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Fluorescence Imaging Spectrometer concepts for the Earth Explorer Mission Candidate FLEX

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Abstract— **The Fluorescence Explorer (FLEX) is one of ESA's 8th Earth Explorer mission candidates, which has been recently initiated for feasibility (Phase A) study as part of the ESA Living Planet programme. Together with the second candidate mission CarbonSat, these missions will undergo a preliminary concept review and a preliminary requirements review. FLEX has reached a status, where the requirements have been consolidated such that the instrument and satellite concepts could be formulated. The selection of the instrument concepts were derived from detailed trade-offs, which had the aim to meet the instrument requirements while staying in line with the allocated resources for the mission. Although the instrument concepts are not yet fully frozen with respect to all aspects, we will report about the most promising configurations and the expected performance as compared to the scientific requirements.**

Index Terms— **Explorer, land and vegetation, imaging spectrometer, grating spectrometer, visible.**

I. INTRODUCTION

Fluorescence Imaging Spectroscopy has been considered by ESA already several years ago [1],[2], since until now, most of the information that has been acquired by remote sensing of the Earth's surface about vegetation conditions and photosynthetic activity has come from "reflected" light in the solar domain. The fact that the measured radiance in space contains a small fraction that is related to the "emission" of fluorescence from the chlorophyll of assimilating leaves as a result of the photosynthesis has mostly been ignored. FLEX has been proposed in a configuration that is making use of the synergy with existing missions by flying in tandem with Sentinel-3. From previous studies [3] it was concluded that a grating spectrometer is the most suitable type of instrument meeting the requirements of the FLEX mission. A number of instrument configurations were identified, which allowed the observation of fluorescence in a broad spectral band. The FLuORescence Imaging Spectrometer (FLORIS) shall fly in formation with Sentinel-3 [4] on a medium to small sized satellite in a Sun synchronous orbit at a height of about 815 km.

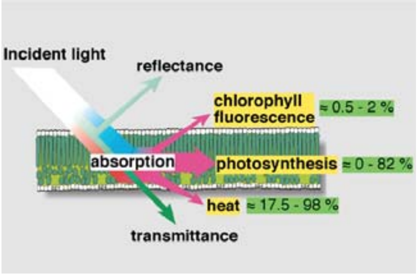
In the frame of the preparations of the Phase A study, the Mission Advisory Group and ESA have generated a Mission Requirements Document and a System Requirements Document. Those documents reflect concurrently the best knowledge of the scientific objectives and requirements and the resulting instrument and system requirements. The requirements are currently based on investigations that were made until now resulting from scientific and instrumental preparatory studies and the requirements consolidation study.

Instead of focusing on the Oxygen absorption lines only, as initially intended, FLORIS will measure now in a more holistic way within a larger and more complete spectral range between 500 nm and 780 nm. It will thereby cover also the photochemical reflection features between 500 nm and 600 nm, the Chlorophyll absorption band between 600 nm and 677 nm, and the red-edge in the region from 697 nm to 755 nm being located between the Oxygen A and B absorption bands. By this measurement approach, it is expected that the full spectrum of the chlorophyll fluorescence signal (F_{Chl}) can be retrieved, and that atmospheric corrections can efficiently be applied. FLORIS will measure Earth reflected spectral radiance at a relatively high spectral resolution of ~0.3 nm around the Oxygen absorption bands. Other spectral areas with less pronounced absorption features will be measured at medium spectral resolution between 0.5 and 3 nm. FLORIS will provide imagery with about 300 m spatial sampling distance (SSD) and similar spatial resolution on ground with a swath width of at least 105 km. This will allow achieving (weather permitting) a revisit time of two weeks for all places on the globe to monitor seasonal variations of the vegetation cycles. The mission life time is expected to be at least 4 years.

The presented results are based on the assessments that were or are being conducted within Phase A together with the industrial study teams. Since the assessment is not yet completed, in this paper we will describe the concurrent status of the mission as far as the scientific and the technical aspects are concerned, but which is considered as not final.

II. MEASURING FLUORESCENCE FROM SPACE

The first step of photosynthetic energy conversion is the so-called 'light reaction'. Photons in the range of 400 nm to 700 nm, i.e. the Photosynthetic Active Radiation (PAR), are absorbed in the multi-pigment complexes of the photosystems and the resulting excited energy states are transferred to the



core complexes (see Figure *1* left). These excited energy states are stabilized by a complex cascade of energy transfer reactions, which drive the photochemical reaction ultimately leading to electrons that are transported in photosynthetically active plant tissue used to produce energy-rich biochemical compounds. The fluorescence signal (Figure *1* right) originates from the core complexes of the photosynthetic machinery, where energy conversion of absorbed PAR occurs. Because the photosynthetic apparatus is a highly complex but organized structure, the emission spectrum of fluorescence that originates from it is well known and it occurs with two peaks having broad bands with maxima around 685 nm and 740 nm. The height of the two peaks is variable reflecting - among other processes - the efficiency of photosynthetic electron transport and thus is a proxy for actual photosynthetic light conversion.

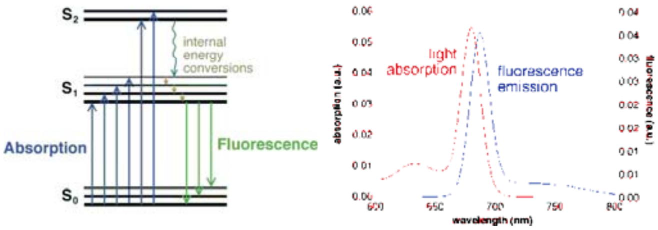


Figure 1 Electron states of the F_{Chl} excitation and down-conversion process (left) and the corresponding light absorption emission spectra (right).

The second step of photosynthetic energy conversion is the fixation of CO_2. Here energy rich compounds are used to fuel a biochemical reaction that fixes atmospheric CO_2 and produces the precursor of sugars and starch that are the basis for all plant material. Depending on the environmental conditions and the plant species, the efficiency of carbon fixation varies greatly. Fluorescence emission ultimately tracks the results of all these complex processes. The relation between photosynthesis and fluorescence is subject of an on-going dedicated study by ESA.

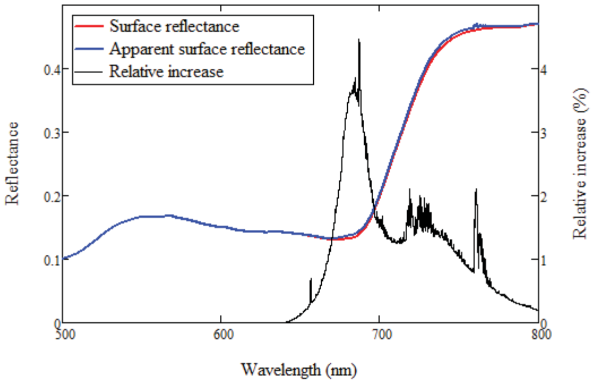


Figure 2 Apparent reflectance of vegetation (comparison of reflectance with and without F_{Chl} contribution) and the relative change in reflectance due to F_{Chl} is shown.

As result of photosynthetic activity, fluorescence emitted by vegetation can be used as vehicle to investigate the vegetation status, a usual procedure in laboratory and field conditions. If observed from space it leads effectively to an alteration of the apparent reflectance of the ground that allows mapping fluorescence at global scales. The difficulty of the measurement from space is that F_{Chl} is partly attenuated when traversing the atmosphere, so that atmospheric corrections have to be applied. Conventional detection of F_{Chl} in the O_2 bands such as usually done on ground does not work here and instead complex models have to be used to extract the F_{Chl}. Figure *2* represents the apparent reflectance curve with and without F_{Chl}: the reflectance would be a smooth function of wavelength in absence of fluorescence, while the presence of fluorescence produces the characteristic peaks that allow the retrieval of F_{Chl}. A closer view of the effect in the Oxygen A band in Figure *3* illustrates this difference in more detail and shows the involved change of reflectance induced by F_{Chl} compared to the nominal reflectance.

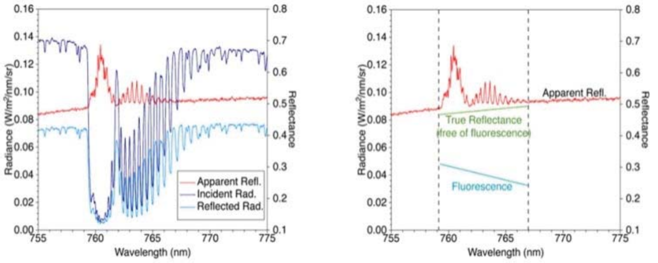


Figure 3 Retrieval approach based on spectral fitting decoupling fluorescence from background reflected radiance.

It has been shown as well that the reflectance is closely related to the chlorophyll content of the leaves. A variation of the reflectance, particular from visible to near-infrared across the red-edge, is particularly sensitive to changes in chlorophyll content and LAI, which in turn are correlated with fluorescence dynamical variations.

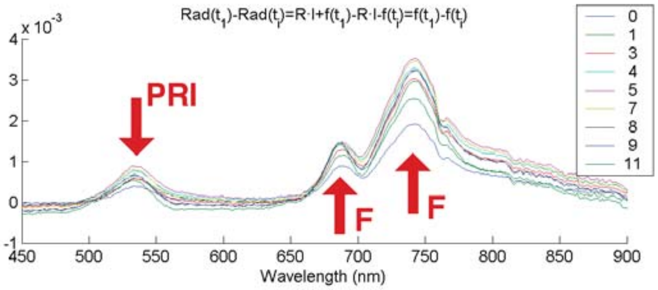


Figure 4 Measured reflectance signal contribution as a result of the dynamics of photoactive processes, which involve both actual changes in reflectance (PRI) and fluorescence emission (F).

The complete information content of the whole spectrum must be used as basis for sophisticated models for the atmosphere and the reflectance properties of vegetation. As can be seen in Figure *4* , the reflectance around 530 nm, which is called the Photochemical Reflectance Index (PRI) region, is affected by the amount and type of photosynthetic activity of the plant, which means that both fluorescence and reflectance can be treated as dynamical contributors. Their variations are correlated and should therefore be modelled together. The sensitivity of the sensor must be high enough to detect the expected changes. In a real spectrum observed from space, a high spectral variability is seen in particular in the areas of oxygen and water absorption. The instrument must have high enough spectral resolution to resolve the features of the Oxygen bands so as to capture the variability of the radiance being generated by variation of the most important parameters, which alter the transmission of the atmosphere. Those parameters are in particular: atmospheric pressure and temperature profile, water vapour content, aerosol optical thickness and aerosols height distribution.

An indication of the multiple aspects to be taken into account in the retrieval approach, which uses a spectral fitting technique [5] to decouple fluorescence from background reflected radiance is given in Figure 5. It must be noted that the fluorescence radiance variations (ΔRadiance) are presented relative to the received signal and generate therefore a spectral signature in strong absorption features, which is actually identifiable when working with enough spectral resolution and quantifiable only if working with enough signal-to-noise ratio.

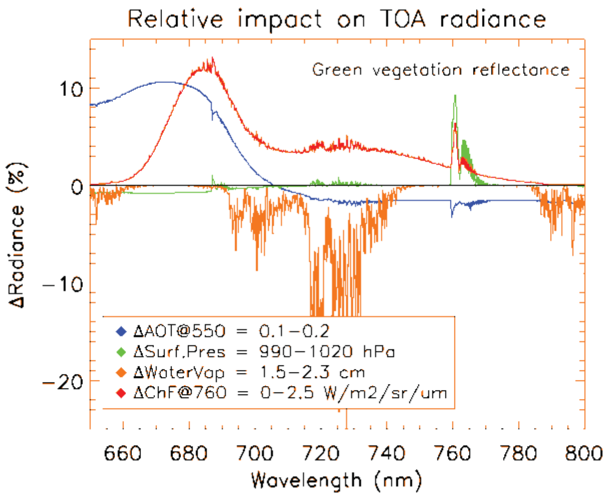


Figure 5 Top of atmosphere radiance variations for several different model parameter ranges. The variation of the radiance resulting from a change of the parameters within the indicated ranges is shown.

At wavelengths around 761 nm for example, an increase of the surface pressure acts similar as presence of F_{Chl}, but aerosol optical thickness (ΔAOT) increase for example is reducing the signal level. Water vapour content on the other hand has no influence on the signal at such wavelengths. The current retrieval method needs therefore to extract the information of all contributors and disentangle F_{Chl} variability from the variability of all other parameters. An apparent challenge is the fact that all model parameters and dependencies need to be highly constraint in order to extract F_{Chl} with high accuracy. Accurate modelling of the surface reflectance is one of the biggest challenges, since it is of similar smoothness as F_{Chl}. The current objective of the mission is to derive F_{Chl} with an accuracy of 10% for its integral across the spectral range and for each spectral region, namely O2-A and O2-B.

III. INSTRUMENT REQUIREMENTS

A. Spectral requirements

In order to measure the above discussed variations of the radiance caused by the fluorescence process, FLORIS needs to cover the spectral range from 500 nm to 780 nm. It is not necessary to have high spectral resolution for the full spectral range. Instead it is sufficient to have a high spectral resolution for the Oxygen-A and Oxygen-B bands only, and medium resolution for the remaining spectral regions. The spectral resolution in the Oxygen bands has been selected such that the instrument will be able to resolve the spectral features on one hand, but the resolution will not be so good that the signal will drop to Zero at the deepest absorption features. As can be seen in Table 1 the best spectral resolution needs to be 0.3 nm. In order to prevent spectral aliasing and to properly measure the spectral features present in the Oxygen bands, the spectral sampling interval (SSI) is selected to be about 3 times better than the spectral resolution. Spectral resolution is meant to be the Full Width at Half Maximum of the spectral response curve.

The FLORIS configuration has undergone a sensitivity analysis of the information loss depending on the spectral resolution of the instrument. Since the spectral fine structure of the PRI band is not important for the measurement, it is sufficient to have a spectral resolution of 3 nm in the PRI band. In the Chlorophyll absorption band spectral information is still valuable and shall therefore be 0.7 nm. The spectral features of the red-edge are dominated by water vapour absorption, which is not needed for the retrieval at high resolution, whereas the shape of the red-edge is important as already discussed. The spectral resolution of the shoulders of the Oxygen-A band is chosen at an intermediate resolution to properly intersect those with the absorption band. There is a potential interest to increase the spectral resolution in the range between 740 nm and 759 nm in order to resolve the Fraunhofer lines, since those are not or least affected by the atmospheric properties.

The spectral requirements have been iterated within the study of the instrument configuration. It is very difficult to design an instrument with high resolution of about 0.3 nm or even better for a large spectral range, because the number of spectral channels would become very large, so that the data

Table 1 Summary of acquisition parameters of the FLORIS spectral bands. The spectral resolution (SR) and the Spectral Sampling Interval (SSI) are given for each band.

Band	**PRI band**	**Chlorophyll absorption**	**O_2-B Band**		**Red-edge**		**O_2-A Band**			
λ [nm]	**500-600**	**600-677**	**677-686**	**686-697**	**697-740**	**740-755**	**755-759**	**759-762**	**762-769**	**769-780**
SR (FWHM)	3.0	3.0	0.7	0.3	2.0	0.7	0.7	0.3	0.3	0.7
SSI	2.0	2.0	0.4	0.1	1.0	0.5	0.5	0.1	0.1	0.5

rate would explode and the focal plane (detector) would be very large. Assuming frame transfer along the spectral direction, the large spectral range also increases the smearing of the instrument coming from the charge transfer of the CCD after its exposure (no shutter present). A large spectral range will also add straylight to each channel since it is in proportion to the extension of the spectral range, at least if no special filtering concept is implemented.

The spectral accuracy of FLORIS is not particularly demanding since the spectral calibration can be made by analysis of the highly resolved data and the comparison with atmospheric transfer programs. The spectral stability of the instrument shall be good enough such that the spectral calibration needs to be carried out only once or twice per orbit. No onboard calibration system is needed to perform the spectral calibration, but it will require a good thermal stability of the instrument. The spectral co-registration (temporally) is almost perfect for this type of spectrometer and is one of the reasons why the concept has been selected or imposed. Optical misregistration of the spectral channels results from spectrometer smile, however, it is expected that this can be corrected by data processing.

B. Geometric requirements

Since FLEX shall provide measurements of vegetation fluorescence on a global scale with a repeat cycle that allows the monitoring of seasonal variations, it has to provide a swath width of at least 105 km. Starting at this swath size, the successive swaths are contiguous at the equator such that global coverage is achieved within 19 days. Of course, many observations will be compromised by the presence of clouds. It is therefore planned to implement a swath size of 150 km, so that the coverage will be enhanced to compensate cloud contaminated observations. The swath size of the instrument drives also the data rate of the instrument and to some degree its image quality in particular at the swath edge. FLEX shall provide data over all vegetated land surfaces at latitudes between -56° S and +75° N including islands greater than 100 km^2 and coastal zones within 50 km from land to ocean waters with a depth of less than 10 m. The Sentinel-3 orbit is very suitable because at the crossing time of 10:00; there is still high fluorescence yield with a good contrast to fluorescence emitted by stressed vegetation.

The spatial resolution or image quality should be as good as possible to avoid the presence of heterogeneous scenes. A relatively small contribution from a signal of bare soil or other land sites, which have a different reflectance properties, will alter the measurement and generate artefacts, which will make it impossible to retrieve fluorescence with sufficient accuracy. Such areas can be as small as 5% of a single imaged ground pixel. It is therefore desirable to implement a very good spatial resolution or image quality. Also here, in order to limit the data rate of the instrument and to make the imaging quality of the optics not too demanding, the spatial sampling distance has been selected to be 300 m. FLORIS will follow therefore the footsteps of OLCI [4], but will provide spectra with much higher spectral resolution. The ratio of swath width and pixel pitch of about 500 is very common for Earth observation instruments. It is noted that the granularity of the image determines also the radiometric performance of the instrument, since the smaller the pixel, the less signal is available, and the more noise will be present in the spectral image.

There are further constraints with respect to the observation geometry for FLEX. For a good co-registration with Sentinel-3, it is planned to have the swath of FLORIS within one of the OLCI cameras. The temporal co-registration with Sentinel-3 shall not exceed 15 s with a target of 6 s. This requires formation flying in close proximity with Sentinel-3. The observation zenith angle (OZA) shall not be larger than 15 degree to minimize the effects of the inclined transition of the radiance through the atmosphere so as to enable better atmospheric corrections. Close proximity to Sentinel-3 allows close to NADIR observation, so that the OZA is kept as small as possible.

C. Radiometric requirements

The instrument sensitivity is one of the most important requirements. Since the variation of the signal due to fluorescence is small as indicated in Figure 2, and since this signal shall be measured with an accuracy of about 10%, it is required to achieve relatively high signal to noise ratios (SNRs).

Table 2 SNR requirement for the O2-A and O2-B bands.

Band	**O$_2$-B Band**	**O$_2$-A Band**	
λ [nm]	**677-697**	**759-762**	**762-769**
SNR	400	200	Linear from 200 to 1200

Table 3 SNR requirement for the remaining bands.

Band	**PRI band**	**Chlorophyll absorption**	**Red-edge**		**O2A**
λ [nm]	**500-600**	**600-677**	**697-740**	**740-755**	**755-759**
SNR	300	300	600	Linear from 600 to 1200	1200

These SNR values were derived from a sensitivity analysis, which has determined the noise level needed/allowed to detect fluorescence from a set of representative vegetation spectra with the required accuracy. This method did not analyse the accuracy of the fluorescence that shall be obtained by the fluorescence retrieval, since the retrieval algorithms are still under development.

In this current configuration, the most demanding SNR requirement is the requirement in the range between 759 nm and 762 nm, which would need to be about 450 if the analysis is purely taking the signal level into account. However, recent investigations have indicated that the spectral range is not so important, so that the requirement can be kept at an SNR of 200, with the consequence that this small spectral range is not driving the size of the instrument.

The combination of high spectral resolution and good SNR is asking for very high instrument sensitivity. The aperture of FLEX needs therefore to be at least 80 mm. This is about 10 times larger in area than for example for MERIS [6] or OCLI and will drive the instrument size. For these FoVs, an inherent problem can be the straylight susceptibility of such spectrometer. Apertures of this size are usually only used for imagers or radiometers.

Apart from the noise requirement, FLORIS shall also provide good absolute and relative radiometric accuracy. Although the absolute accuracy is less stringent for the retrieval of fluorescence in principle, it is currently anticipated to guarantee the absolute and relative radiometric accuracy at a level of 2% to 3% and 1%, respectively. These requirements will demand an onboard calibration system. It is noted that although cross-calibration with Sentinel-3 can be performed, it is assumed to be better to implement a calibration system for FLORIS, because of the much different spectral resolutions and spectral coverage will limit the cross-calibration accuracy with Sentinel-3.

D. Polarisation sensitivity

The presence of aerosols and molecules in the atmosphere will alter the composition of the polarization states of the radiation. Depending on the height of the molecules or aerosols, there is more or less attenuation of the radiation passing through the atmosphere, and this will depend on the polarisation state of the radiation. The attenuation can be so strong that the degree of polarization can reach almost 100 % at the Oxygen-A absorption band. Due to the variation of the height of the aerosols and molecules, the degree of polarisation is highly variable. Typical error spectra resemble the absorption structure of the atmosphere (compare ΔSurf.Pres. in Figure 5). In general, the sensitivity of a grating spectrometer depends on the polarisation state of the incoming radiation. If the polarisation state is not randomly distributed, then a large radiometric error can be induced. In order to not compromise the radiometric accuracy of the instrument, it is required to make it insensitive to the polarisation state of the incoming radiation to a level of 1% at the Oxygen-A band and to about 2% elsewhere. A polarisation scrambler as employed for MERIS and OLCI seems to be mandatory.

IV. FLORIS INSTRUMENT CONFIGURATION

A. Instrument concept

The presented background information and the discussed requirements give the rationale for the current FLEX instrument configuration. FLORIS has to cover a relatively large spectral range from 500 nm to 780 nm and has to deliver relatively high spatial and spectral resolution with good co-registration properties. By this measurement approach, it is expected that the full spectrum of the fluorescence signal can be retrieved, and that atmospheric corrections can efficiently be applied using also information from Sentinel-3. FLORIS is designed as hyperspectral imaging spectrometer. The general concept is shown in Figure 6.

As already indicated, it is almost impossible to provide high spectral and spatial resolution with a single instrument without splitting the bands. It is therefore natural to separate the high and the medium resolution part of FLORIS. There are several solutions for a design, which is compatible with this demand as already discussed in [3].

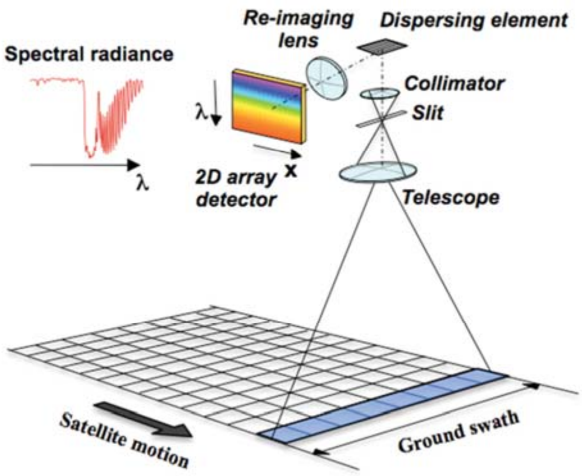


Figure 6 Hyperspectral pushbroom imaging spectrometer concept.

FLORIS will have two main functionalities: A narrow band spectrometer shall measure the region of the Oxygen bands, whereas a broad band spectrometer must provide spectral imaging capability at medium spectral resolution. For the implementation it is either possible to have (1) a common front telescope and separation of the bands at the spectrometer level or (2) two separated front telescopes and therefore two separate instruments. Both solutions are compatible with the requirements. The first solution makes the instrument slightly more compact and provides optimum co-registration properties, whereas the second solution allows a better optimisation of the performance since there is no inter-dependence. There are further differences in the applicable cleanliness levels and the expected assembly, integration and testing sequences. In case (2) a second front telescope is needed and the implementation of the calibration system becomes more difficult. Performance wise case (2) is superior to case (1) and bears less risk because each instrument can be built straight forward (ignoring co-registration requirement).

In addition to the elements of the hyperspectral imager, FLORIS will need a baffle to minimise the out-of-field straylight, and it needs a calibration mechanism allowing Sun calibration with one or two diffusers. In every case, there will be two spectrometers for FLORIS in all identified concepts. The two spectrometers, which are named the FLORIS Narrow Band Spectrometer (FLORIS-NBS or in short NBS) and the FLORIS Wide Band Spectrometer (FLORIS-WBS or in short WBS) will employ two different gratings.

B. Optics layout

Choice of the optics of the spectrometer and the telescope can be based on either refractive, reflective or catadioptric concepts. An example of a refractive configuration as presented earlier in [3] is repeated here in Figure 7 for illustration.

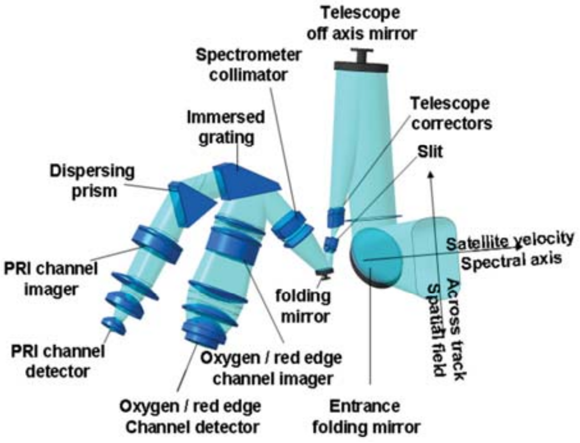


Figure 7 Mostly refractive concept of a hyper-spectral imager (FIMAS concept 1).

Such refractive concept has the advantage that the lens manufacture and mounting is straight forward. A disadvantage is that the large number of lenses and therefore surfaces is generating more scattering and also more loss in transmission, since each lens will have a coating where a certain amount of radiation will be lost (e.g. 1%). For the demanding straylight requirements of FLORIS, there will be a high cleanliness requirement, which will make the assembly and integration more difficult.

Another example of a suitable configuration is shown in Figure *8*. For both concepts, the telescope can also be made reflective by using a three or four mirror combination (e.g. a Three Mirror Anastigmat). In this case, care has to be taken to minimise the out-of-field straylight that might enter the spectrometer, so that an intermediate field stop might be required.

C. Gratings

Several grating concepts have been discussed for FLEX. One of the FIMAS concepts (Figure *7*) was based on an immersed grating. Such grating would be an enabling technology in case a spectral resolution of 0.1 nm would be needed. Since the spectral resolution for FLORIS has been set to 0.3 nm, it is not necessary to use such grating. Other gratings are more efficient and provide less polarisation sensitivity, such that this concept has been abandoned. Inspired from the achievement made for the GAIA grating, we have stimulated the investigation of the use of transmission gratings with binary or multi-binary index modulation [7]. A binary grating based on a quartz substrate and used for the spectral range between 600 nm and 780 nm provides an efficiency of more than 90%, as can be seen in the example in Figure *9* for a grating designed here for 31.5 degree of incidence, which is close to the Littrow configuration. This example for the grating has only been optimised for its aspect ratio. As can be seen, there is little polarisation sensitivity. The high efficiency of such gratings supports a high throughput of the instrument. Further optimisation is possible by optimising the ratio of bar and gap width and the depth of the groove.

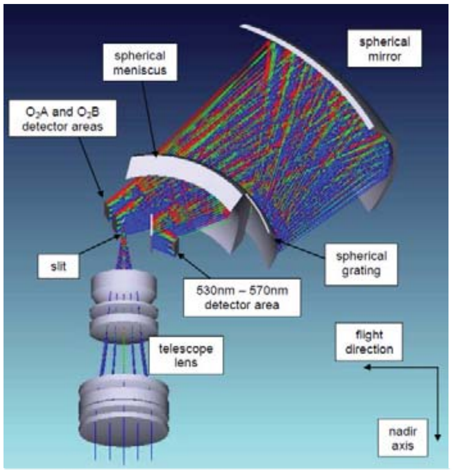


Figure 8 Combination of refractive (telescope) and catadioptric (spectrometer) concept of a hyper-spectral imager (FIMAS concept 2).

The grating for the WBS needs to provide less resolution and dispersion. The line density may therefore be much smaller than for the NBS. If the groove density is reduced, there will be several diffraction orders present in the diffracted beam. It is therefore necessary to find a configuration, where the higher orders will not disturb the signal obtained from the main diffraction order. It seems to be advisable to have also for the WBS grating a grating period which is about half of the grating period of the NBS grating. Reflective gratings are also suitable for FLORIS; the final grating configurations have not been fully frozen.

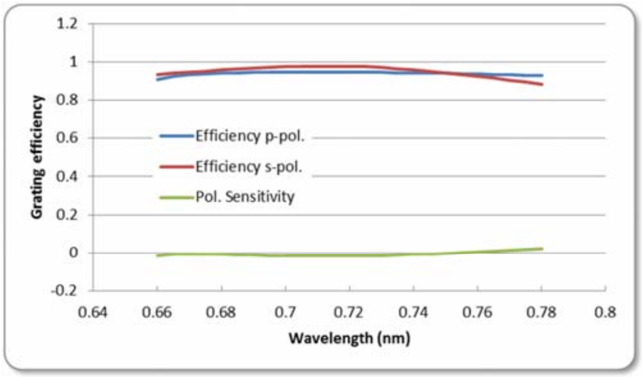


Figure 9 Example of the grating efficiency as calculated for a grating with binary index modulation and for a line density of 1500 lines/mm.

D. Detector configuration

Current instrument concepts foresee a slit width of about 80 µm. The spectrometer will image the slit 1-to-1 onto the detector, so that the pitch of one SSD corresponds also to about 80 µm. The dispersive direction or plate scale is adapted such that 80 µm correspond roughly to 0.3 nm. Since oversampling with an SSI of 0.1 nm is requested, the detector will need at least 3 pixels in the dispersive direction. A suitable detector pixel configuration would therefore be 80 µm x 80/3 µm. The across-track pixel size can be further reduced to make the pixel more squared. A detector area of $(80\ \mu m)^2$ will have to handle a charge of ~1.5 Me^- or somewhat higher. FLORIS needs a very high dynamic range for the detection chain, because the signal at the Oxygen-A absorption line at 761 nm is very low (~3% of the maximum). In order to achieve a SNR of 200 as required in this region, the dynamic range of the detection chain must be 77 dB at least. CMOS detectors are not suitable for FLORIS, because they do not offer enough sensitivity and the readout noise is too large to achieve the required dynamic range for the given pixel size. In the anticipated configurations, the detector architecture will demand state-of-the-art CCDs, but without any particular technology requirement. A pre-cursor CCD is the Sentinel-4 CCD for which the basic building blocks needed for FLORIS are currently under development.

E. Performance

Emphasis is put on the optimization of the signal to noise ratio and the relative spectral accuracy and cleanliness. This will require an accurate instrument configuration with low straylight levels and a calibration system to achieve high radiometric accuracies. FLORIS will measure Earth reflected spectral radiance at a relatively high spectral resolution of ~0.3 nm around the Oxygen absorption bands and sample those at a spectral sampling interval of 0.1 nm.

Other spectral areas with less pronounced absorption features will be measured at medium spectral resolution of about 2 to 3 nm and a spectral sampling interval of ~1 nm or less with the possibility to reduce the data rate by binning spectral bands, where spectral resolution is unimportant. The spectral response function is determined by the slit width, the detector pixel size and the point spread function of the optical beam. It has a nearly trapezoidal shape.

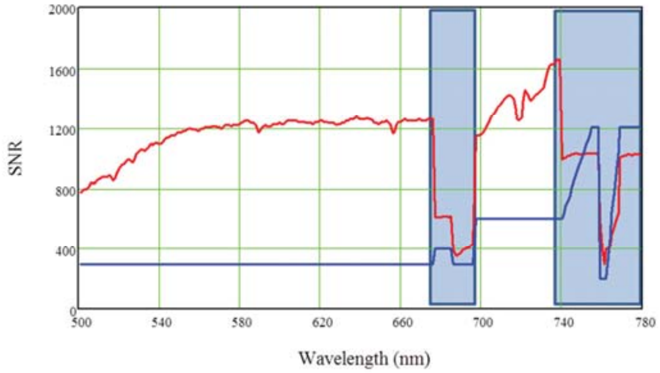


Figure 10 The signal-to-noise ratio of the WBS (red line) for the assumptions as given in the text. The blue areas are covered by the NBS and are not to be compared to the requirement (blue line).

The optical quality of FLORIS is driven by the integrated energy requirement. This requirement demands to integrate more than 70% of the total energy, which is emitted by 1 SSD along-track and received by the perfectly resolving instrument. For the optical quality, this means that the RMS spot size must be better than 10 µm. FLORIS will therefore have good imaging performance.

Radiometric performance depends on the throughput of the instrument. The major parameters for this are the number of lenses, the grating efficiency, the filter transmissions and the detector efficiency. CCD detectors can reach more than 95% quantum efficiency; the assumption of at least 80% of QE for the complete spectral range is therefore well justified for the NBS. Since the coating might not be fully optimised everywhere for the WBS, a more conservative value of 0.7 may be assumed. With a grating efficiency of more than 60%, a conservative assumption of 0.15 for the optics transmission leads to a SNR at given in Figure *10*. The SNR plot gives further an indication of the spectral resolution of the WBS, the spectral sampling is performed at 1nm here. The SNR of the NBS is shown in Figure *11* where the spectral sampling is performed at 0.1 nm. It can be seen that the current configuration is well compliant with the SNR requirement.

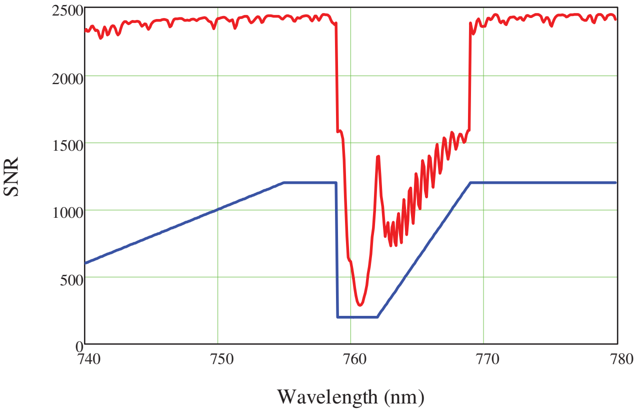


Figure 11 The signal-to-noise ratio of the NBS Oxygen A band (red line) for the assumptions as given in the text.

V. THE FLEX-SENTINEL-3 MISSION CONFIGURATION

FLORIS will provide imagery with about 300 m resolution on ground with a swath width of at least 105 km but with the clear aim to provide 150 km swath width. This will allow achieving a revisit time of at least one month for all places on the globe to monitor seasonal variations of the vegetation cycles, and more frequent visits in areas closer to the poles. The mission life time is expected to be at least 4 years. In order to ensure a good temporal co-registration, the FLEX satellite will fly in formation and in close proximity with Sentinel-3, so that only a few seconds of time difference exists for their observations of the same ground location. Sentinel-3 and FLEX will fly in formation in a Sun synchronous orbit at an altitude of about ~815 km. Sentinel-3 observations will complement FLEX observations in particular in the thermal infrared region for the temperature retrieval and will allow to perform cloud detection also using information from the infrared domain. An overview of the bands of the Sentinel-3 instruments OLCI and SLSTR are given in Figure 12. Further information on Sentinel 3 can be found in ref [8].

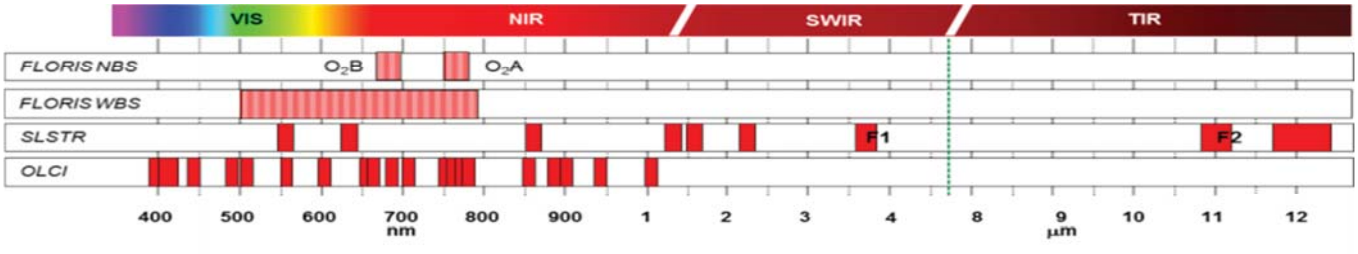


Figure 12 Comparison of FLORIS spectral ranges and the bands of the Sentinel-3 instruments.

The useful bands of Sentinel-3 are those outside the continuous spectral ranges covered by FLORIS itself. The OLCI bands O1 to O3 shall be used to complement the estimation of aerosol optical depth and height, but also to complement the fluorescence induced modulations of the vegetation reflectance. Overlapping bands in the range between 500 and 780 nm (OLCI O4 to O12) can be used for cross-calibration purposes and will therefore support the radiometric calibration of FLORIS. It will also allow an improvement of the co-registration of both observations. The OLCI bands above 780 nm will be useful for the retrieval of surface reflectance, in particular since no F_{Chl} contribution is expected above 800 nm. SLSTR channels will enable the retrieval of temperature distribution on ground and allow the detection of cirrus clouds and the aerosol content (Band S6). The dual view of SLSTR should contribute to derive an accurate aerosol characterisation. The details and the usefulness of the Sentinel-3 data products for FLEX and vice versa are still under investigation. Since FLEX data products will have superior spectral resolution, those could in principle also enhance Sentinel-3 data products by correcting the fluorescence contributions with good accuracy.

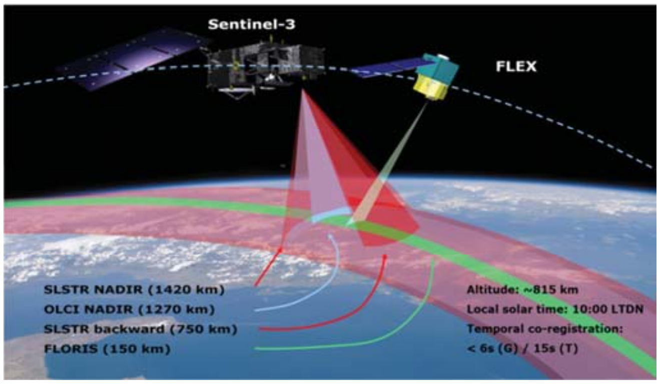


Figure 13 Artistic view of the FLEX – Sentinel 3 formation flying configuration.

Figure 13 gives an impression of the formation flying configuration. The distance between Sentinel-3 and FLEX will be about 100 km. The proximity will ensure that the temporal co-registration requirement is met. The orbit control and selection of FLEX will be done such, that the risk of collision is extremely small. The satellite needed for the accommodation of FLORIS is of medium size. The accommodation of FLORIS on a satellite as foreseen in one of the mission concepts is shown in Figure *14*.

VI. CRITICAL ELEMENTS AND PRE-DEVELOPMENTS

The performance assessment has shown that the FLORIS instrument concept is expected to be compliant with the requirements as reported. For our missions, we are following a policy, which demands the instrument components to be on a technical readiness level of 5, which means that the basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. For FLORIS, it is planned to build a breadboard of the optical module, which is reasonably representative to demonstrate the performance in the laboratory.

The most critical requirement currently is the straylight requirement. It is expected from the instrument that it can work also under the condition that clouds are present within the observed scene. In such case, the straylight generated by the presence of a cloud should not generate a signal which is of the same magnitude as the fluorescence signal. With other words, assuming half illumination of the scene, then the straylight shall be, if normalised to the cloud scene, less than 10^{-4} within the dark part of the scene. For the given instrument concepts, this requirement is demanding. It is therefore expected that the cleanliness of the optics has to be maintained at a high level. The demonstration of the ability to maintain the cleanliness during manufacture may be subject to the FLORIS breadboard activities.

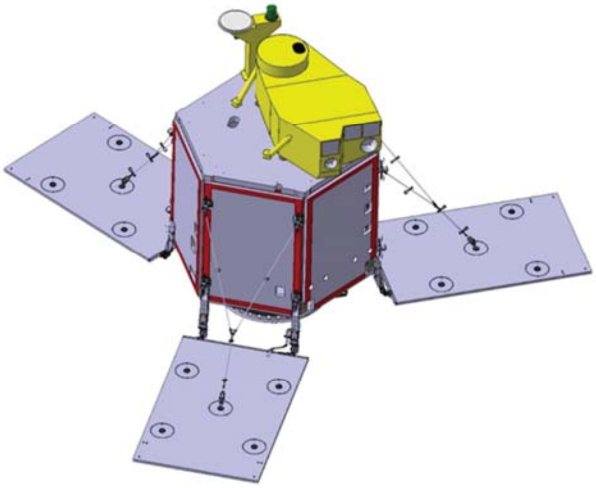


Figure 14 Example of the FLORIS satellite accommodation.

ACKNOWLEDGMENT

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