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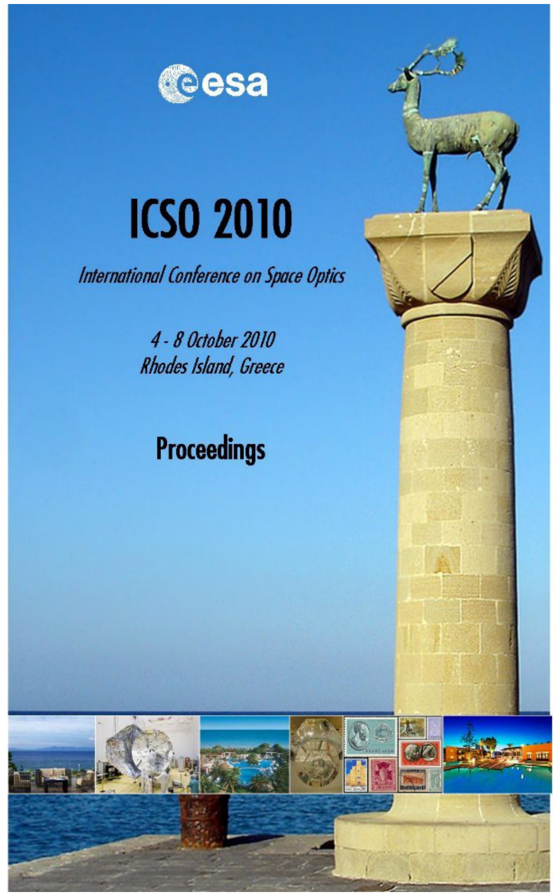

FIMAS: feasibility study of a fluorescence imaging spectrometer to be flown on a small platform in tandem with Sentinel 3

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FIMAS – FEASIBILITY STUDY OF A FLUORESCENCE IMAGING SPECTROMETER TO BE FLOWN ON A SMALL PLATFORM IN TANDEM WITH SENTINEL 3

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I. INTRODUCTION

Resulting from a call for ideas for the 7th Earth Explorer mission, the Fluorescence Explorer (FLEX) mission [1] was selected for assessment as one of the six Earth Explorer missions to be studied within Phase 0. After the review of the study outcome by the Earth Science Advisory Committee (ESAC), FLEX was not selected for Phase A study. Although not selected, ESAC has expressed a clear recommendation to make an in-orbit demonstration of the measurement of vegetation fluorescence from space. Since FLEX involved four different instruments that would be required by an autonomous satellite to measure the chlorophyll fluorescence signal and to make the necessary atmospheric corrections, a new strategy has been proposed, which should make use of existing missions. The aim of this feasibility study is to identify a suitable instrument concept that is compatible with the expected resource limitations.

II. STUDY OBJECTIVES

A. Instrument objective – measuring fluorescence

Detecting fluorescence from space is a difficult undertaking since the signal as part of the top of the atmosphere radiance L_{TOA} is faint and hidden in diffuse and directly reflected flux $E_{dir/diff}$ of Sun radiance impinging on the Earth L_0 and then being reflected on the Earth and transmitted through the atmosphere [2].

$$L_{TOA} = L_0 + \frac{\left[\frac{(E_{dir}\cdot\cos(\vartheta_{ill}) + E_{diff})\cdot R_{Earth}}{\pi} + \cos(\vartheta_{view})F_{fluor}\right]\cdot T_{atmosphere}}{1 - Albedo_{spherical}\cdot R_{Earth}} \quad (1)$$

Whereas the total radiance contribution is typically 120 mW/(sr m^2 nm), the fluorescence signal contributes only less than 10% of it. The fluorescence signal is extracted by measuring changes taking place within the spectral ranges of the Oxygen A and Oxygen B bands and by applying a retrieval algorithm, which was recently further developed. The retrieval algorithm is using a fitting method that is making use of the complete information content. Compared to a conventional fluorescence line detection method, this method is extracting the fluorescence from the spectral information provided by a larger spectral range, in which the fluorescence signal is contributing and in which information about the surface properties allows efficient modelling. The spectral resolution which is required for the different regions varies over the full spectral range. This means that the instrument must deliver variable spectral resolution data and must provide high resolution only there, where it is essential. Our present best knowledge of the required SSI is presented in Figure 1 in form of threshold and goal SSI values together with the typical radiance level. An optimisation of the configuration to enhance the scientific content, to minimise the data rate and the complexity of the instrument is expected in future.

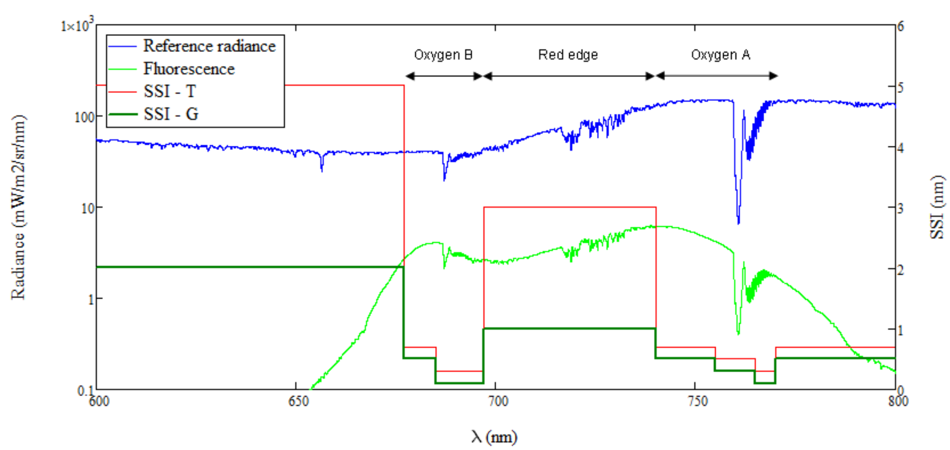

Figure 1 The plot shows the typical radiance received by the instrument, the contribution of the fluorescence signal (note the log-scale) and the requirement on the spectral sampling interval (SSI).

B. Definition of instrument configuration

Measuring the signal within the Oxygen A and B bands is not sufficient. Surface pressure, surface temperature, atmospheric aerosols and reflectance changes which enter equation (1) are essential variables which will alter the received signal and if these parameters are not properly modelled, large errors for the fluorescence contributions will occur. The FLEX mission configuration consisted therefore of an instrument suite composed of five instruments, namely the Fluorescence Imaging Spectrometer (FIS) dedicated to Oxygen A and B bands, two instrument to measure the visible and the SWIR spectral features and cloud masking, plus a thermal IR radiometer to determine temperature, and an instrument to measure the aerosol content.

Almost all of this information becomes, although in a different configuration, available from the measurements that are planned with Sentinel-3. The optimisation of the configuration and the expected scientific retrieval is subject to further investigation, but will not be further discussed here. The mission would be realised by using data and products from Sentinel-3, which would be flying in tandem with a smaller satellite carrying a Fluorescence Imaging Spectrometer (FIMAS). We have implemented a currently running parallel study with the aim to show the feasibility of FIMAS that could be realised as in-orbit demonstrator or possibly as a mission with reduced resource budget such as the coming Explorer 8 opportunity mission. In the frame of such a mission, it is expected that an affordable small platform will offer only limited resources for the instrument. For this reason, it is required to reduce the resources considerably compared to previous findings from the FLEX mission assessment, which indicated a mass of about 120 kg excluding system margin for FIS.

Without exact knowledge of the expected mass, volume and power resources being expected for a small satellite mission, at the beginning of the work definition we have estimated the target mass to be 55kg and the power target to be 40W, since this seemed to be an upper limit for being implemented on a PROBA-II class of satellite. A summary of the most important instrument requirements, which were originating from the FLEX mission assessment (Phase 0) and refined for FIMAS, is given in Table 1.

Table 1 Summary of the FIMAS instrument specifications.

Parameter	*Threshold value*	*Goal value*	*Notes*
Scene radiances	See Figure 1		Maximum, minimum and typical radiances are considered.
Platform altitude	815 km		Imposed by Sentinel-3
Spectral ranges	2 x 20 nm bands	27 nm + 54 nm	wider ranges are desirable - see Figure 1
Spectral sampling interval (SSI)	0.3 nm	0.1 nm	See also Figure 1
Swath width	>100 km		150 km desirable
Spatial sampling distance (SSD)	1000 m	300 m	500m breakthrough Comparable to Sentinel-3 products
Dwell time	151.5 ms	45.5 ms	without slew mode
Slew mode	Platform pitch may increase dwell period by a factor up to 2		
Signal to noise ratio at reference radiance	See Figure 1 and Figure 4		> 200, at 2nm SSI, for wider spectral ranges
Temporal registration	15 s	2 s	6s breakthrough
Out-of-band signal in any channel	<2%	<1%	with respect to spectral average
Polarisation sensitivity	<2%	<1%	
Radiometric accuracy including stray light errors			
Absolute	<5%	<2%	
Relative spatial	<2%	<1%	
Relative spectral	<2%	<1%	
Stray light: dark to bright separation	±20 SSD	±10 SSD	For a given reference pattern
Instrument resources			
Mass	<80kg	<55kg	Mass range for IOD or EE8
Power	< 40W		
Envelope	25 cm x 50cm x 50cm	50 cm x 60cm x 60cm	Volume range for IOD or EE8

C. Tandem configuration

What remains unchanged is the fact that the measurement is only possible if the instrument provides sufficient sensitivity by yielding a high signal to noise ratio. After the FLEX Phase 0 assessment study, we have stimulated a scientific study which had the objective to analyse a suitable configuration with adequate but possibly relaxed requirements that would result in a demonstration of the measurement of fluorescence from space. Flying in tandem with Sentinel-3 did not particularly improve the instrument sensitivity, since the orbit had to be changed from an altitude of 650 km to 815 km. The photon limited signal noise scales inversely with the satellite altitude, so that this approach started up with a handicap (factor of 1.25 for the SNR). However, as an outcome of this investigation we found that the following adaptations to the mission objectives or instrument requirements would be effective to arrive at a suitable mission configuration:

1. Reduction of the swath with from 390 km to > 100 km (which is equivalent to discarding the requirement to achieve full coverage within 10 days)
2. Reduction of spectral resolution from 0.1 nm down to 0.3 nm
3. Achieving higher SNR by a satellite slewing manoeuvre
4. Acceptance of a larger SSD up to 1km

The study had further the objective to find the most suitable instrument configuration and concept that would result in the least resource demanding instrument configuration. It was requested to analyse at least four instrument concepts which where Grating Spectrometer (GS), Fabry Perot (FP) Spectrometer, Linear Variable Filter (LVF) Spectrometer and Fourier Transform Spectrometer (FTS).

The study was open to other instrument concepts or certain concept variations, but no other concept was suggested by the two industrial consortia (SSTL and EADS Astrium). As another outcome of the scientific support studies, it was found that it is useful to provide further information in spectral bands that cover the full range from 530 nm to 800 nm. This side aspect was found to be very beneficial for the retrieval algorithm. In exchange for this requirement, it was found that spectral resolution can be reduced in large spectral regions, and must be high only within a small spectral range within the vicinity above the main absorption lines. The template illustrating this requirement was given in Figure 1.

III. OUTLINE OF DIFFERENT INSTRUMENT CONCEPTS

In this chapter, we are describing directly the investigated instrument concepts and the advantages and disadvantages in general and particularly for the FLEX mission. Due to the limited space within this paper, the results are directly given without a detailed description of the analysis. Also, due to some confidentiality aspects, not all results could be shown since the study is still ongoing.

A. Dispersive Imaging Spectrometer

A dispersive imaging spectrometer of type grating spectrometer provides sufficient resolution down to 0.1 nm, although 0.1nm is considerably more demanding than 0.3 nm. Already the FLEX FIS concept was based on a grating spectrometer. In order not to end up with a similarly high volume and mass configuration, it was clear that the spectrometer must be extremely compact. The essential simplification here comes from the fact that a smaller field of view allows the optics to remain relatively simple and the spectrometer optics compact. Grating spectrometers operated in Littrow configuration in general yield relatively high grating efficiency and good dispersion properties. The Littrow configuration was therefore found to be a good candidate for FIMAS. A possible draw-back is its relatively high susceptibility to stray light generation, since the beam passes twice through the optical element without any possibility of shielding. Due to the relatively high resolution of the spectrometer, the grating needs

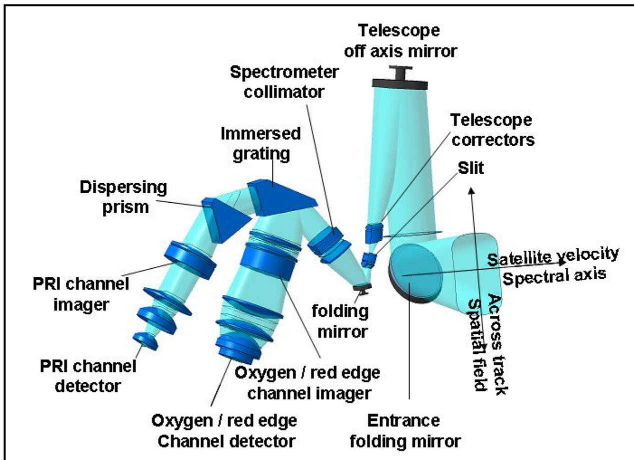

Figure 2 Dispersive grating imaging spectrometer concept. For description, see text.

to be large. Reduction of the grating size can be achieved by employing the concept of immersed gratings – see e.g. [3]. Such gratings provide higher resolution scaling with the index of refraction (compared to air) in which the grating is embedded. In case the grating spectrometer is not used in Littrow configuration, it is possible to use the 0^{th} order to enhance the spectral coverage. Such a configuration is shown in Figure 2.

A folding mirror followed by a off-axis telescope image the swath of about 100 km x 300 m onto a slit, the beam is then expanded and collimated onto the immersed grating. The angles are chosen such that the 1st order is used for the Oxygen B and A bands including the region in between (red edge), and the 0th order is used for the Photochemical Reflectance Index (PRI) channels at 531 nm and the remaining spectral range up to 760 nm. Reimaging is then performed by two lens systems onto two detectors. This configuration seems to provide an excellent match of the intended measurement.

B. Fabry Perot Spectrometer

The FP Imaging Spectrometer has been identified already during the Phase 0 of the FLEX mission as potential spectrometer concept hat could reduce the required resources. The principle uses one or several FP etalons, which consist each of a pair of mirrors for which the transmission or reflectivity is adapted such that light is transmitted effectively in interference mode in which light around wavelengths equal to the thickness of the mirror substrate interferes such that it is transmitted with high efficiency. Unfortunately, if the width of the main transmission line becomes small, then also the distance to the lines of the next neighbor lines is getting smaller, so that the free useful spectral range starts to become limited. To overcome the problem another etalon with a slightly different period can be used to suppress adjacent transmission lines and to enhance the useful spectral range. In the case of FIMAS, the required out of band transmission is so high that even three etalons need to be used. The location of the transmission line depends on the incidence angle. This dependency can be employed to design an imaging spectrometer since different points on ground impinge at different angles and represent different wavelengths. For a FP Spectrometer with etalons that are not tilted with respect to the observed scene, the positions at constant wavelengths are described by concentric rings. If the etalons are tilted, then the radius of curvature becomes larger and close to straight lines as presented in Figure 3.

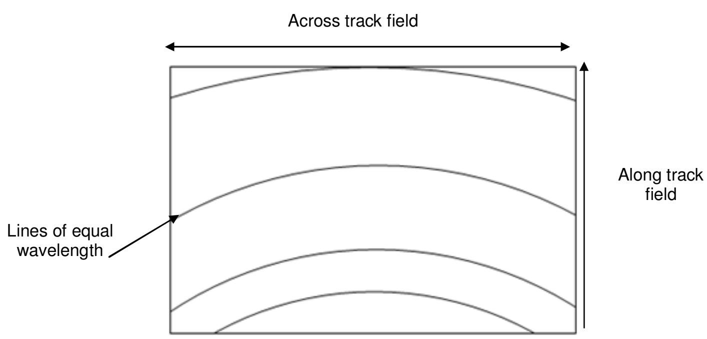

Figure 3 Demonstration of the circle sections corresponding to the transmission of equal wavelengths.

In the case of FIMAS, an angle of about 20 to 30 degree offers a configuration with sufficiently straight lines, so that the pushbroom concept can be applied. Clear disadvantage of this concept is the limited temporal co-registration.

C. Linear Variable Filter Spectrometer

The LVF Spectrometer concept is based on interference filter concepts in which the thickness of the interference filter changes in the direction corresponding to the along track direction. Ideally the filter is placed in the focal plane in front of the detector. Since the resolution for FIMAS is very high for such a filter concept, it is required to limit the incidence angles on the filter to a few degrees. For FIMAS it means that the effective f-number must be more than 10. The resulting filter needs to have a size of about 10x10 cm. It seems therefore impractical to put the filter onto the focal plane. Instead the filter would have to be placed in a virtual image plane. This measure unfortunately takes away the large benefit of having a small and compact instrument, so that the LVF Spectrometer looses out its main advantage. Also the filter fabrication is expected to be challenging.

Otherwise, the LVF concepts is comparable to the FP concept since the wavelengths are acquired successively, which means that also here the temporal co-registration time of the instrument would be relatively large. The spectrometer concept remains relatively simple but not small.

D. Fourier Transform Spectrometer

The Fourier Transform Spectrometer (FTS) concept was suggested upon the stimulation given in paper [4]. Several FTS concepts were investigated amongst which static and dynamic concepts. It was found that although the FTS concepts can in principle compete with the other dispersive spectrometers, it is expected that the complexity of such an instrument would be much higher, since the FTS needs an accurate and fast metrology system, it has to read a full detector array at very high speed and to pre-process the data to be sent to ground. The main disadvantage comes from the fact that the cumulated noise from the complete spectrum makes the performance in the vicinity of the absorption line unfavorable.

IV. SUMMARY OF PRELIMINARY STUDY RESULTS

The result of the trade-offs and the most important instrument properties are shown in Table 2. It was concluded that all instrument concepts are within or close to the target requirements with respect to the resources. The grating spectrometer seems to have the best properties since it provides good spectral and imaging performances, has no temporal misregistration and good sensitivity. If the instrument resources can be confirmed, it is likely that the concept selection (not yet completed for both industrial teams) will favour the grating spectrometer.

Table 2 Comparison of the essential properties of the different instrument concepts.

Spectrometer concept	*Grating*	*Fabry Perot*	*Linear Variable Filter*	*Fourier Transform*
Spectral resolution	0.1 nm	<0.1 nm	0.3 nm (at best)	0.1 nm or less
Spatial resolution	300 m	300 m or less	300 m	300 m
Spectral range	660 nm – 770 nm @ 0.3 nm possible	Limited to ~20 nm	660 nm – 770 nm (limited by size of detector array)	Theoretically large – practically small (due to noise increase)
Instrument mass	Compatible	Compatible	Compatible	Compatible
Instrument power	Compatible	Compatible	Compatible	Possibly incompatible
Radiometric performance (at same mass)	Good	Acceptable	Acceptable	Likely insufficient
Temporal co-registration	-	4 to 10 s	~5s Oxygen A ~10s Oxygen B	Up to 15s (stare time)
Out of band rejection efficiency	Very good	Good, but blocking filters required	Good, but blocking filters required	Requires apodisation
Complexity	High	Medium	Low	Very high

Apart from the spectral and the imaging performance, the signal to noise ratio (SNR) of the instrument is the most important feature. For the study we have defined a template for the SNR which was derived from the scientific support study. The template and the calculated instrument performances are shown in Figure 4. The presented performance assumes a slew down manoeuvre of the satellite such that the measurement dwell time is increase by a factor of two. Otherwise, the SNR is worse by about a factor √2. We note that improvement of SNR performance can also be achieved by increasing the SSD and that the presented performance is calculated for the goal SSD of 300m. With this configuration the SNR stays above the threshold value of the template and comes close to the goal values. Such performance is expected to be sufficient for the FLEX /Sentinel-3 tandem mission configuration.

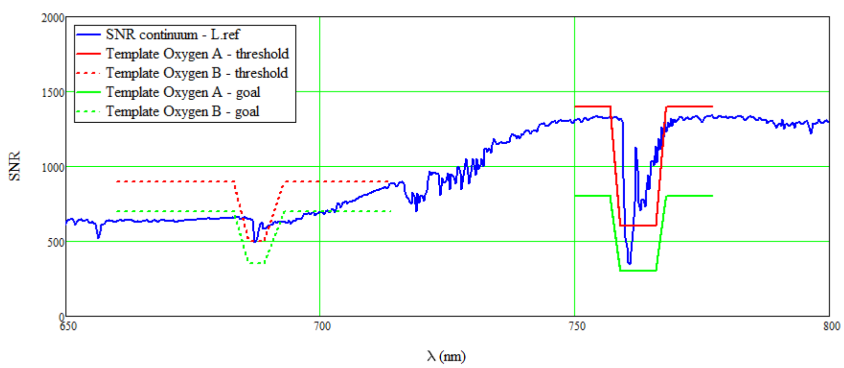

Figure 4 Calculated signal to noise ratio (SNR) for FIMAS with the assumptions: Dwell time 91 ms (slew down factor = 2), aperture size of 80 mm, SSD 300m and an instrument transmission of 0.2.

C. Instrument and satellite configuration

All instrument concepts have been analysed with respect to their accommodation and expected resources. All concepts are more or less compatible with the targets that where set out. We show the example of FIMAS being implemented as grating spectrometer. The left part of Figure 5 indicates an important aspect of FIMAS. Since the instrument will rely on observational data provided by Sentinel-3, it will be difficult to perform the calibration by using calibrated Sentinel-3 data as those will not be observed at the same high resolution as with FIMAS. FIMAS will therefore have to rely on its own calibration. Therefore FIMAS will be equipped with a calibration device such as for example a diffuser, which can be flipped into the optical path.

FIMAS can be accommodated on a small satellite platform such as the CNES MYRIADE or the SSTL Bus 150 platform. Such a configuration should fit the cost constraints such as given by the Earth Explorer Opportunity mission. It is planned to assess the instrument performance for a configuration that would fit an even smaller platform such as PROBA-II by scaling the instrument mass and performance according to well established scaling laws.

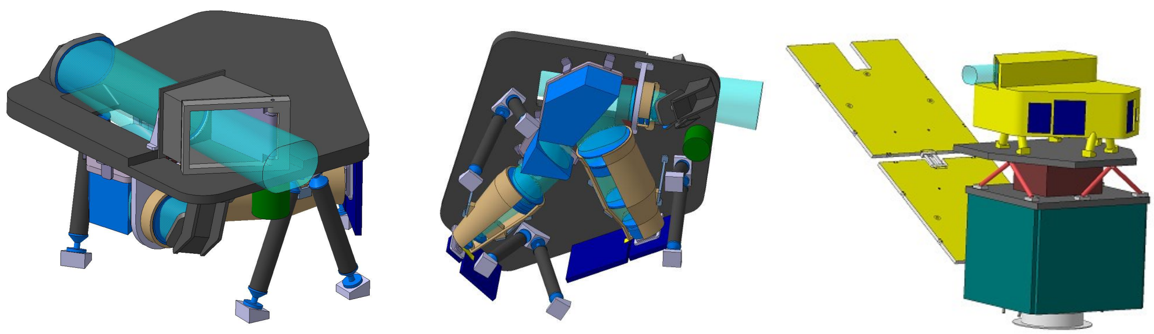

Figure 5 Example of FIMAS instrument configuration as seen from the top (left) and from the bottom (right). The optical concept from Figure 2 is easily recognized although the beam is folded here in order to keep the instrument within an acceptable volume. The most-right figure shows a possible accommodation of FIMAS on a MYRIADE platform.

V. CONCLUSION AND OUTLOOK

The study has identified and analysed suitable instrument concepts and will further investigate the feasibility of the most promising concept at the requested resource allocation compromising at the same time as little as possible the scientific objectives and the instrument requirements. After the Instrument Concept Selection Review, we will mature the instrument configuration, optimise the most important instrument parameters and design the instrument to level, where we become highly confident in the estimation of the required resources.

Acknowledgement

The material which was presented within this overview and status of the FIMAS feasibility study was generated largely by EADS Astrium, Toulouse, France and SSTL, Oakridge, UK. We would like to acknowledge the work of the two study teams and their optical lead engineers Dominique Dubet and Dan Lobb. We would like to thank further José Moreno from the University of Valencia for the many fruitful discussions on the scientific objectives, which lead to a consolidation of the instrument requirements. The provision of the data on the expected radiances and the individual contributions were kindly provided by Luis Guanter, who is closely working together with José Moreno on the subject.

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