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A 100 M GROUND RESOLUTION GLOBAL DAILY COVERAGE EARTH OBSERVATION MISSION

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I. INTRODUCTION

PROBA-V has been successfully launched on 7th May 2013 and is providing a global monitoring in the continuity of the SPOT-VEGETATION mission. The progress in terms of ground resolution between Spot VGT and PROBA-V is a factor 3 (1 km to 1/3 km ground resolution product). The User Community requirements for the next generation of global monitoring are a 100 m ground resolution product. This means an additional factor 3 improvement, but in a short time frame (5 years). After success of the PROBA-V mission, the Belgian Science Policy (BELSPO) initiates a PROBA-V Successor feasibility study. This study was undertaken by VITO and CSL to identify potential tracks to achieve a follow-on mission which is expected to be relevant for the User Community. The mission analyses for each of these tracks was evaluated. Today the PROBA-V mission lifetime is expected to expire by mid of 2018. Since the interest for global land monitoring is expected to continue in the future, this study proposes mission requirements and a shortlist of optimal mission scenarios for a follow-on mission in this short time frame. The goal of such a new PROBA-V mission is clear: it should ensure the data continuity of global vegetation monitoring, while taking the opportunity to further improve the data quality. Data continuity is essential for understanding long term trends of land use that may affect the global equilibrium of the planet (in the context of scarcity for land or food, natural disasters, climate change). As for added value, a fine example is the improvement of spatial resolution when comparing PROBA-V with the spatial resolution in SPOT-VEGETATION products. An improvement in spatial resolution towards a full 100m product is considered by the user community as the main target for a PROBA-V follow-on mission.

On the optical point of view, TMA (Tree Mirrors Anastigmat) have already been used successfully in several space missions. In the case of PROBA-V for example, three TMA, with individual field of view of 34°, are used in a fan-like configuration to cover a total 102° field of view. On a sun-synchronous orbit at 820 km from earth, it provides daily images of the earth with resolution of 100 meters at the center of the FOV (Field Of View), 350 meters at the edge.

Increasing the resolution requires to increase the instrument size, thus increasing the optical aberrations. This would result in a decrease of image quality, especially at the edge of the individual instruments field of view. More than 3 TMA with a smaller individual field would thus be required. In order to minimize the total number of instruments, FMA could be used as they provide good image quality over higher FOV than TMA.

The decision on such a mission has to be made against several constraints, including financial constraints. To put such considerations in a coherent frame, a set of mission scenarios has been defined showing how different choices tend to affect mission performance and innovation, but also potential risk and complexity of the mission. Also, some mention is made of mission heritage, and already existing technological assets and facilities. A set of mission scenarios has been defined showing how different choices tend to affect mission performance and innovation, but also potential risk and complexity of the mission. One main assumption used in the evaluations is to achieve 100 m resolution on ground. Single payloads as well as satellite constellation mission were proposed.

II. MISSION COMPARISON

PROBA-V is a mission with a daily global coverage on most part of the world, and a full global coverage every 2 days. It is useful to compare the future PROBA-V mission with other missions able to monitor land cover, in terms of coverage frequency and spatial resolution. Targeting a spatial resolution of 100m, a PROBA-V successor mission would already be in a niche between two categories of missions.

As seen in **Fig 1**, in the top-left are missions with a higher spatial resolution, but a coverage frequency of several days, the most interesting being Sentinel-2 and Landsat-8. Landsat-8 is operational as of 2013, while the Sentinel-2 constellation is targeting launch in 2015.

A mission such as PROBA-V successor could offer support for these missions, using the method of time series data fusion. The near-daily coverage of PROBA-V successor could be used to fill the 'time gap' between observations of the higher-resolution mission, which would allow the more high resolution data to be more relevant. This data fusion concept is not a new idea and has already been used between SPOT-VGT and HRVIR [1] and Landsat and Modis [2]. In particular, SPOT-VEGETATION and SPOT-HRVIR data fusion notes severe issues when the 'spatial resolution gap' is large, such as the factor of 100 between (1km compared to 10m). This gap can now be reduced to a factor 3 between Landsat 8 and PROBA-V, indicating that a more comfortable opportunity presents itself.

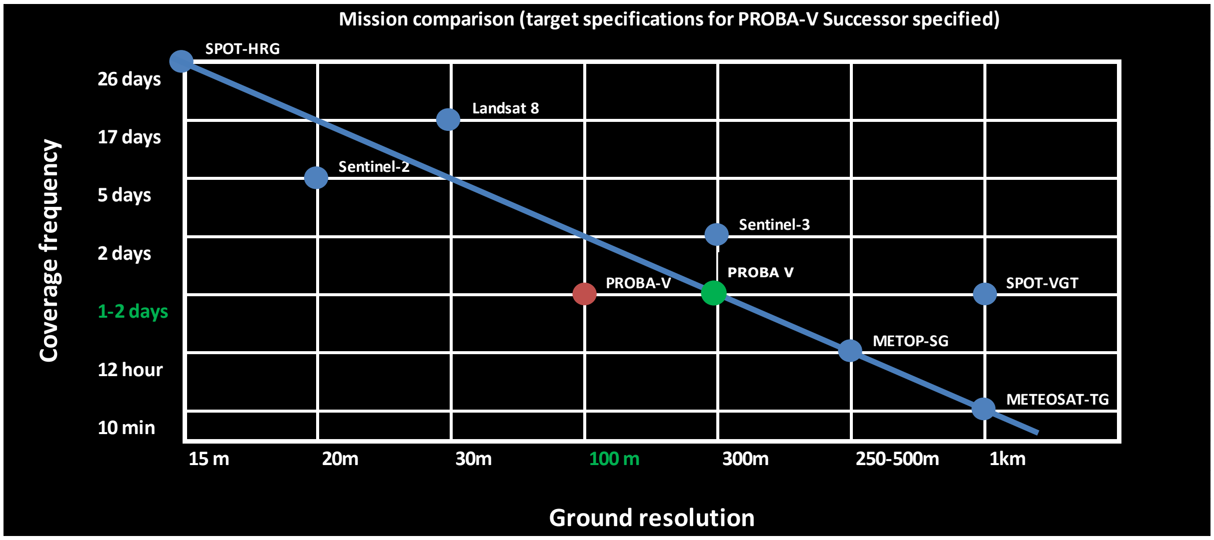

Fig 1: Comparison of coverage frequency and spatial resolution

In the bottom-right are missions with a lower spatial resolution, but a faster-than-daily coverage frequency. The polar-orbiting METOP-SG is targeted for 2020, while the geostationary Meteosat-TG is targeted for 2018. Data fusion could again be considered here. It should be noted that the spatial resolution gap, with a factor of 10 in this case, might be less of an issue for land cover monitoring when looking at lower resolutions. Many land cover features are within the order of 300m or less. The difference between 300m and 100m is therefore expected to be of more impact than the difference between 1km and 0.33km, at least for land cover monitoring. Thus, time series data fusion between 100m and a 1km mission like Meteosat-TG can still be useful.

Finally, the two-satellite Sentinel-3 constellation can be considered as a mission with similar resolution and coverage frequency as aimed for PROBA-V. Indeed, Sentinel-3 has been proposed as a means to achieve data continuity for the VEGETATION time series. While both missions can serve this purpose, it's meaningful to see them as complementary:

- PROBA-V successor will be dedicated to global land monitoring. As such, its focus is to improve spatial resolution and coverage frequency, if possible to 100m daily products.
- Sentinel-3, like MERIS, will support land applications but is principally designed for atmospheric and ocean monitoring. Thus, its focus is to have improved radiometric discrimination and atmospheric detection, albeit with slightly lower resolution and coverage frequency.

In summary, PROBA-V successor will discriminate more precise features and is a dedicated land mission on a smaller scale, while Sentinel-3 will discriminate features with better accuracy and supports a large scope of applications.

III. MISSION REQUIREMENTS CONTEXT

The high level requirements are the one of the current PROBA-V mission (i.e: altitude of 820km, FOV of 102.4° and LTDN of 10:45) plus:

- a Ground Sampling Interval (GSI) of 100 m.
- Deorbiting. PROBA-V is not equipped with a propulsion system. While one scenario examined the option of launching at a lower altitude to allow for deorbiting without propulsion, this scenario has been found incompatible with the requirement for long-term data continuity. Thus, propulsion must be fitted in the PROBA-V successor platform or platforms.
- Short roadmap. The time to completion for the PROBA-V successor mission is less than five years. For this reason, each scenario needs to be evaluated in terms of design complexity and PROBA-V mission heritage.

The scenarios focused on the 100 m GSI requirement.
The propulsion issue is a spacecraft problem that's already addressed in the next PROBA spacecraft.
The short roadmap is tackled with the following timeline:

- First (in 2014), to have PROBA-V operational, with 1km as mandatory product and 1/3km as goal product.
- Next (in 2017-2018 end of life of PROBA-V), to launch a new mission like PROBA-V, but with 1/3km as mandatory product and 100m as a goal product.
- Lastly (beyond 2020), to have 100m as a mandatory product, fully operational. The vision beyond 2020 has been stressed as a major focus for the user community.

As has been done for the transfer between SPOT-VEGETATION and PROBA-V, a time of overlap must be present between each of these mission steps, to be sure that data can be cross-checked for consistency between the respective instruments.

IV. MISSION SCENARIOS

To meet the goals outlined here above, it must be recognized that PROBA-V is already capable of delivering 100m raw data for a part of the covered area, although this data is reduced to 1/3km quality by lossy compression to cope with data rate limitations. Thus, to meet this spatial resolution for the full coverage, there are three ways to improve:

- Improve the current payload, such that for the full swath 100m is achieved
- Keep the payload's central camera (or all) and launch multiple satellites, such that 100m is achieved for the full coverage by having a sufficient coverage with a constellation of satellites.
- A combination of both.

The scenarios considered here focus on technologies which are largely based on proven concepts from previous PROBA projects. Two families of scenarios are proposed: one satellite configurations and constellation configurations (Fig 2).

Scenario 1 consists in 5 identical TMA with a FOV of 20.4°. They are used to cover the full swath with a resolution of 100m at the edge of the field of view (VNIR). To achieve the target of 100 m, the GSI at center of the FOV has to be 27m.The required focal length is 385 mm and pupil diameter 55.5 mm, basically three times larger than PROBA-V since the required resolution is a factor 3.

Scenario 2 consists in 2 identical FMA with a FOV of 51°. The ground sampling distance is also 27m at center of FOV, 100m at edge of FOV, thus the focal length and pupil diameter are the same as scenario 1.

In the two preceding scenarios (1 and 2), the central camera has the same focal length as the edge cameras. Thus, the ground sampling distance is smaller at center of FOV compared to the edge. Because the requirement specifies a GSI target of 100m overall the swath, the central camera could be replaced by a camera with a smaller focal length. In that case the central camera could be chosen as the same as the one of PROBA-V. That camera has 100m GSI at center of FOV and 110m at edge.
Using such a central camera presents numerous advantages; firstly, the central camera is smaller and lighter. Secondly, the detector of central camera needs fewer pixels and no binning. Consequently the amount of data becomes smaller and impacts directly the downlinking.
For the edge cameras, two situations are considered. A first case where the cameras are TMA, while in the second case the cameras are FMA (only the second case is presented in Fig **2**). In both case, 34° FOV have to be covered on both side. The focal length and pupil size are the same as for scenario 1 and 2.
Scenario 4 consists in the use of 2 FMA in a Time shift satellites mode: 3 satellites, each contains a FMA with an individual FOV of 51°, Nadir oriented. In order to get a 100m product pixel at edge of FOV (VNIR), the FMA focal length must be 135 mm and pupil diameter 19.4 mm.
Scenario 5 consists in a constellation of 5 or less satellites. Each contains TMA cameras with an individual FOV of 34°, Nadir oriented. The focal length and pupil diameter of the TMA are the same as in PROBA-V.
The last scenario assumes again the focal length of 110mm. The same exercise is carried out to derive the edge spatial resolution but for the lower altitude of 570 km. It is demonstrated that three satellites with two cameras are needed to obtain an 100m product, but two satellites are enough to achieve a sufficient quality. In terms of spatial resolution, this scenario is therefore acceptable. However, the issue here is to keep the satellites in phase during the whole lifetime of the mission, which seems unlikely.

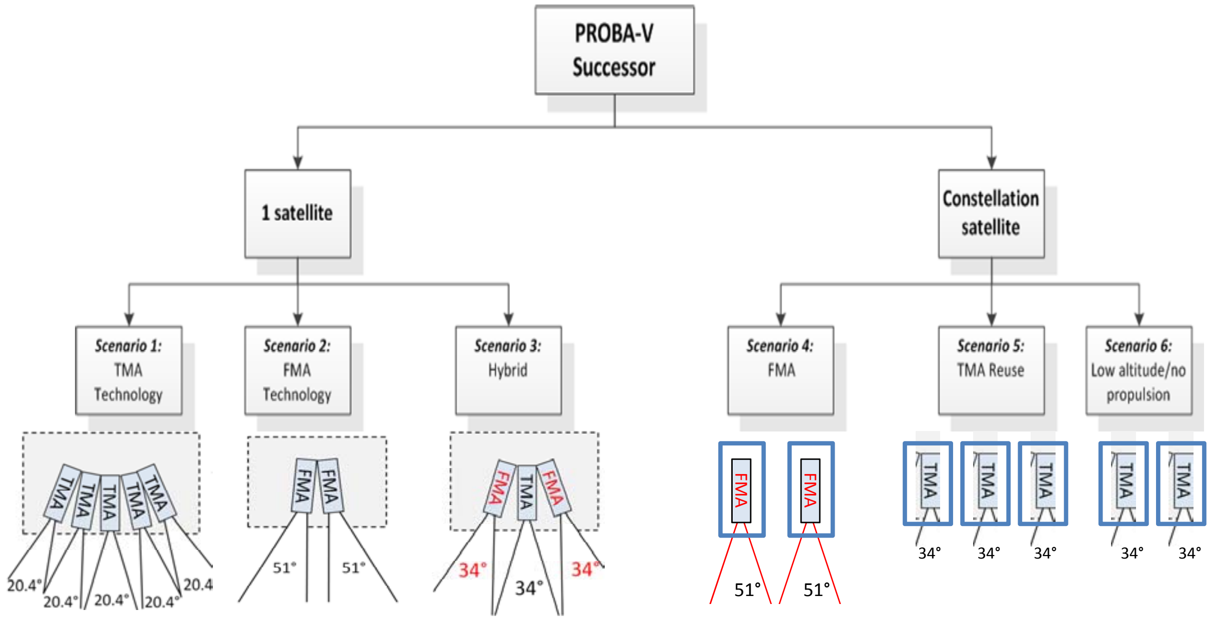

Fig 2: Considered scenario configurations for PROBA-V Successor

In the case of a **single satellite** (scenarios 1-3), achieving 100m implies to improve the payload of PROBA-V. However, all improvements are based on reflective mirror optics, and thus allow to take advantage of the Single Point Diamond Turning (SPDT) manufacturing technology used in PROBA-V. Aside from the known camera concept of three-mirror anastigmats (TMA), a new concept of four-mirror anastigmats (FMA) is introduced. FMA cameras allow to have a larger Field-of-View (FOV) per camera [3]. By improving both FOV and focal length, the spatial resolution of the satellite can be improved. The pupil size of the cameras is scaled together with the focal length.

In the case of a **constellation**, multiple satellites are used together to achieve the full coverage of the mission. This effectively reduces the coverage required for each separate satellite. A reduced coverage can be traded for an improvement in spatial resolution, and can be achieved in three ways:

- Changing the payload to have a higher focal length (scenario 4)
- Keeping the payload but for a smaller Field-of-View per satellite (scenario 5)
- Lowering the altitude of the satellite (scenario 6)

V. MISSION SCENARIOS ANALYSIS

In all the considered scenarios, the main instrument change proposed is in the camera design or configuration. We start from the FOV specifications of each platform scenario and, using the specification of focal length and pupil size, derive suitable optical designs in terms of FOV and spatial resolution. Also the mass budget, volume budget and the distortions for the optical designs are derived. Scenario 1-4 consider payload changes where the focal length of the optics is increased. The scenario 5 and 6 make use of the same optical design as in PROBA-V

Further analyses are carried out on the impact of the optical design on SNR and also data rate. This includes specifications for a.o. the amount of detectors to be used, taking the PROBA-V detector design as a baseline.

VI. FOCAL PLANE CONFIGURATION

As much as possible, the objective is to reuse the data handling chain of PROBA-V. That means to reuse the detector itself but also the Read Out Electronics (ROE) and the Mass memories (MMM) specifically developed in the PROBA-V program. However, because of the pixel number increase due to GSI decrease, the focal plane has also to be slightly redesigned.

When considering a camera with a larger focal length than PROBA-V, the magnification is also larger. Consequently, to record the same spatial field, the linear arrays must be longer. On the other hand, if the detector is the same as PROBA-V, the spectral field can be reduced (see Fig 3). As the recorded spectral field range is smaller, the scene is recorded on each array detector with a smaller time shift.

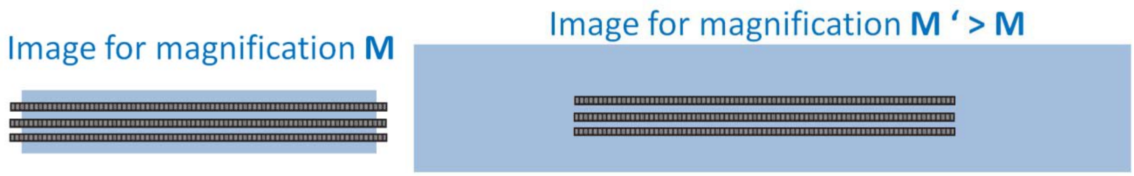

Fig 3 – (a) Image of the same scene for a magnification M (b) image for a magnification M'>M. Three array detectors are represented.

To fit with the specification a longer PROBA-V like detector has to be redesigned, as illustrated on Fig 4.a. However one of the goals of the present study is to reuse the same detector as PROBA-V. The idea is thus to use several such detector and align them next to each other. Because of the detectors mounts, a part of the spatial field would then be lost as Fig 4.b illustrates. The best option is thus to align the detector with a shift along the spectral field direction (see Fig 4.c), the dead zone are then avoided. Because the magnification is sufficiently large compared to PROBA-V, the spectral field doesn't need to be increased.

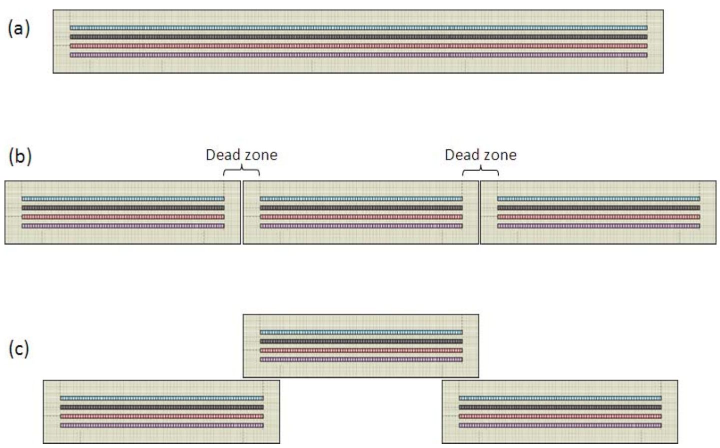

Fig 4 - (a) PROBA-V detector redesigned with a larger length. **(b)** PROBA-V detectors aligned next to each other. **(c)** PROBA-V detectors aligned with a shift along spectral field direction.

With PROBA-V optical specifications, a spectral field range of [-1°, +1°] gives an image height along spectral field direction of 3.6 mm. In most of the presented scenarios, the image is up-scaled by a factor 3.7. The spectral field [-1°, +1°] range is in conclusion enough to cover the detectors disposed in the (c) configuration Fig 4(c).

A similar approach could be made with the same conclusion with the SWIR detector. In conclusion, the detector developed in the frame of the PROBA-V mission could be fully reused in return for a focal plane adjustment.

VII. SWIR DETECTOR

The major improvement modification in the PROBA –V SWIR detector is it spatial resolution. This can be achieved by reducing the pixel pitch. SWIR technology improvement could allow to improve the SWIR pitch to 12.5um. In this way it would be possible to have a raw spatial resolution equal to that for the VNIR detector. An immediate consequence is however that at least 6 staggered SWIR arrays are required to cover the same optical FOV, which would be more challenging for alignment. An improved speed for the readout would also be required to be able to cope with the increased data rate. The increased data rate and increased amount of required SWIR arrays would also have to be accounted for in the data and power budgets.

VIII. SYSTEM CONSTRAINTS

The spacecraft constraints are to stay within PROBA-type platform limits. For this study, a maximum allowed mass of 150kg has been considered. In the PROBA-V design, the allowed payload volume posed an additional constraint for the instrument. This is because of its boxed design: the instrument dimensions must be fitted within the boxed volume of the platform bus. Different designs exist, where the instrument is put as an additional module on top of a boxed platform, allowing more room inside the platform bus. One example is the

Parasol mission, a mission using the French platform Myriade, with very similar specifications compared to the PROBA-type platform. .

The higher data volume for the 100m mission goal will also put higher requirements on the platform's data and power budgets. In the constellation scenarios, the data volume can be shared over different satellites and is therefore not an issue. For single-satellite scenarios however, the on-board data chain and/or downlink will have to be improved to cope with this higher data volume.

IX. CONCLUSIONS

This study has demonstrated that a successor of PROBA-V mission with a 100 m resolution product is not a "mission impossible". Most of the required technology are mature or operational today.
All of the scenarios are able to meet the system constraints and can be retained. Based on the available information, a piggy-back launch option for the single-satellite scenarios seems viable. This could help reduce the launch cost for these scenarios, and it's therefore recommended to optimize mass and volume constraints to comply with a piggy-back launch. For this aspect, the scenario 3 has been shown to be the most optimal of the single-satellite scenarios.

A further recommendation is to adapt the platform architecture, such that the payload is a free-standing module. In this way, volume constraints for the payload are less critical, which could be important for the scenarios with a larger payload volume.

For constellation scenarios the recommendation is to opt for a shared launch if possible, to reduce the launch cost. The platform volume for these configurations is expected to allow a shared launch of up to 4 comparable platforms.

However such a shared launch is expected not be an option in scenario 4, because of the instrument volume size. The constellation scenarios can be considered more mature because they are compatible with most of the PROBA-V hardware as-is; except that whatever the selected scenario, all of them require a spacecraft with propulsion.

For single spacecraft scenarios further challenges exist which require platform improvements. The 100m spatial resolution combined with the required swath, leads to a rise in the data volume, requiring improvements in the on-board data chain and/or the downlink configuration. Similarly, power consumption will increase because of the higher data volume and the need for more detectors.

Furthermore, the following proposed options to improve performance have only minor impact on the power budget, and are thus strongly favoured for future missions:

- Solar diffuser calibration
- Partial thermal control (for fluctuations around the current average tempetarure only) to improve geometric accuracy

Based purely on design considerations, the use of FMA will allow to reduce the weigh and the amount of data.
It is known that alignment issues are more important for FMA optics compared to TMA optics. An analysis of optical tolerances for MTF performance has been performed on the TMA concept and the FMA concept is implemented in scenario 3. This preliminary analysis shows that the FMA concept is able to achieve an acceptable performance, and a performance comparable to the TMA concept [Ref 3]. This performance can be achieved provided an extra compensator is considered for the FMA alignment. It is expected that this improved alignment procedure also has a minor impact on the total cost and complexity of the mission.

ACKNOLEDGMENTS
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