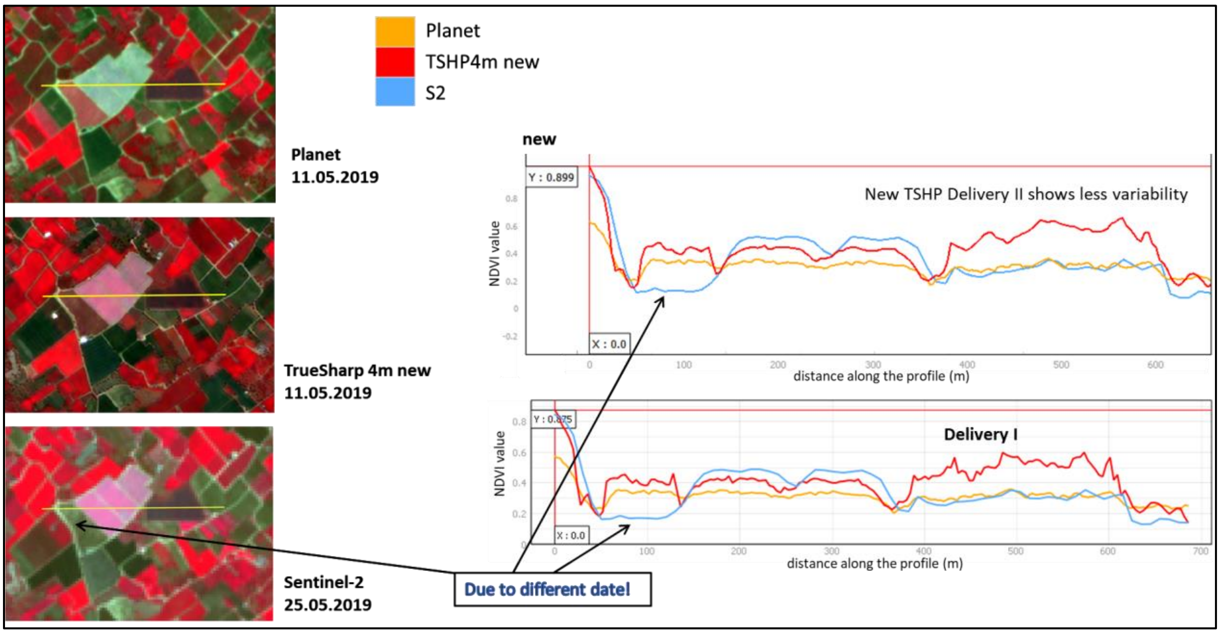




*Figure 36 - Bottom: Spatial NDVI profile (Delivery (I), and (II)). Area A East (Puglia), IT. Top: solar panels over second parcel.*

### 4.3.2 Profile - Flanders

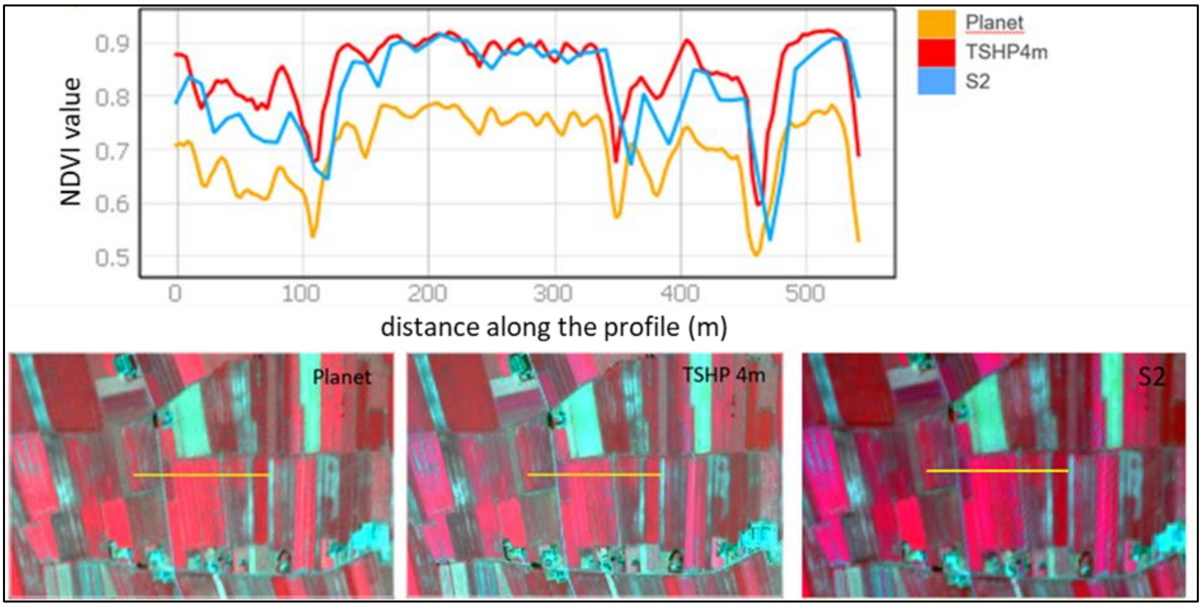



*Figure 37 - NDVI comparison over spatial profile; Area Eeklo, BE_FL;*

Similarly, as for Puglia, PlanetScope has a lower NDVI throughout which confirms our findings from above radiometry test (I) which confirms its 'damped' NDVI value.

### 4.3.3 Similarity Index

To assess sensors performance regarding DN values (and subsequent NDVI index) in a spatial dimension, we compared the NDVI profiles of the cross cutting line (see Figure 37 above, and Figure 38 below) for each sensors combination. For the similarity evaluation we used a simple similarity index [ref. ii] which is based on a linear interpolation of missing values and Pearson's correlation coefficient as an estimator of similarity. The NDVI profiles were considered as similar if the Pearson's correlation coefficient resulted higher than 0.5 with 95% of probability. The decision of similarity (column to the right below) takes into consideration both the correlation coefficient and confidence interval and results in that all NDVI profiles are similar and we can therefore assume that the NDVI profiles that these sensors provide across the tested lines are comparable.

| Place of cross-cutting line | Sensor combination | Correlation coefficient | 95% Confidence interval | Similarity decision |
|---|---|---|---|---|
| **FL 1** | S2 x TSHP | 0.77 | <0.64, 0.86> | yes |
| | S2 x PL | 0.82 | <0.71, 0.89> | yes |
| | PL x TSHP | 0.91 | <0.88, 0.94> | yes |
| **FL2** | S2 x TSHP | 0.86 | <0.77, 0.92> | yes |
| | S2 x PL | 0.89 | <0.82, 0.94> | yes |
| | PL x TSHP | 0.92 | <0.89, 0.94> | yes |
| **FL 3** | S2 x TSHP | 0.74 | <0.59, 0.84> | yes |
| | S2 x PL | 0.78 | <0.64, 0.86> | yes |
| | PL x TSHP | 0.94 | <0.92, 0.96> | yes |

*Table 4 - Results of NDVI profiles similarity assessment; Area Eeklo, BE_FL;*

The NDVI profiles across the three cross-cutting lines over Eeklo are shown below. The shapes of the profiles are similar visually, the PlanetScope's NDVI is always the lowest.

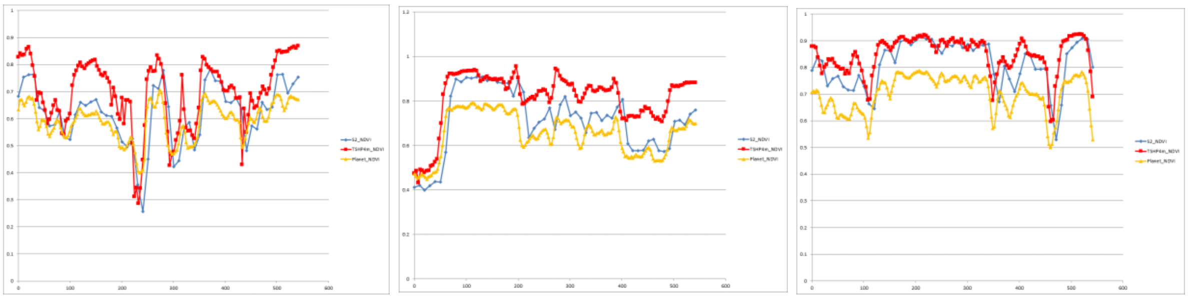


*Figure 38 - NDVI profiles across the three cross-cutting lines over area Eeklo, BE_FL (x- axis shows the distance along the profile; y – axis shows the NDVI value)*

## 4.4 Parcel Heterogeneity

One of the checks we wanted to carry out was to see if the enhanced spatial resolution offered by TSHP4 data would give better performance in detecting heterogeneity in agricultural parcels than that of PlanetScope or S2 images.

We analysed S2 data time series close to the acquisition dates of available TSHP4 and PlanetScope images and selected a parcel (2.7 ha) that showed heterogeneity.. The left part of Figure 39 shows the calendar view of S2 False Colour Composite images (using bands 8,11,4 RGB). The "half-weekly" calendar view displays the first cloud free image available in a given half-week period. For 2018 June Week 4B the period is from 28th to 30th June (inclusive). For this parcel, there are 2 S2 images in Week 4B as it is in an area of overlapping orbits (orbit 94 and orbit 51). The calendar view shows that the parcel is rather homogeneous throughout the season and it gets heterogeneous only around the end of June (red bounding box).

For analysing heterogeneity we use the S2 image acquired on the 30th June instead of 28th June indicated in the calendar view because the TSHP4 image was acquired on 30th June (and PlanetScope on 29th June).

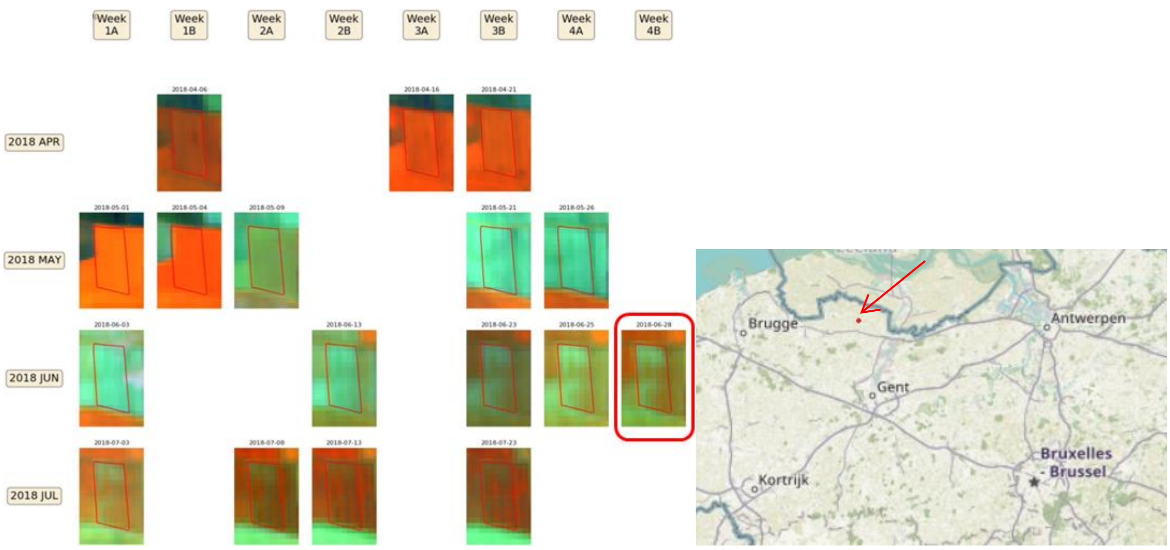


*Figure 39* - Calendar view of Sentinel-2 False Colour Composite images (using bands 8,11,4 RGB) with an agricultural parcel boundary overlaid (left). The Sentinel-2 image acquired at the end of June 2018 shows heterogeneity within the parcel boundary (highlighted with red box). The map on the right shows the location of the parcel (red arrow pointing at the location of the parcel).

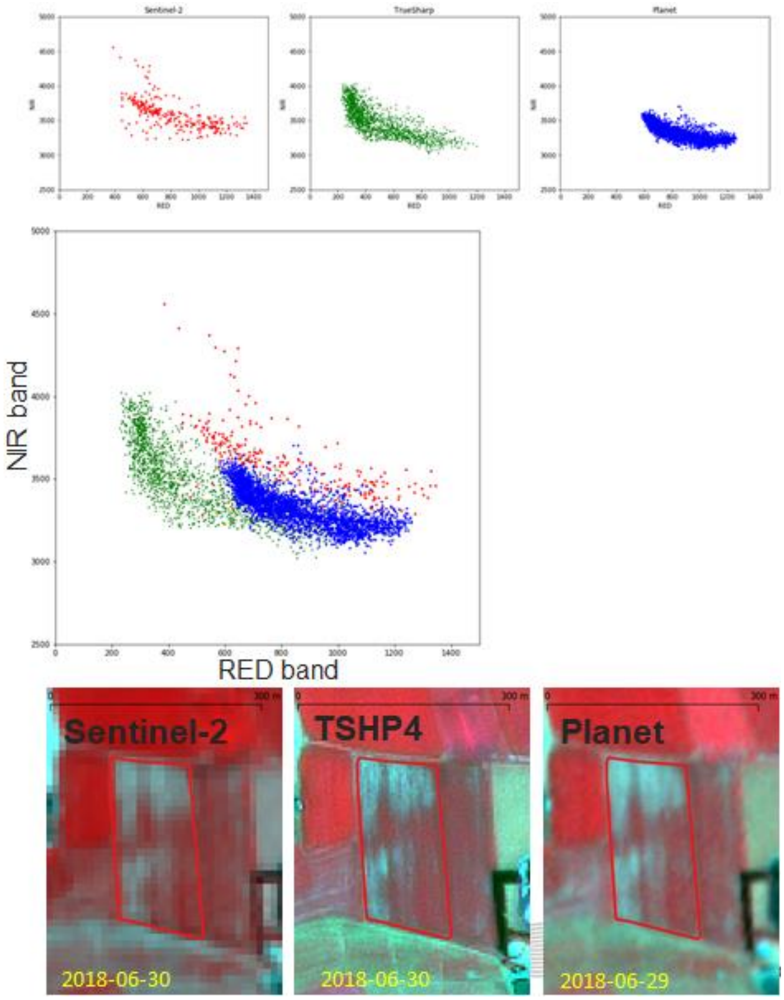



*Figure 40* - nIR Colour Composite of Sentinel-2 (8,4,4 RGB), TSHP4 (4,3,2 RGB) and PlanetScope (4,3,2 RGB) images (bottom) and corresponding scatterplots of bands Red (horizontal axis) and Near Infrared (vertical axis) calculated from the pixels within the parcel boundary (top) .

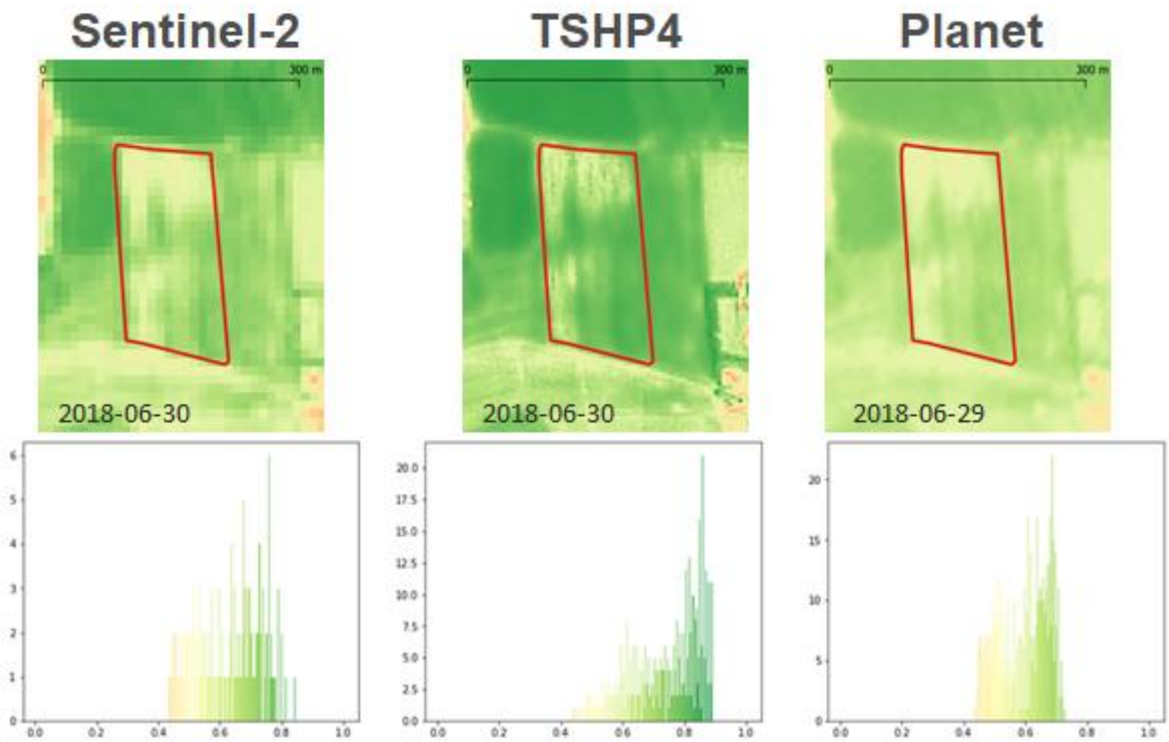



*Figure 41 - NDVI images (top) and corresponding histograms (bottom) calculated from pixels within the parcel boundary for Sentinel-2, TSHP4 and PlanetScope images (from left to right respectively)(x- axis shows the NDVI value; y – axis shows the number of pixels)*

The nIR Colour Composite images of S2, TSHP4 and PlanetScope (Figure 40 bottom) and corresponding scatterplots of bands RED (horizontal axis) and nIR (vertical axis) calculated from the pixels within the parcel boundary (Figure 39 top) show that parcel heterogeneity can be detected to almost the same level of detail on all 3 types of imagery. One obvious difference is that TSHP4 reflectance values are lower than those of the other two images in the Red band and that PlanetScope reflectances in the NIR band are lower than those of the other two images.

Heterogeneity can be detected at almost the same level of detail if we look at the NDVI images and corresponding histograms (Figure 41 top and bottom). The shapes of the histograms are very similar, a small difference is that the maximum of the PlanetScope NDVI values are lower (around 0.7 while the maximum of the other two are above 0.8)

The important result is that heterogeneity is not more evident in either of the HHR data sets (PlanetScope, TSHP) compared to S2. This should however be tested on more parcels with smaller sizes than the one tested (2.7 ha), where indeed the ‘macro’ heterogeneity was already visible at S2 resolution, in order to determine whether there is an advantage with the HHR datasets.

# 5 Issues of geometry

See Figure 31 above over Flanders, re-presented below with additional (dotted ellipses). This is a clear indication that the S2 profile is displaced and indicates a geometric shift cf. TSHP and PlanetScope. Therefore, an extracted TSHP (or PlanetScope) profile can be used to detect a “bad” S2 geometry. We made no re-alignment of the imagery for these tests, but it is clear that the co-registration of images from different sensors is essential before making comparisons of time stacks to avoid any AP position “jitter”. It can be mentioned in this context that S2 geometry should improve throughout as geometric refinement making use of the newly introduced Global Reference Image (GRI) will be fully implemented.

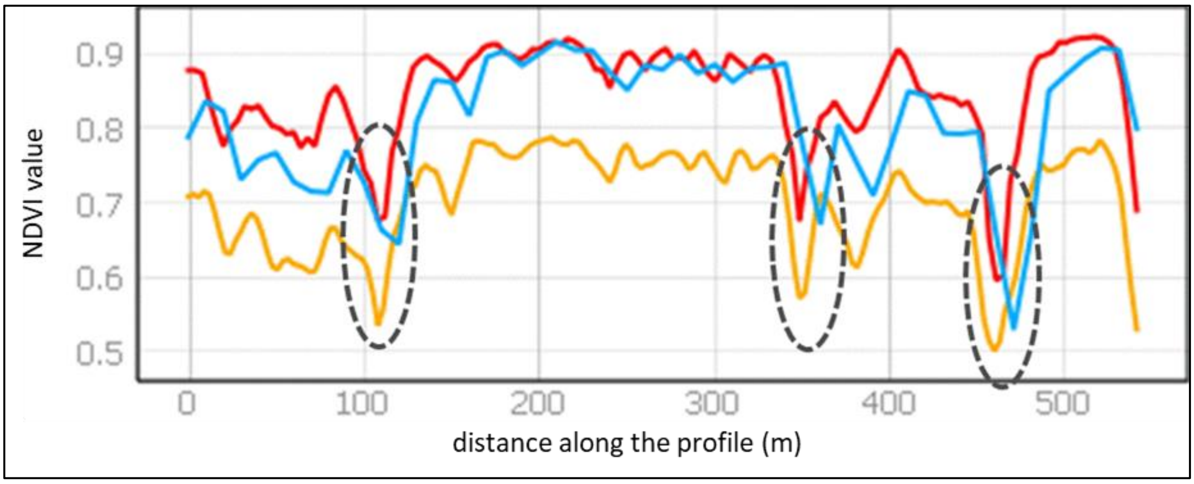



*Figure 42 - The S2 (blue) profile is shifted cf. TSHP, and PlanetScope; Area Eeklo, BE_FL.*

The shifts indicated in the figure above are further demonstrated in the example below. While the parcel boundary fits well to the Pleiades (1), TSHP (SPOT) (2) and PlanetScope (3), there is a clear visible shift (>7.5 m) comparing S2 and Pleiades.

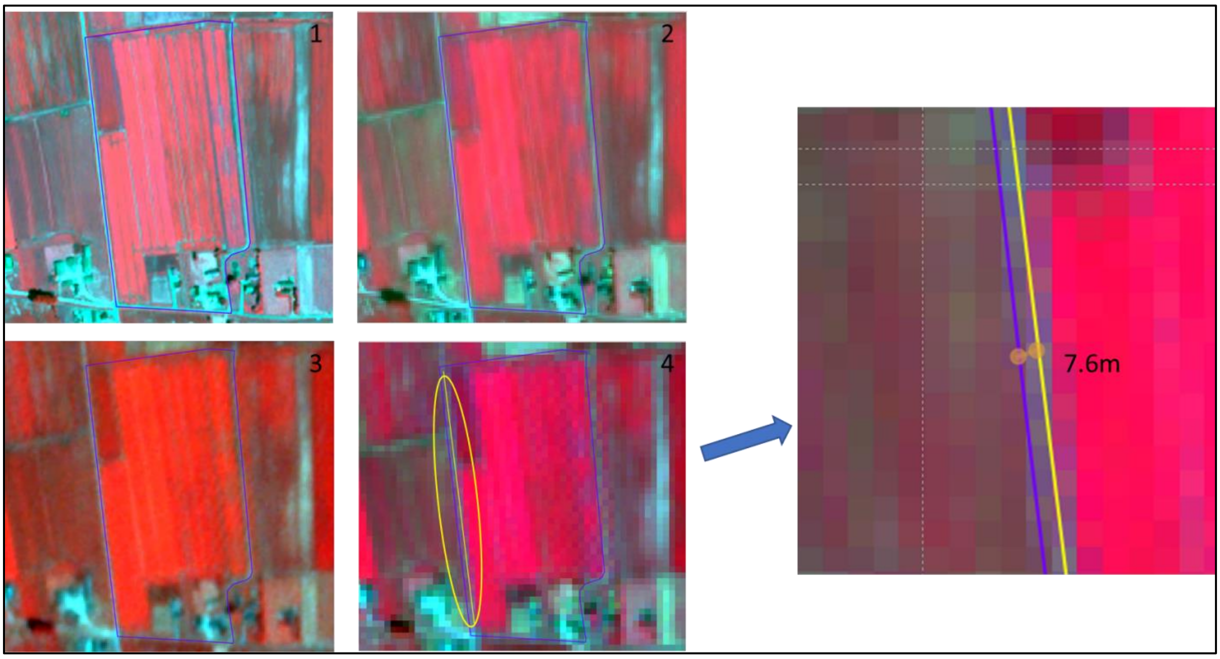



*Figure 36 - 1. Pleiades, 2. TSHP4 (SPOT), 3. PlanetScope, 4. S2; Area Eeklo, BE_FL;*

# 6 Summary and Conclusions

## 6.1 Summarizing the experiences

In summary, visual and radiometric quality assessment of TSHP processed imagery was conducted by comparison of mainly TSHP4 with available S2, PlanetScope, source SPOT, and Pleiades imagery.

The test was performed for two restricted geographic areas, Puglia, Italy and Eeklo, Belgium, Flanders, with suitable arable land and with “small” or elongated agricultural parcels, where Airbus had SPOT and Pleiades imagery and JRC had reference data on the crop type for some parcels.

The test was divided into a visual comparison, and a radiometric one. The latter one involving a series of tests including numerical comparison and linear regression of DN and NDVI values, comparisons of values along spatial profiles and finally a parcel heterogeneity test.

Airbus promptly re-processed the TSHP4 imagery after JRC request which produced a second dataset (Delivery II). This result was a less crispy image and maybe slightly less good for large scale visual interpretation. On the other hand, the delivery presented a more homogeneous product with better radiometry and better characteristics for small scale visual interpretation.

Visual comparison:

- TSHP 4m compared with TSHP 2.5m looks very similar, however on 4m product narrow features/sharp edges show the effect of resampling of the pixels
- TrueSharp demonstrates a clear improvement of the resolution compared to PlanetScope. TSHP actually appears to have a better spatial resolution.
- Comparing TSHP4 and PlanetScope, the TSHP4 shows some more blurriness at border of a homogeneous area (parcel or part of a parcel). This was however noted only in the Puglia area.

Comparison of radiometry of the TSHP, S2 and PlanetScope:

- All image sets appear to react correctly over the two crop types considered in Puglia (agricultural land not in production, and dill; dill reflecting higher at time of acquisition);
- nIR values of PlanetScope are lower, and often RED values of PlanetScope are higher than those of both S2 and TSHP4. This results in a lower NDVI. This is a consistent finding, i.e. that the resulting PlanetScope NDVI often shows a somehow ‘damped’ value;
- NDVI values of S2, and TSHP4 are very much aligned especially for the “clean” pixels compared over the selected parcels;
- Linear regression on 40 points (5 parcels, 8 points each) in Puglia shows a good linear dependency in RED, nIR and NDVI values among all sensor products. The best NDVI $R^2$ value is obtained between TSHP4 and S2 of delivery (II) 0.9122. $R^2$ values are slightly lower in Flanders (it was however not intended in this test to assess the variability in the radiometry of the PlanetScope imagery).
- The Profile comparisons confirm the ‘damped’ NDVI values of PlanetScope mentioned above for the visual comparison.
- The TSHP Delivery (II) showed a more homogeneous profile, with less variability (less high spatial frequency noise than Delivery (I). This was due to Airbus suitable filtering prior to the TSHP process.
- S2 geometricy shift cf. TSHP and PlanetScope can be detected with help of profiles
- To assess the sensors performance regarding DN and NDVI in a spatial dimension, Pearson’s correlation coefficient was used as an estimator of similarity. The results over three parcels in Flanders showed that they are similar and that we can assume that the NDVI profiles for the three sensor products are comparable.
- The parcel heterogeneity test over a sample parcel in Flanders shows that all three sensor products present a similar histogram shape with the important result that heterogeneity is not more evident in

either of the HHR data sets (PlanetScope, TSHP) compared to S2. This should however be tested on a larger set of parcels with smaller size (the area of the considered parcel was 2.7 ha).

- When extending the radiometry comparison to a larger area (10x5km over Eeklo, BE_FL) over it can still be concluded that the dependency between the image sets are strong, $R^2$ values are high, and the measurements from the different sensors over the larger area are well represented with a linear relationship, as could be expected over this mainly agricultural landscape. The dependency between S2 and TSHP is mainly explained with a scale parameter, while for Planet there is also a strong bias component.
- Also, in the tests over the larger area (10x5km over Eeklo, BE_FL) scatterplots of RED band .vs. nIR band of each sensor (TSHP, S2, PlanetScope), give a cloud of points which assume similar shapes, but the Planet response results are shifted and compressed with respect to the other two cases. This confirms the scale and bias dependency and is likely the reason for the overall damped NDVI value (higher RED and lower nIR gives lower NDVI) seen in the visual comparison.

Open issues:

- the test was limited to a single acquisition date, and thus for establishing the real complementarity of TSHP to other products, a test on the time series frequency of acquisition should be made.
- This test was limited to include (1) a small set of parcels, (2) a larger overlapping area (10x5km) with more APs, but visual and radiometric comparisons over yet larger more heterogeneous areas is suggested to complete the quality assessment of the TSHP imagery.
- the comparison of PlanetScope (CESTEM corrected data from the next generation Dove-R, and SuperDove) with TSHP, and S2 should be performed.
- the analysis of a real case where S2 is missing and examine whether TSHP can compensate for the deficiency is also suggested.

## 6.2 Conclusions

From the exercise performed by the JRC, there is clear visible enhancement of the spatial resolution in the TSHP 4m product compared to PlanetScope (and obviously S2).

The TSHP processing has been applied to SPOT imagery. Visual comparison of the extracts of true colours rendering (RGB) or nIR false colour composite (NIR/R/G) does not show the radiometric difference between TSHP and the standard SPOT product or the difference is very small. TSHP in addition shows comparable or better radiometry with respect to PlanetScope for visual interpretation.

Thus, the visual comparison shows that the product (TSHP) makes the visual interpretation just as feasible as with the other products.

Comparison of the radiometric values of TSHP with the two other products (S2 and PlanetScope) and with resulting linear regression showing a good correlation in RED, NIR and NDVI values, and best NDVI correlation of TSHP vs. S2 ($R^2$ of 0.9122 in Puglia), confirms the visual and can bring to the conclusion that all three products can supplement each other. This is confirmed also when extending analysis from the small subset of parcels to a larger area (10x5km).

It should be re-iterated that the test was limited to a single acquisition date, and thus for establishing the real complementarity of TSHP with other products, a test of the time series frequency should be made. Also, as mentioned above, these visual and radiometric comparisons should be made over a yet larger and more heterogeneous area to complete the quality assessment of the TSHP imagery.

Regards to determining whether the HHR TS specification can be revised permitting the use of SPOT TSHP equally as the source HHR data with an inherent better GSD, the answer is positive with respect to spatial resolution and radiometric BOA reflectance. An assessment of the above mentioned frequency of acquisition is still missing.

# 7 Hypothetical use cases within the CAP 2020+

HHR data obviously and by definition is situated in a spatial resolution range between HR resolution data like Sentinel2 (10m) and VHR data like some satellite and aerial imagery (< 0.75m). Some also have a temporal resolution similar to S2 data contrary to the present VHR imagery.
From the first tests done [ref. i] real benefit of HHR use still has to be investigated and demonstrated in the frame of future CAP checks and management. To date, it has been observed that for parcels of area < 0.3, 0.2 ha, HHR temporal profiles do not bring further information than the 'pure' intra-parcel pixels temporal profiles of S2 data. In such context, the systematic use of HHR data instead of Sentinel ones, may be of interest only in some regions covered almost exclusively by small arable land parcels e.g. Malta.

However, HHR data present a potential for the discrimination of landscape elements (e.g. landscapes features) definitely not discernible on Sentinel data. Nevertheless, one should investigate if HHR data would bring benefit compared to other solutions already available. For instance, most of landscape features are in nature rather permanent elements. There, automatic extraction from VHR aerial orthoimagery, available from national coverage campaigns, will certainly be more cost effective and accurate than through the use of HHR data.

Another potential field of investigation would consist in verifying if, for specific situations, additional information on intra-parcel pixels homogeneity or heterogeneity of HHR data compared to HR data, could allow to conclude on some parcel maintenance activities or abandonment. Also in such situation, one has to evaluate if alternative solutions like the multi-annual evolution of HR temporal profiles or the activities of LPIS update would not consist in more cost-effective and accurate solutions.

Other fields of research may arise depending on the detailed settings currently under discussion for the next CAP.

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# 9 List of Abbreviations

| Abbreviations | |
|---|---|
| AGEA | AGenzia per le Erogazioni in Agricoltura (PA Italy) |
| AL | Arable Land |
| AMS | Area Monitoring System |
| AOI | Area Of Interest |
| AP | Agricultural Parcel |
| BRDF | Bidirectional Reflectance Distribution Function |
| BOA | Bottom of Atmosphere (reflectance) |
| CAP | Common Agricultural Policy |
| CAPI | Computer Aided Photo-Interpretation |
| CbM | Checks by Monitoring |
| CESTEM | Cubesat-Enabled Spatio-Temporal Enhancement |
| COM | European Commission (EC) |
| CwRS | Control with Remote Sensing |
| DOVE | Triple-CubeSat miniature satellites built by Planet Labs, Inc., US; see PlanetScope below |
| DN | Digital Number |
| GSD | Ground Sample Distance |
| GRI | Global Reference Image |
| HHR | High High Resolution |
| JRC | Joint Research Centre of the EC |
| L2A | Level-2A (processing level of S2 data) |
| LC | Land Cover |
| LUT | Look Up Table |
| MS | Member State |
| MSP | Multispectral |
| ML | Machine Learning |
| NDVI | Normalized Difference Vegetation Index |
| OTSC | On-The-Spot Checks |
| PAN | Panchromatic |
| PlanetScope | PlanetScope satellite constellation consists of multiple launches of groups of individual cubesats (DOVEs). |
| S1 | Copernicus Sentinel-1 |

| | |
|---|---|
| S2 | Copernicus Sentinel-2 |
| **Acronyms cont.** | |
| TS | Time Stack |
| TSHP | TrueSharp |
| TSHP4 | TrueSharp 4m |
| VHR | Very High Resolution |

# 10 List of figures

# 11 List of tables

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