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Approach to build a dedicated space born small aperture UV telescope for the long term study of comets (Comet-UV project)

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Abstract. We present the concept of a small-aperture 20 cm wide field UV telescope for a long term detailing study of comets in UV range. Because of the small size and autonomous repointing system, the proposed telescope can be installed on various satellites as an auxiliary instrument. It also can be used on the future International Lunar Research station (ILRS). The main goal of the mission is the long term detailed study of comets and other minor bodies in the Solar System. We briefly discuss variants of the optical schemes, methods of pointing the telescope, scientific filters and modern CMOS detectors. A small dedicated UV telescope with a modern detector will obtain a lot of new information to study comets in the UV range.

Key words: Comets – Space telescope – UV

1. Introduction

Comets are important "eyewitnesses" of Solar System formation and evolution. It is also a rich material for the study of the formation of exoplanets (Fossati et al., 2014). The data in the UV range of the electromagnetic spectrum helps to determine the chemical composition and to study the physical processes in cometary nuclei and coma (Shustov et al., 2018).

Comets were observed many times in UV by large space telescopes such as HST, FUSE, GALEX (see a review by Sachkov (2016)). The World Space Observatory - Ultraviolet (WSO-UV) project, which is scheduled to launch in 2025, will effectively solve most problems in the field of ultraviolet studies of comets and can become an important research tool (Sachkov et al., 2018, 2019). At the same time, because of the lack of available observing time to study comets with large space telescopes, we are looking to build a small and relatively cheap dedicated instrument, optimized for a specific scientific task, to observe comets in the UV range, which is inaccessible for any ground telescopes.

Small aperture and, therefore, lack of sensitivity of such a small instrument can be compensated by a huge amount of observing time to observe each comet of interest. Digital co-adding of large amounts of images taken with dithering will allow us to get reasonably detailed images of extended comet tails with both acceptable angular resolution, sensitivity and dynamic range even with a small telescope.

The Comet-UV project is based on the ultraviolet telescope and a modern CMOS detector with a special multilayer quadrant UV filter with excellent suppression of visible light.

The CMOS detector, which is not sensitive to local overexposure and has a low readout noise, will allow to achieve a high S/N ratio when adding a large number of frames of the comet's nucleus and tail. The presence of a bright comet nucleus will not affect the telescope's ability to observe a weak tail.

In the basic version, a full-aperture slewing mirror will be installed in front to repoint the telescope. The slewing mirror will be used not only to point the telescope at the selected area, but also to switch between filters and perform dithering. The image of the comet will be sequentially projected onto 4 areas of the detector covered with different filters, and for each filter several images will be obtained with a small (a few pixels) image offset inside one filter in order to reject the traces of cosmic particles and detector defects.

The future International Lunar Research Station (ILRS) can be considered as a place to install this small aperture (15-30 cm) UV telescope (Sachkov et al., 2020). It can be used for the long term detailed study of comets and other minor bodies in the Solar System in several FUV and NUV bands, as well as in visible and possibly IR.

The proposed UV telescope also can be part of scientific payload on other spacecraft.

2. The telescope

Several optical schemes are considered for the Comet-UV project.

In the simplest option, a two-mirror axial scheme without a corrector with the detector located in the Cassegrain focus can be used. The main advantages of this option are simplicity, compactness and maximum transmission in UV. The main disadvantages are limited field of view (less than 0.5 deg) and presence of distortion at the edge of the detector.

To increase the field of view and compensate distortions, it is possible to use a lens corrector from MgF_2 or CaF_2. The operation of such a corrector in a wide range of wavelengths from vacuum UV to the visible region needs additional investigation.

The most promising is an off-axis multi-mirror optical scheme that provides excellent image quality over a field of 1 deg, wide spectral range and symmetrical PSF due to the absence of secondary mirror mounting spiders. The main disadvantages are the complexity of manufacturing, adjustment and the strict requirements for the mirror position stability.

Due to the small aperture and compactness of the Comet-UV telescope, it is possible to manufacture such off-axis schemes, including structural elements, entirely from materials with low coefficients of thermal expansion. Accurate focusing of the telescope can be carried out by controlled heating of some structural elements.

Preliminary, as a baseline for the Comet-UV conceptual design, we have chosen a classical RC optical system with enhanced CaF_2 lens corrector which operates from FUV to optical wavelength ranges. It provides image quality of 0.5 arcsec in all filters. If necessary, a filter wheel can be installed in front of the detector. The preliminary parameters of the telescope are as follows:

Table 1. The main parameters of the Comet-UV telescope.

Parameter	Value
Telescope aperture	200 mm
Optical scheme	RC with CaF_2 corrector
Focal length	3000 mm
Field of view (round, diameter)	0.54×0.43 deg (on 23×18.4 mm detector)
Spectral range	125–900 nm
D_{80}	9 μm @ 125 nm 30 μm @ 500 nm
Central obscuration	32 %
Detector	CMOS GSPRINT4521
Detector size	23×18.4 mm
Detector format	5120×4096 pixels
Pixel size	4.5 μm
Pixel scale	0.38 arcsec pixel^{-1}
Typical single exposure	up to 600 s
Slewing mirror size	320×220 mm
Slewing mirror tilt angles	pitch +30°...+90° roll ± 60°
Area of observation with a slewing mirror	60°×120°
Time of repointing	3 s
Telescope length	600 mm
Telescope with slewing mirror length	1100 mm

Depending on the available detector, the field of view of the Comet-UV telescope will be about 0.54°×0.43°. We propose to use a detector with a small pixel (4.6 μm) and electronic shutter.

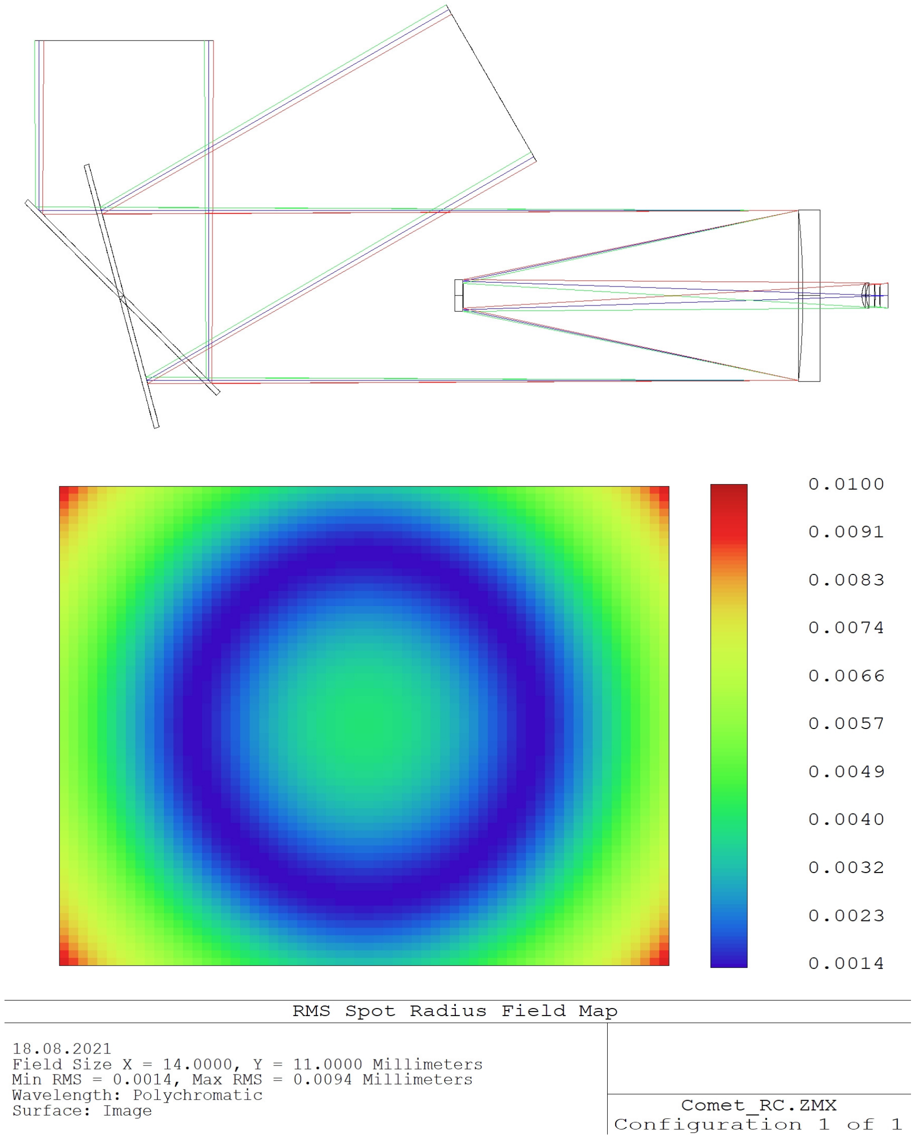

Figure 1. Optical scheme of the telescope with a repointing mirror (top), image quality (bottom).

3. Telescope repointing system

In large projects, the telescope is usually rigidly mounted to the platform. Telescope pointing at the object is carried out by moving the entire spacecraft, followed by precise stabilization of the platform.

When designing a relatively small telescope, operated as an additional payload, or if there are a large number of other scientific instruments on the spacecraft with their own requirements for the orientation of the platform, the telescope should provide an autonomous repointing system to point, stabilize and track the object of interest. It also may be required to compensate for residual drifts of the space platform.

Autonomous repointing of a small telescope can be carried out in two ways, by using a full-aperture mirror installed in front of the entrance pupil of the telescope, or by installing the telescope on a two axis mount.

The main advantages of repointing using a full-aperture mirror are the speed of repointing, small moment of inertia, and, as a result, small perturbing moment during repointing and possibility of its compensation. The disadvantages are an increase in the dimensions and weight of the optical assembly (the mirror dimensions should be larger than the telescope entrance aperture) and an additional reflecting surface in the optical path.

The main advantage of repointing using a two axis mount is a larger area of observation. The disadvantage is an increase in complexity of the mechanical design.

Preliminary, as a baseline for the Comet-UV conceptual design we have chosen to put a slewing mirror in front of the telescope. The repointing area will be about $60^\circ \times 120^\circ$.

4. Detector and filters

For a long time, the pixel size of a scientific grade CCD could not be reduced below the threshold of about 10 μm without significant losses in the well capacity, limitations in the CCD production technology and problems with readout time and noise. In the last few years, thanks to the rapid development of CMOS technology, it has become possible to manufacture an active pixel with a size of 3-5 μm, sufficient well capacity (tens of thousands of electrons), low noise and high quantum efficiency. Due to the very low CMOS reading noise (down to 1 e^- RMS), a dynamic range of such small pixels can be more than 5000:1, which is comparable to a classic CCD.

With small pixel size CMOS it is possible to improve the spatial resolution by having better sampling or to increase the field of view of the telescope while maintaining sampling.

Observation in UV with CMOS and CCD detectors faces two challenges, low quantum efficiency in UV and the red leak of UV filters.

It is shown in (Nikzad et al., 2012), that it is possible to design simple coatings using different materials to achieve >50% of quantum efficiency in different parts of the UV range: MgF_2 for 130-160 nm range, Al_2O_3 of different thickness for 160-200 nm and 200-230 nm, HfO_2 for 230-280 nm.

The other problem of using CCD or CMOS detectors for observations in the UV range is the long pass transmission (red leak) of filters. It is possible to build a multilayer filter with an acceptable suppression (down to E-5) of the optical component for the near-UV range, however the photometric correction of the observed data will be required for the far-UV range in any case.

For example, in the DORADO project (Singer et al., 2021), it is proposed to use a multilayer dielectric filter on the CCD surface with a band pass of 180-230 nm, which provides a suppression of the optical component down to E-5, twice better than the WFC3 common standalone multilayer filters.

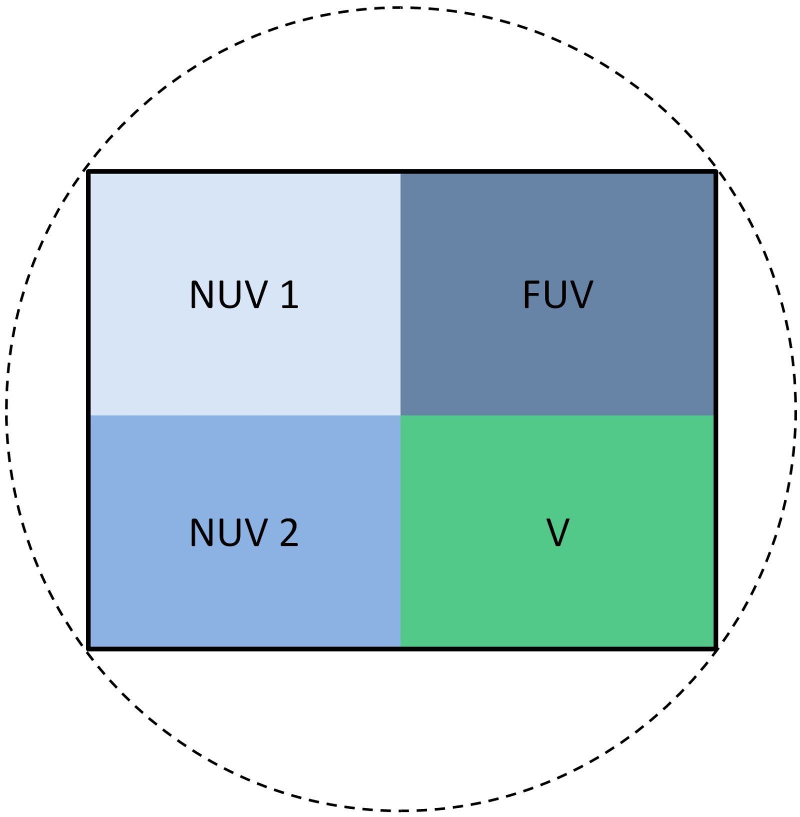

Figure 2. Focal plane and filters layout.

For the Comet-UV project, it is planned to use a modern CMOS from the Chinese company GPEXEL with a special treatment of the back side of the silicon wafer to increase sensitivity in the UV range (Shugarov et al., 2021).

As an example, we can mention a modern CMOS GSPRINT4521 with a global shutter, photosensitive area of 23×18.4 mm, pixel size of $4.5\,\mu$m, pixel capacity of $30000\,e^-$ and readout noise of $3\,e^-$ RMS. We hope that the technology of multilayer coating, similar to the DORADO project, can be applied for GPIXEL's back illuminated CMOS.

For the Comet-UV project, we suggest to deposit 4 multilayer light filters directly on the CMOS chip (Fig. 2). Three UV filters (FUV, NUV1, NUV2) are the main scientific filters and one standard V filter is needed to correct the long-pass transmission of UV filters, e.g. for red leak calibration.

5. Conclusion

Despite a small aperture, the proposed telescope will allow to perform a detailed study of comets in the UV range, which is inaccessible for ground telescopes.

The key technical innovations of the project are the usage of a modern CMOS detector with small size pixels, coated with different multilayer UV filters with good red leak suppression.

Because Comet-UV is a dedicated project to observe comets, it will have a lot of observation time to study each comet of interest. Adding a huge amount (up to hundreds) of images taken in different filters with dithering will allow us to create very detailed images of the comet nucleus and tail in three UV filters and one visible one with reasonable resolution (0.5 arcsec) and high dynamic range of the resulting image. Comets can be observed many times during their travel through the Solar System, including the regions close to the Sun.

The Comet-UV instrument can be installed on various satellites as an auxiliary instrument or on the future International Lunar Research station.

The telescope also can be used to observe other objects of opportunity. Astronomers will receive a relatively universal and inexpensive orbital telescope, operated in UV and optical ranges, suitable for the detailed study of comets and for a wide range of other scientific tasks.

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