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MESSIER: exploring the ultra-low surface brightness universe with a curved focal plane based satellite

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ABSTRACT

The extremely low surface brightness sensitivity required to observe the ultra-low-surface brightness universe lead us to propose MESSIER, a space mission designed to drift-scan the entire sky in 6 filters covering the 200-1000 nm range and reaching unprecedented surface brightness levels of 34 and 37 mag arcsec^2 in the optical and UV, respectively. Here, we present the ground-based MESSIER pathfinder aimed at testing several breakthrough technologies involved (e.g. curved detectors) and carrying out observations. We present here a detailed analysis of the optical quality achievable through photon Monte Carlo simulations of the system, including atmospheric effects.

Keywords: Curved detectors, end-to-end simulations, PSF, surface brightness

INTRODUCTION

In spite of major advances in both ground- and space-based instrumentation, the ultra-low surface brightness universe (ULSB) still remains a largely unexplored part in observational parameter space. Yet, ULSB observations would critically improve our understanding of the evolution of the universe by detecting and characterizing ultra-faint galaxies, currently predicted to be abundant but missed by current surveys due to their lack of sensitivity to these extended objects.

Another fundamental science goal, which also tests the LCDM paradigm of structure formation, is the observation of the cosmic web of filaments which is supposed to contain the missing fraction of baryons at low redshifts. The extremely low surface brightness sensitivity required to observe such faint and extended astrophysical sources lead us to propose MESSIER[1], a space mission designed to drift-scan the entire sky in 6 filters covering the 200-1000 nm range, and reaching unprecedented surface brightness levels of 34 and 37 mag/arcsec^2 in the optical and UV, respectively. Here we present the basic concept of the proposed satellite mission that has not a single refractive surface and has filter coatings directly deposited on the CCDs (Section 2).

We also present the ground-based MESSIER pathfinder aimed at testing its breakthrough technologies and carrying out ULSB observations. Unlike its space-based counterpart, the demonstrator has one inevitable refractive surface, the window for the cryostat, but it still delivers a Point Spread Function (PSF) with extremely compact wings, a key factor for the detection of ULSB features in the sky. As the focal plane of the pathfinder is curved, the use of a curved CCD enhances the performances in terms of transmission and PSF shape.

We also present here the design and the first results obtained through full-system photon Monte Carlo simulations (Section 3). The great potential of our optical design is enhanced by the introduction of curved CCDs. This new technology hugely simplifies the overall system and also eliminates the need for field-flattening lenses, while preserving the wide field of view.

Section 4 describes the most recent developments on curved detectors and presents the conclusions.

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MESSIER CONCEPT AND DESIGN

In order to have a systematic study of the LSB universe, a large survey is needed. This survey has to observe both large- and small-scale structures (to be scientifically relevant) and cannot use any refractive surface to avoid both internal scatterings and the production of Cerenkov emission which would both increase the surface brightness background levels. The large scale and low surface brightness features (e.g. the cosmic web) are in fact predicted to be brighter in the UV (Lyman-alpha emission), which makes it much harder to observe them from ground.

To fulfill the requirements (Table 1), fast optics with a wide field of view but no lenses has to be designed. In addition, the observation of LSB objects requires that the wings of the observed Point Spread Function (PSF) have to be extremely compact, which translates into a fast telescope design (F/2) with no obscuration and spider and with no high spatial frequency power on the optical surfaces. Moreover, the drift scan has been selected as observing mode to not be limited by the flat fielding precision[2]. Thus, the design must also provide a distortion-free PSF at least in the direction of the scanning.

Considering all the requirements, the proposed space mission MESSIER[1] was initially based on an optical design of a freeform Three Mirrors Anastigmat[3] (TMA) shown in Figure 2-1.

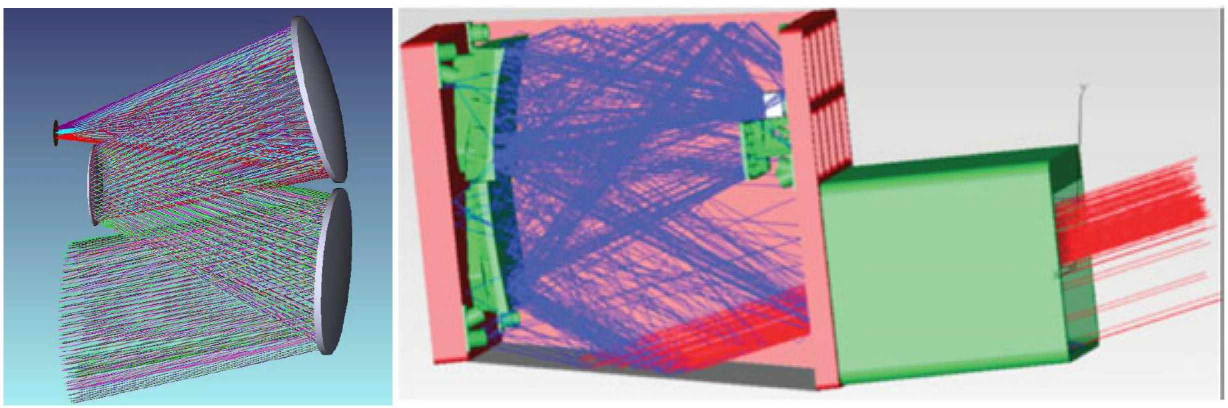

Figure 2-1. Left: TMA freeform design for MESSIER [3]. Right: The TMA design is shown within the payload. The pop-up baffle provides the straylight mitigation.

The flat focal plane is divided into 12 independent EMCCDs distributed along two rows. The anti-reflection coatings and QE of these detectors will be optimised for the optical bands (310-980 nm) that MESSIER uses to characterise the stellar populations of the galaxies, plus a broad and a narrow UV filter centered around 200 nm.

Allowing the design to have a curved focal plane would provide a more performing and manufacturable telescope design[3], however because of the currently low Technology Readiness Level (TRL) of the curved detectors (especially for longer wavelengths) it is not yet selected as baseline.

Table 1. Requirements for the MESSIER space mission.

Quantity	Value
Field of view	$2^{\circ} \times 4^{\circ}$
Central obscuration	none
Wavelength range	150-1000 nm
Diameter	50 cm
Survey solid angle	4π

With the design shown in Figure 2-1, the requirements in Table 1 and a 770 km Sun-Synchronous Orbit (SSO), MESSIER will provide observations of LSB objects of 34 mag/arcsec^2 in the visible wavelength range and of 37 mag/arcsec^2 in the UV, which is the predicted emission level of Lyα in the cosmic web at redshift z~0.7 [4,5].

PATHFINDER: DESIGN AND SIMULATIONS

The proposed satellite mission features a flat focal plane to keep the TRL as high as possible. However, by using a curved focal plane the performance of the optical system can improve substantially and the design itself can become more compact. The MESSIER pathfinder[6] has hence been proposed as a technological demonstrator to show all the advantages of curved detectors for astronomy and test their performances on-sky.

Pathfinder design

The ground-based MESSIER is a fully reflective Schmidt design with an anamorphic primary, flat secondary and spherical tertiary mirror, and features a curved focal plane (Figure 3-1). In Table 3 its main characteristics are described. In spite of a small primary mirror (35.6 cm), it allows observations over a wide field of view of $1.6^{\circ} \times 2.6^{\circ}$.

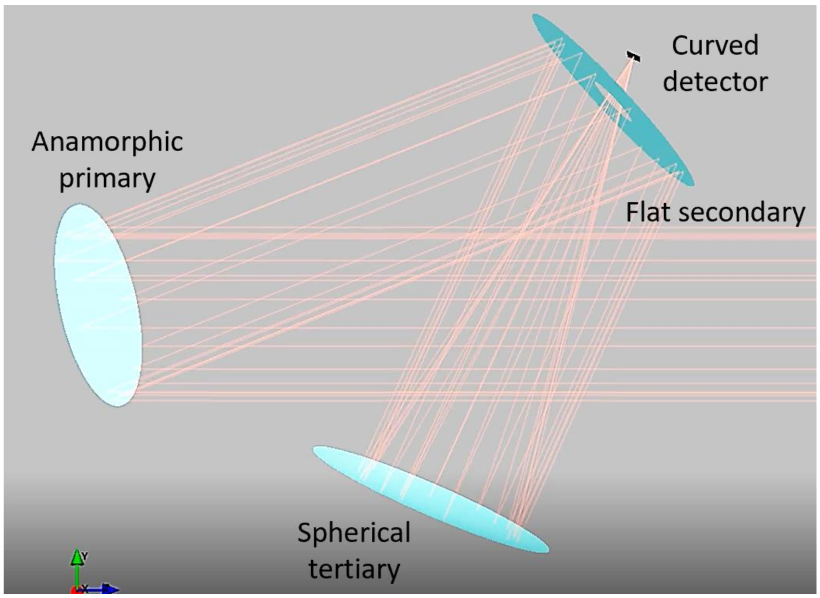

Figure 3-1. The MESSIER pathfinder design[6].

Unlike its space-based version it has one refractive element: the window of the dewar, which is necessary to cool down the CCD (only one detector in the focal plane). In order to reduce as much as possible the number of refractive elements, we combined the window with the bandpass filter. It is also possible to design a solution in which we have two different filters, side by side, on the window so that we are able to observe in two wavelength bands. For simplicity, in the rest of the paper, we only consider one filter band that is a *g* LSST-like filter.

The planned location for observations is Tenerife with the possibility to move the demonstrator to La Palma where the sky background is lower and more suitable for LSB observations.

Table 3. Characteristics of the design for the MESSIER pathfinder.

Quantity	Value
Field of view	$1.6^{\circ} \times 2.6^{\circ}$
Diameter	35.6 cm
F/#	2.5
Distortion	<0.5% in one direction
Detector shape/radius of curvature	Convex/800 mm

End-to-end simulations for the pathfinder

We use an end-to-end photon Monte Carlo simulation software (PhoSim[7]) to verify the performances of the full telescope and characterise the PSF at very large distances from the center of the field of view. The software simulates the full light path from the astrophysical source, passing through the Earth atmosphere, the telescope and can model also the CCD effects such as dark current, read out noise, CTE, etc.

We also account for the altitude, typical seeing and wind speed/direction values for La Palma, to make the simulation as realistic as possible. As the observation mode is drift scan (similarly to the satellite version), the design is distortion-free at least in one direction. We prove that this is verified also when adding all the distortion introduces by atmospheric effects and wind, by simulating an observation of a star at the center and at the corner of the field of view.

In Figure 3-1 and 3-2 are shown these simulations at the center and at the corner of the field ($0.7^{\circ}\times1.2^{\circ}$) respectively. Each image represents the position of photons on the sensor once we apply the different effects. First we simulate the pure optical design with only the telescope (equivalent to a ZEMAX simulation). Second we insert the effects due to misalignment, tilt and dust accumulation on the surfaces (perturbations), then we apply the effects due to seeing/wind (all seeing) and the atmospheric refraction (all atmosphere). Finally, we plot the image as it appears when readout from the CCD (CCD effects).

The photons are located in a region of the sensor that is smaller than the pixel size in most cases. By comparing Figure 3-1 and 3-2, we find no large difference or quality degradation at the corner of the field. The photons are more dispersed than at the centre of the field of view, but they are still mostly contained within a pixel.

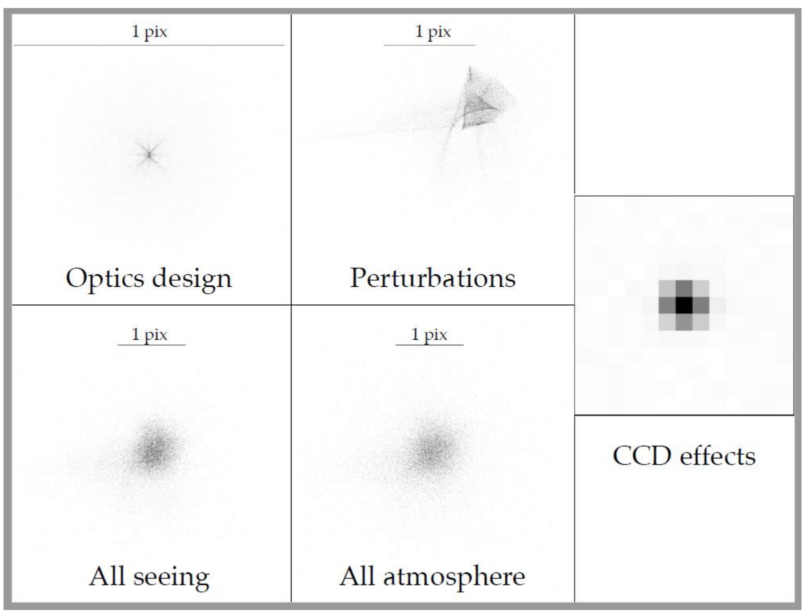

Figure 0-2. Simulation of a star observed by the pathfinder at the center of the field. The different squares indicate the effects added in the simulations and the horizontal bar on top of each image represents the dimension of 1 pixel (10μm).

We can even push the simulations a step further and have the observed star moving across the short side of the field of view as it would do in a real drift-scan observation. We can do this by moving the star from one pixel to the next one and generating every time a different image. Then we recombine all these images in such a way that the star observed in every image is centered at the center of the field of view. From this we obtain the composite PSF of a complete drift-scan image.

In Figure 3-4 are shown the results from such simulations for the pathfinder including all effects such as the optical design, the perturbations (dust on surfaces, tilt and shift of surfaces) and all the atmospheric effects (seeing, wind, diffraction).

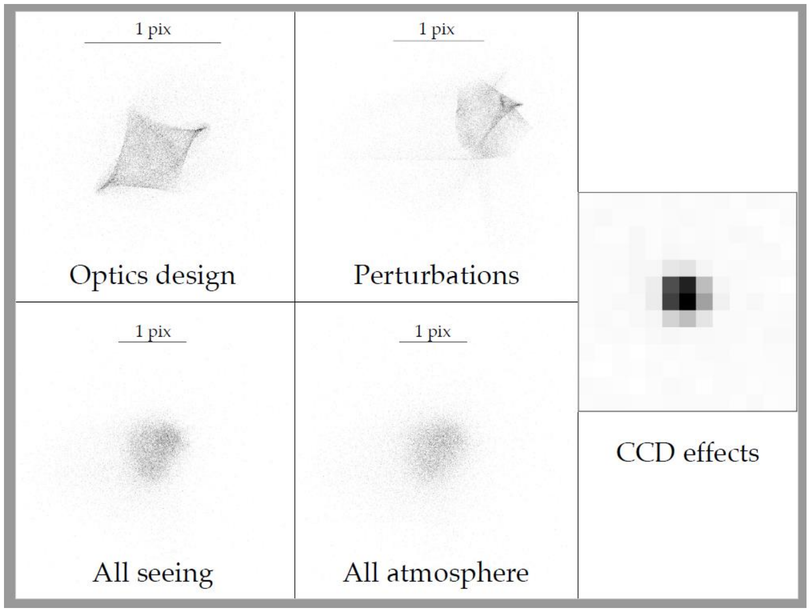

Figure 0-3. Simulation of a star observed by the pathfinder at one corner of the field ($0.7^{\circ}\times1.2^{\circ}$). The images indicate the effects added in the simulations and the horizontal bar on top of each image represents the dimension of 1 pixel (10μm).

The PSF of the pathfinder features very compact wings even at large distances from the center of the field of view, reaching averaged values of 10^{-6} around $1.7^{'}$. At larger radial distances the PSF has a bump produced by the reflection off the CCD and by the scattering of the dewar window. At distances between 0.25°-1.6° the PSF decreases again reaching averaged values of $10^{-7.5}$.

These results show the importance of producing full-scale realistic simulations during the design stage. Additionally, it also proves the necessity of building a satellite mission, that avoids all the refractive elements and provides even more compact PSF wings.

Figure 3-4 shows the simulation of a star in the center of the field of view as observed by the Large Synaptic Survey Telescope (LSST). This simulation includes all the effects mentioned and it is performed with the classical point and stare observing mode. For computational reasons the simulation stops at a much shorter distance from the center of the field of view compared to the simulations for the pathfinder. We can already see, however, how the design optimised for LSB observations has much better PSF wings with respect to a design (e.g. LSST) meant for observations of point-like or compact sources.

The use of better AR coatings for both the dewar window and the CCDs, or a version of the current design without central hole (or both), would enable the PSF halos to be further reduced.

Curved detectors development

The pathfinder design shown in the previous section is rather simple. One of the technological challenges for its realization is the development of curved detectors. There are many ongoing activities and prototypes that have already demonstrated their feasibility and potentiality[8-15] (mostly for CMOS sensors).

The opto-electro characterization of some of the existing prototypes have also proved that there is no visible degradation in performance[9,15], in terms of noise properties (readout noise, dark current, pixel-relative-non-uniformity) and gain value, of the curved samples with respect to the flat sensors. In some cases, it is also found a decrease of dark current for the curved detectors.

More development is still needed to ensure that the surface precision of these detectors fulfills the quality standards required by astronomical applications.

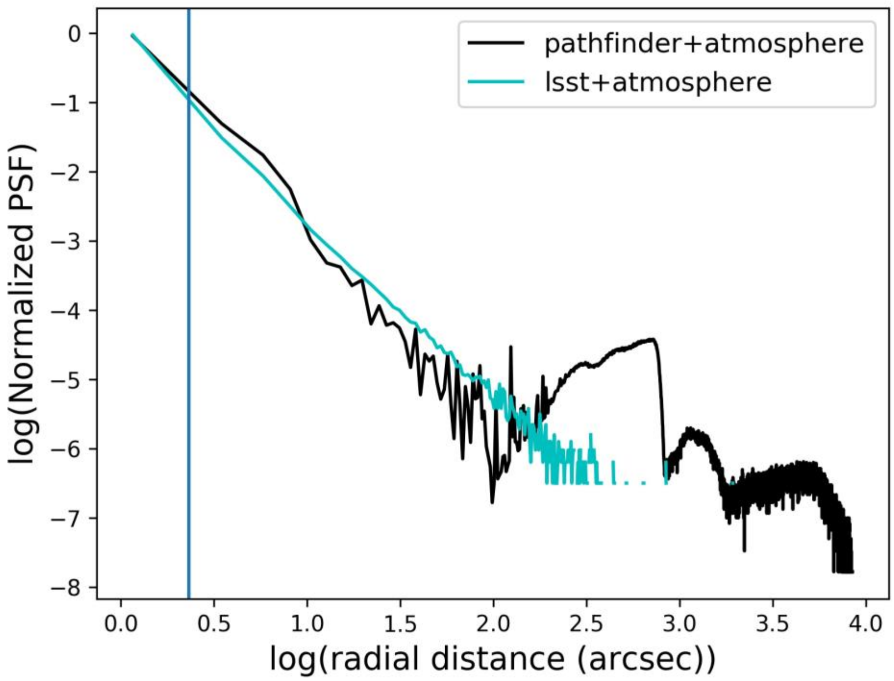

Figure 0-4. The preliminary photon Monte Carlo simulated PSF as function of distance from the center of the field of view in arcsec is shown. Note that both scales are logarithmic. The pathfinder simulations are in black and for LSST are in cyan. Both simulations include all effects (optics, perturbations, seeing and atmosphere) and are normalized to the total flux. The vertical line represents the dimension of a pixel for the pathfinder (2.32") which is the binning chosen for both PSFs.

CONCLUSIONS

In this paper we present the basic concept for the proposed satellite mission MESSIER aimed at observations of ultra-low-surface-brightness objects. MESSIER will be able to observe objects of 34 mag/arcsec^2 in the visible wavelength range and of 37 mag/arcsec^2 in the UV. As a technology demonstrator we propose a scaled-down version of MESSIER for ground-based observations of LSB objects. The pathfinder has a fully reflective Schmidt design with an anamorphic primary of 35.6 cm, a field of view of 1.6° × 2.6° and a curved focal plane.

The results of the end-to-end photon Monte Carlo simulations performed here, to compute the PSF of the pathfinder over the full extent of its field of view, show that the design does not show signs of distortion when comparing observations of a star at the center and at the edge of the field of view, which is a fundamental requirement for drift-scan observations. Additionally, we find that the wings of the PSF have a small bump due to the scattering off the CCD and dewar window at distances of 1.7' form the center of the field of view. The PSF value decreases again to $10^{-7.5}$ for distances larger than 0.25°.

To reduce even further the already low halo of the PSF we have to consider an improved AR coating for both the dewar window and the CCDs and/or optimise the design by eliminating the central hole.

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