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ON-GROUND CHARACTERIZATION APPROACH OF THE SENTINEL-5 INSTRUMENT

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I. INTRODUCTION

Sentinel-5 is part of the Metop SG instrument suite. Metop SG is a series of three Meteorological Operational (MetOp) satellites which will provide continuity and enhancement of these observations in the timeframe of 2020 to 2040.

The Sentinel-5 mission objective is to monitor the composition of the Earth atmosphere for Copernicus Atmosphere Services by taking measurements of trace gases and aerosols impacting air quality and climate. The high resolution spectrometer system is operating from the ultraviolet (270nm) to the short-wave infrared (2385nm) range. With a swath width of ca. 2670 km, the Sentinel-5 UVNS mission will generate a daily global coverage of the Earth atmosphere with an unprecedented spatial resolution of 7x7 km2 at nadir.

The Instrument Optics Module comprises two telescopes, polarisation scramblers and Beam Splitter Optical Assemblies (TSBOA VN and TSBOA US), two Calibration Subsystems and five spectrometers (UV1, U2V, NIR, SWIR-1 and SWIR-3) which are combined as follows:

- U2V + NIR behind the "VN" telescope assy
- UV1 + SWIR-1 + SWIR-3 behind the "US" telescope assy

In order to be able to meet the instrument stringent L1b product accuracy requirements, elaborate instrument on-ground characterization is required. Calibration Key Data parameter values will be determined for use in the L01b processor.

II. INTRUMENT CONFIGURATION

The instrument main performance parameters are summarized in table 1.

Table 1. Sentinel-5 instrument main parameters

	UV1	UV2VIS	NIR	SWIR-1	SWIR-3
Spectral range [nm]	270 - 310	300 - 500	685 - 773	1590 - 1675	2305 - 2385
Spectral resolution [nm]	1,0	0,5	0,4	0,25	0,25
Spatial sample alt x act [km]	43 x 45	7.1 x 7.4	7.1 x 7.4	7.1 x 7.4	7.1 x 7.4
SNR [-]	100	1000-1500	500	variable	Variable
Radiometric accuracy [%]	3	3	3	6	3.5
Detector type	CCD	CCD	CCD	CMOS	CMOS

The instrument configuration is illustrated in figure 1. It consists of 2 telescopes, establishing the Earth port, with large 108° FoV in across track direction, corresponding to a 2670 km swath width at an orbit height of 817 km. The telescope FoV in along track direction is 0.2° (0.4° in UV1). Polarisation scramblers are implemented in the telescopes.
For in-orbit calibration, each telescope has its own calibration subsystem CAS consisting of sun diffusers (nominal and monitoring), White Light Source (WLS) and associated diffuser and further a mirror for deep space viewing. The sun port baffles provide a 22,1° x 11,5° (azimuth x elevation) FoV, enabling solar calibration over the south pole, just before entering in eclipse. For the NIR and SWIR wavelength regions, laser diodes are implemented so that an in-orbit wavelength scan can be performed which enables monitoring of the Instrument Spectral Response Function (ISRF). Finally, the spectrometer units themselves are equipped with LED's close to the respective detectors for in-orbit linearity measurements.
The instrument thermal radiators are located at the +Y side of the instrument. A dedicated shield protects the cold and intermediate stage radiators, for the detector cooling, from the Earth radiation. Heatpipes are employed between radiator and dissipative elements and inside the radiator panels themselves. The instrument is actively thermal stabilized by closed loop controls.

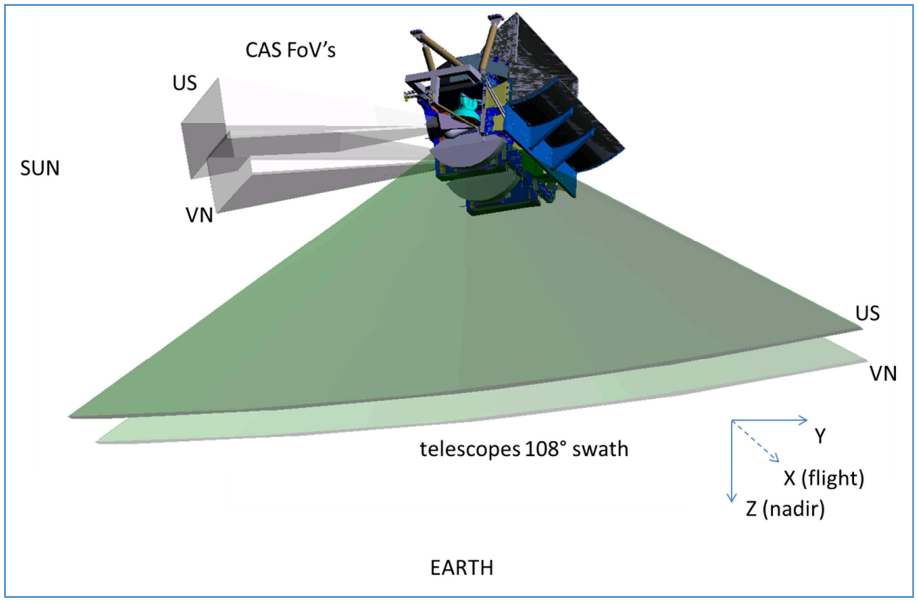

Fig. 1. Sentinel-5 instrument configuration showing the telescopes FoV towards Earth and the Calibration subsystem FoV towards the sun over the South Pole.

III. ON-GROUND CHARACTERIZATION SETUP

On-ground characterization of the instrument will be performed under flight representative, thermal vacuum, conditions in RAL facilities (GB). The 5 m diameter Thermal Vacuum (TVC) facility is equipped with 2 OGSE windows, allowing parallel stimulation of the instrument telescopes by Optical Ground Support Equipment (OGSE) in the adjacent cleanroom. Parallel measurements are foreseen to the extent possible, to limit overall duration of the C&C measurement campaign.

The instrument is mounted on a TVAC Rotation System (TRS). Its vertical rotation axis is parallel to the instrument Y-axis, whereas the horizontal rotation axis is parallel to the instrument X-axis. The centre of rotation has been selected in-between the telescope entrance pupils. Where needed, the (ambient) OGSE is mounted on translation stages to compensate any resulting translational shift, due to the fact that the centre of rotation is not exactly around the telescope pupil. This approach limits required diameter of TVAC windows, OGSE beam as well as beam homogeneity requirements. The TRS ensures full coverage of the instrument telescope and CAS FoV (either telescopes or CAS's visible through the windows) while ensuring horizontal orientation of the heatpipes.

The TVC is equipped with two pairs of rails: the quiet rails supported on a seismic block which extends beyond the TVC length axis so that the Optical Ground Support Equipment (OGSE) can be positioned on it in the CR. The noisy rails which are connected to the facility itself, which in turn is disconnected from the seismic block.

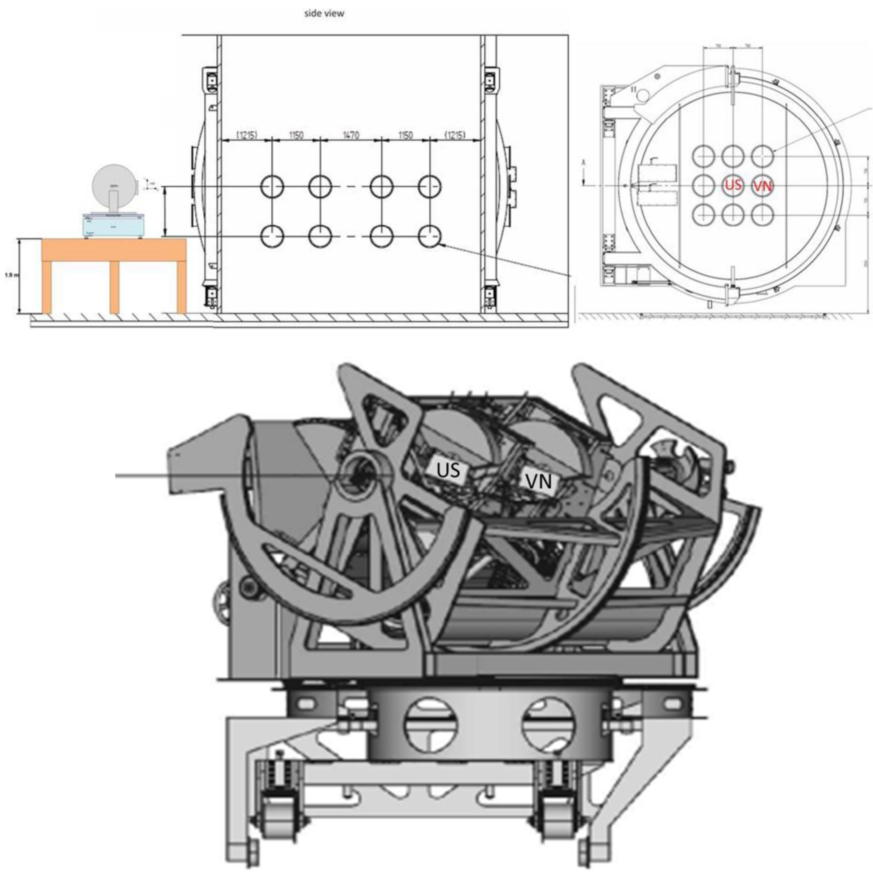

Fig. 2. Instrument mounted in the TRS in CAS measurement configuration (US and VN sun baffles indicated) as viewed from the OGSE. Note the independent rail supports for the instrument and CRAS. (credits APCO/RAL)

Whereas the TV facility shroud is used for general instrument cooling, the intermediate and cold stage radiators requires a dedicated Cold Radiator Shroud (CRAS) to ensure representative detector temperatures for any measurement orientation throughout the test. To this end, the CRAS moves with the instrument, but to avoid vibrations into the instrument from the LN_2 cooling loop, it is mounted on an independent support structure, which rests on the noisy rails of the TVC.

IV. ON-GROUND CHARACTERIZATION MEASUREMENTS

The on-ground characterization measurement are divided into five categories equal to five categories of instrument key-parameters defined by ESA in the Systems Requirement Document [4].

A. Detector and electronics

The first category is the detector chain, which relates to all electronic and detector related aspects. For this characterization mainly the instrument internal sources are used. To determine the linearity of the detector chain response the internal LED's close to the detector are used. The LED will illuminate the complete detector homogenously. In a stable environment LEDs prove to be very stable in output. In this case the instrument is temperature stabilized, which guarantees a stable environment for the LED (after warm-up). For the measurement the LED output is kept stable and the just exposure time of the detectors is varied creating different filling levels of the detector pixels.

The aim is to not only characterize the level of linearity but also to obtain a correction to the level of 0.1%. This correction shall be used for the full in orbit dynamic range as determined by the Earth and solar spectra. Due to the LED low radiance levels, this approach requires that the detector exposure times can be set to levels which are much different from the values used for Earth / sun observation. To cover the large dynamic range, in case of the CCD's, this requires very long exposure times, leading to long in-orbit measurements. To reduce the measurement time, the full dynamic range is therefore split over 2 LED's with a factor 10 difference in radiance.

For the CMOS detectors this approach is not necessary because the exposure times of the CMOS can be set much shorter.
Another very important parameter is the pixel response non-uniformity (PRNU). This parameter needs to be corrected for as its dynamics can be comparable of the science product. The PRNU is caused by tolerances of the detector manufacturing process and is wavelength dependent. This wavelength dependency rules out the use of the LED measurements since these measurements are not via the spectrometer and thus the wavelength reaching the pixel is different from the wavelength that pixel will see from the earth observation scene. Therefore the instrument is equipped with a white light source delivering a smooth spectrum via the spectrometer. Knowing that the WLS has a smooth spectrum, high frequency features in the measurement will be classified as PRNU. During the C&C campaign, also a WLS as part of the OGSE will be used for this measurement.

B. Spectral

The second category defined by ESA is the spectral calibration. Two main parameters are to be determined; the wavelength assigned to each pixel and the instrument spectral response function (ISRF) of each pixel. The latter will also give the full width half maximum of the spectral band measured by the pixel.
At first the spectral assignment was foreseen to be measured with spectral emission lamps and absorbing gas-cells. This approach has been applied to all Sentinel 5's predecessors (GOME, SCIAMACHY, OMI, GOME-2, TropoMI). A disadvantage of this approach is that a good distribution of the spectral calibration lines is not always possible. This is illustrated in figure 3 for the FPA-3 (400-600nm) band of the GOME-2 instrument. As can be seen there is a substantial gap between pixels 200 and 400. In the picture it might not seem harmful but consider that the required wavelength allocation accuracy is 0.04 pixel.

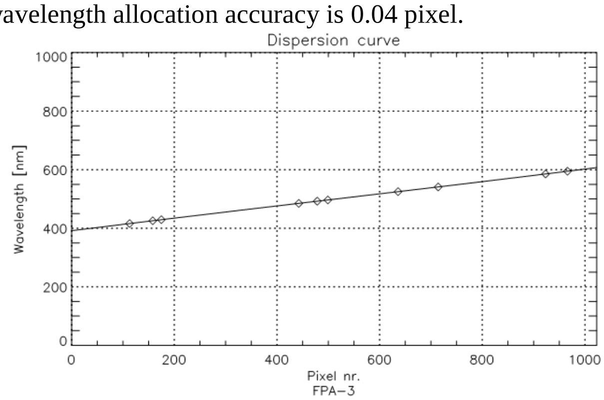

Fig. 3. Dispersion curve determined for the FPA-3 of the GOME-2 instrument. The diamonds indicate the spectral emission lines of the source used as fitting points.

As it is nowadays possible to determine the wavelength of the laser output with sufficiently high accuracy, this limitation can be overcome, using the tuneable laser wavelength scans required for the ISRF characterization. Since for the ISRF there will be several lines measured per pixel there will be more than enough lines available for the spectral assignment.

C. Radiometric

The third category defined by ESA is the radiometric calibration. The approach foreseen is rather traditional using a calibrated source from NIST (1000W FEL lamp). The source, in combination with a calibrated external diffuser (ODIFF), is primarily used for the absolute radiance response at nadir. This absolute radiance response is then transferred to all other viewing angles and to the sun irradiance response using a combination of measurements with an integrating sphere and a sun simulator. How the different measurements are combined is depicted in figure 4.
The absolute radiance response at nadir is determined with the FEL via ODIFF measurement. This product is combined with the relative radiance response, based on measurements with an integrating sphere, to the radiance response over the complete telescopes field of view.
For the absolute irradiance response a dedicated sun simulator (Susi) will be used. This source simulates the sun in the sense that the illumination geometry is comparable to the sun and not necessarily the irradiance level of the sun (unlike commercial sun simulators, which focus on high output flux). There are several reasons not to use the FEL source as irradiance source. The main reasons are the low UV flux of the FEL lamp and the limited calibration validity (50 burn hours), making it impossible to measure at several sun incidence angles. Since the Susi is not absolute calibrated, the irradiance calibration of the FEL is transferred using radiance measurements

for both sources on nadir. The measurements with the Susi on the sun port will be performed for several angles such that the relative dependence on the sun incidence angle can be determined.
Finally the instrument BSDF needs to be determined. The instrument BSDF is the ratio between the absolute radiance response and the absolute irradiance response of the instrument. This ratio will be based on the Susi measurements for radiance and irradiance.

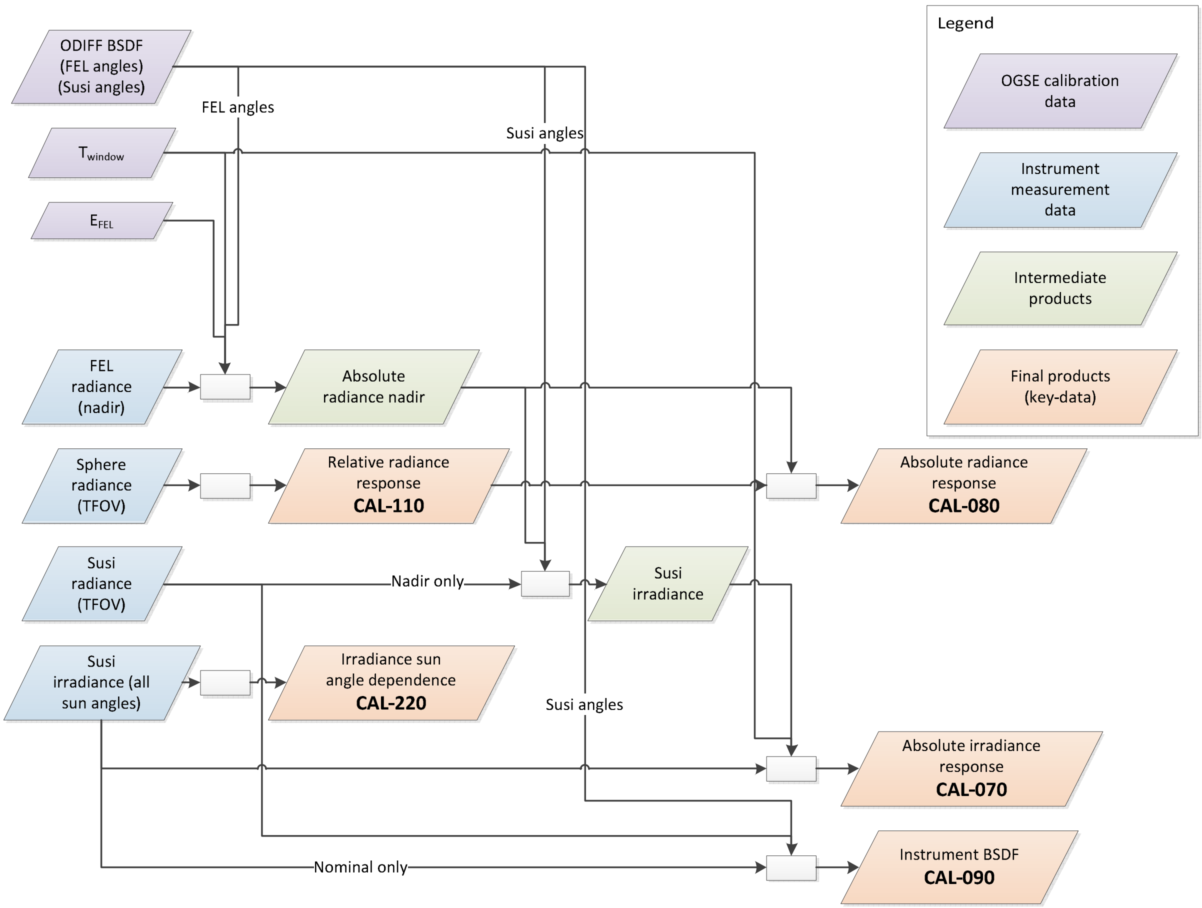

Fig. 4. Determination of the radiometric key-data from measurement data.

D. Geometric

The fourth category is geometrical calibration. Here the viewing angle of the earth and sun port are meant as well as, for the earth port, the instrument spatial response function. The viewing angles of the sun port are determined by the sun port baffle. The sun diffuser itself does not have a field of view. The sun port baffle is designed such that for the calibration angle the sun diffuser can be fully illuminated by the sun. Outside those angles the sun diffuser can only be partly illuminated by the sun (or any other source) until at a certain angle the light is blocked completely by the baffle. For the on-ground calibration it is foreseen to only characterize and verify the clear field of view i.e. determine instrument response as function of Susi angle of incidence on the diffuser for those viewing angles where the Susi fully illuminates the diffuser. There will be a limited set of measurements going beyond the field of view to check performances. For the measurements themselves an extension (more incidence angles) of the sun simulator measurements over the sun port are foreseen.
The earth field of view measurements have to deliver input for both the line of sight with respect to the Instrument Alignment Cube (IAC) as well as the spatial response function. For this a field scan with a with a narrow field source in one direction (along track or across track) is foreseen. Tto cover the complete wavelength range, a White Light Source (WLS) will be used. For the across track viewing properties, the field will be narrow in across track direction and this will be scanned along the swath. In order to be able to measure several pixels in parallel, there will be a number of those narrow field lines across part of the swath. In the along track direction a similar scan will be made, but in this case only one narrow field is offered to the instrument. The approach is shown schematically in figure 5. Illuminating multiple pixels at the same time shortens the measurements time.

The measurement will give as results a spatial response function in two directions. From this function the centre of gravity will be determined to give the line of sight and the full width of half maximum will give the field of view.
Due to the presence of the polarisation scrambler, the viewing properties are expected to be polarisation dependent. Therefore, The scans will also be repeated for with polarised light to determine the polarisation dependence of the viewing properties.

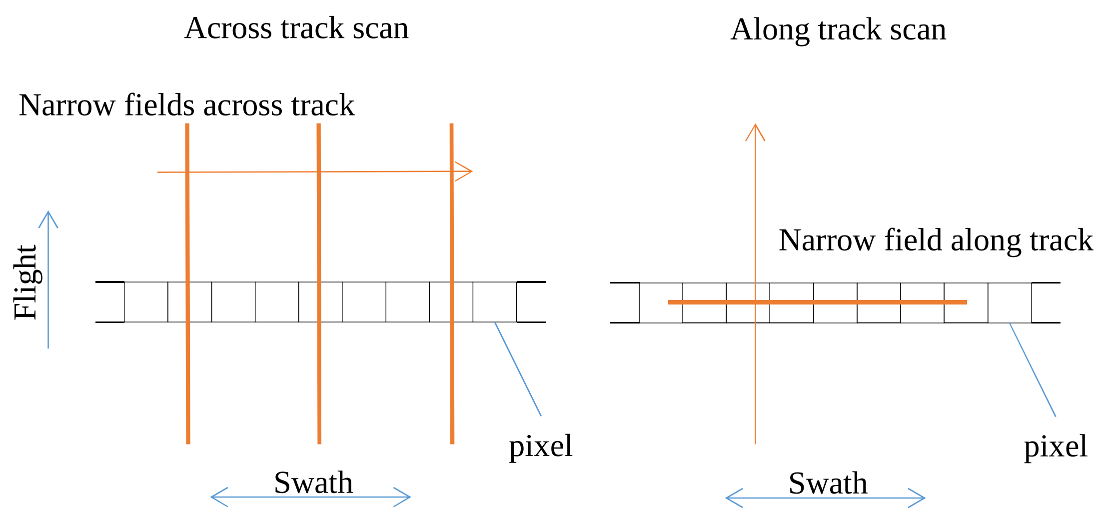

Fig. 5. Field of view scan principle.

E. Others

The last category defined is “others”, which in case of Sentinel 5 covers stray-light and polarisation. For polarisation it is required to determine the first three elements of the Müller matrix. The first element of the Müller matrix is the absolute radiometric response. The second and third element will be determined relative to the first element with a scan of linear polarised light in front of the earth port.
Stray-light will be measured with a laser and with filter measurements. The laser measurements will be performed via the earth port and will result in a spot on the detector. Theoretically this is the best measurement, but in practice it is limited by the dynamic range of the detector. To overcome this a larger part of the detector has to be illuminated leading to more energy on the detector with respect to the not illuminated part (i.e. the part where the stray-light needs to be measured). This is done by using filters with a much broader wavelength band than the laser. The disadvantage of this approach is that stray-light ghost will be blurred. The filter measurements are most useful for the stray-light coming from scatter, which has a more uniform nature.
In addition to the measurements on the earth port also measurements on the sun port will be performed. These measurement are mainly to check and improve the earth port measurements since they will illuminate the complete swath, i.e. resulting in a line on the detector. Similar kind of checks will be performed with the earth port, using WLS based radiometric measurements. In this case the full spectrum is illuminated but only a small part of the swath.

V. FORESEEN ANALYSES OF INSTRUMENT SPECTRAL RESPONSE FUNCTION

The ISRF is one of the most demanding parameters to measure. The spectrometer does not resolve the lines of the spectrum so the data products from Sentinel 5 are relying on a good knowledge of the ISRF. The ISRF is used to convolve sun and earth spectra in the forward model used in the retrieval algorithms. The same forward modelling is used for the wavelength calibration in orbit, using both Fraunhofer lines and absorption lines to assign a wavelength to the pixels. The required knowledge of the ISRF is specified as 1% (2% on instrument level) of the peak value for that part of the function where it is higher as 1% of the peak value. In case of the short wave infrared (SWIR) the requirement is even more stringent at the lower edges.
The ISRF is measured using a wavelength scan with a tuneable laser. Each pixel will be scanned on subpixel level. For the analyses it is assumed that the ISRF will not change significant over a couple of (neighbouring) pixels. With this assumption it is possible to use neighbouring pixels to determine the ISRF for a pixel. This has the advantage that the position and the energy of the lines can be obtained from the measurement itself, making the measurement less dependent on stimulus performance (knowledge).

In reality the ISRF will change over the spectrum due to changes in the slit image and the changes in the PSF. For this reason requirements on the spectrometers are set such that it is safe to assume that over a range of four times the FWHM the changes are low enough to be neglected. So around the pixel to be analysed a range of +/-2 times the FWHM can be used to analyse and determine the ISRF.
The steps taken to combine the pixel data depicted in figure 6. Here only a few measured lines are shown to demonstrate the principle (in reality a more dense scan will be used). In the top left the true ISRF is shown which is in this case a Gaussian with a FWHM of 3 pixels wide. In the top right simulated measurements are shown. The circles indicate the measured points and the striped lines are only there to guide the eye. The first step is to normalize these measurements such that the integral energy is unity. Result of this is shown in the bottom left of the figure. The next step is to find the centre of gravity for each measured line. Under the given assumption that the ISRF does not change much from one pixel to the next, all lines can be aligned around a common centre of gravity of each line as shown in the bottom right. Here a detailed scan of the function is given, which will be assigned to the pixel under investigation (i.e. the centre pixel in this case number 500). The ISRF is now determined as function of detector pixel. Using the wavelength calibration it can be determined as function of wavelength.

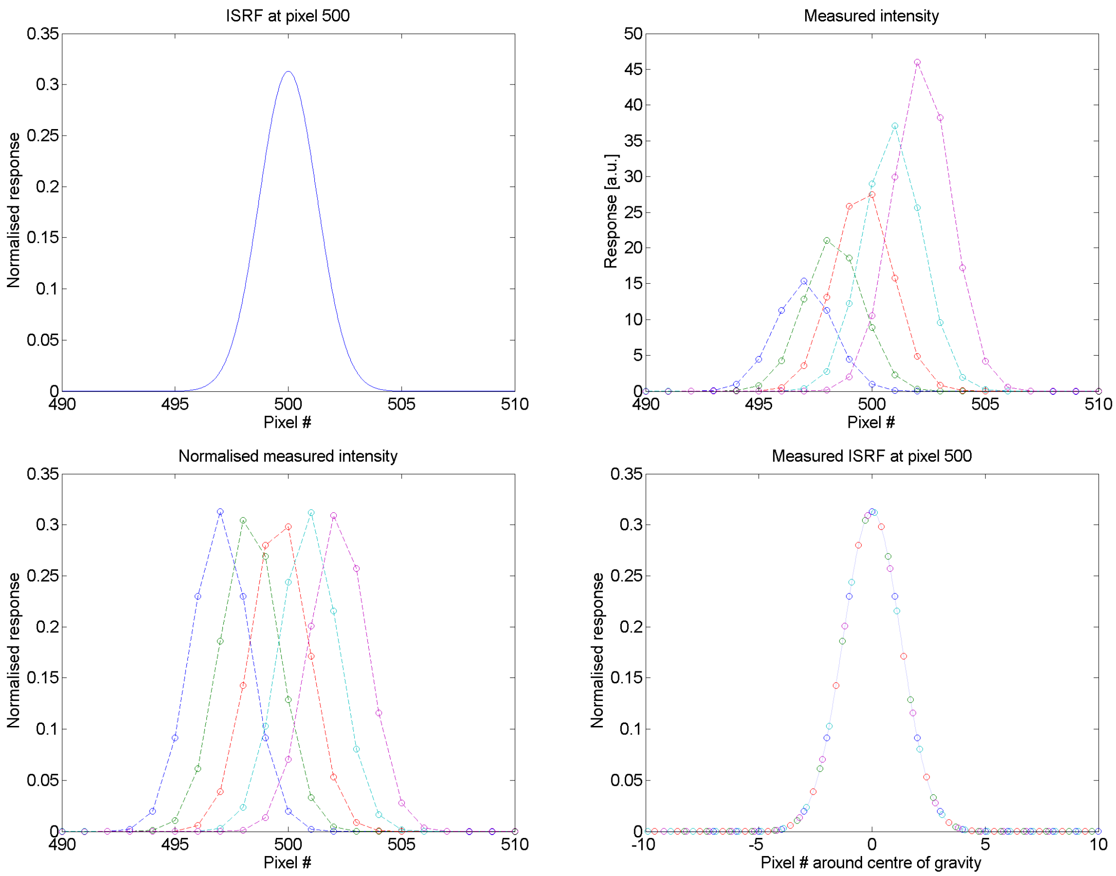

Fig. 6. Combining information from neighbouring pixels. Top left is the original ISRF at pixel 500. Top right a measurement of several laser lines around pixel 500. Bottom left the same measurements but now each measurement is normalised such that the energy is unity. Finally at the bottom right all normalised measurements are centred around their common centre of gravity, the line through points represents the original function as given at the top left but now centred around the centre of gravity.

Note that the absolute value of the points are arbitrary. Only the relative shape of the function is needed as final results. When applying this function later in a convolution the normalisation should be redone matching the sampling density applied in that convolution. In the analyses the normalisation is only needed to match the points.

CONCLUSION

The approach for the Sentinel 5 calibration is based on heritage from previous hyper spectral imagers. There are some changes to the measurement approach making use of new insights and the availability of new technologies such as wide range tuneable lasers and large vacuum chambers dedicated to calibration. Results are yet to come but the high level of detail going into the preparation gives us confidence that these will be high quality.

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