The Robotic Earthshine Telescope

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ABSTRACT

Lund Observatory is presently designing and constructing a robotic telescope dedicated to studies of the Earth's albedo by measuring the ratio between the intensity of the dark and bright sides of the Moon. The telescope will operate both in broadband and narrow-band modes over the entire visible wavelength range and will transmit observational results back to the operation team over the Internet. Design challenges, in particular related to choice of CCD and stray light suppression, are described, together with the design of the optics, control system, and enclosure. Finally we present results from laboratory tests. The telescope will go into operation in the first half of 2011.

Keywords: robotic telescope, Earth's albedo, Earthshine

1. INTRODUCTION

Exact knowledge of the Earth's albedo is of fundamental importance for climate research and modeling[1]. The Earth's albedo can be determined by photometry of the dark side of the Moon, which is illuminated by the Earth. Systematic, reliable and long-term measurements of the earthshine need a sophisticated and well designed telescope. Development of the Lund Robotic Earthshine Telescope (RET) was initiated in 2006 as a collaborative effort between Lund Observatory (LO) in Sweden and The Danish Meteorological Institute (DMI)[2,3]. The original design was a two-armed telescope, which has later been modified to a one-armed version. The small robotic observatory will incorporate the specially designed telescope, an Astro-Physics brand 1200GTO mount, a commercial dome with a small aperture, a high-sensitivity CCD camera, and additional auxiliary devices, all controlled by a single PC running National Instruments LabVIEW under Windows 7. Many components including the software environment were designed, developed and manufactured by our team at Lund Observatory.

RET is going to operate in four different modes, respectively called BBSO (Big Bear Solar Observatory), modified BBSO, Co-Add and Lund mode. The BBSO mode works by sequential observation of the dark side (DS) and bright side (BS) of the Moon and the Earth's albedo is computed by taking the ratio of DS intensity to BS intensity[1,4,5]. When taking the DS exposures, the BS is blocked in the first focal plane to suppress straylight. Since the CCD is exposed to close to saturation, DS observations may require typically 10^4 longer exposure times than BS observations. The modified BBSO mode operates similarly to the BBSO mode except that a neutral density filter dims the BS observation and therefore prolongs the BS exposure time, which improves the relative precision. The co-add mode works by stacking several Moon images, which are exposed close to saturation on the BS. This results in a reduction of the high Poisson noise in the single DS exposures. In the Lund mode a reflective neutral density filter or Knife Edge Density Filter (KEDF) is placed in the first focal plane in order to dim the BS of the Moon image such that the intensity of the DS and the BS is of the same order of magnitude on the CCD camera. The KEDF was custom-made by evaporating aluminum on a glass plate with a diameter of 20 mm and a thickness of 1 mm (Ferroperm Optics). Both sides of the glass plate were also anti-reflex coated. This type of neutral density filter is much more uniform/neutral than the absorption glass filter and can be manufactured for a wider spectral range. The degree of attenuation depends on the coating thickness and normally the uniformity of the coating thickness calls for careful control of the coating process.

In Section 2 a brief review of the LO/DMI RET design and construction process will be presented. Section 3 is devoted to experimental results.

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2. OVERVIEW AND DESIGN CONSIDERATIONS

2.1 Earthshine telescope specifications

Basic design criteria of the RET were to construct a refractive telescope with a 40 mm aperture, a focal ratio of 12.5, a camera field of view of ~0.9°, a working wavelength of 380-800nm and very low ghost image and stray light levels[3]. The system includes a CCD camera model Andor iXon897-BV, an Astro-Physic 1200GTO German equatorial mount and control programs based on LabVIEW software.

The detector is a back-illuminated CCD camera with a 512x512 pixel array consisting of 16 μm×16 μm pixels. It has excellent quantum efficiency (QE ~ 0.9 slightly varying over the spectral range). The camera field of view of ~0.9° allows observations of the Moon including its surroundings out to around 0.2° from the limb, which provides sufficient detection capability for scattered light removal. The pixel size of 16 μm is matched to the PSF of the telescope, and the 512×512 pixel array provides 0.94° field of view. The high Full Well Capacity (FWC) of 155000e and low read out noise ~8.3e of the camera provides a high dynamic range around 18500. The camera is equipped with a 16 bit A/D converter. The high dynamic range of the camera is especially suited for measuring the faint Earthshine intensity DS and high intensity BS of the Moon with single exposures in Co-Add mode. The frame transfer architecture of the CCD chip provides lower smearing effects and higher frame rates than a full frame type CCD chip, but still a fast mechanical shutter from Uniblitz is used to get rid of the smearing effects at short exposure times.

RET has been design in order to operate in four different modes, where the optical configurations of each mode are summarized in Table 1. Both white light and broad band photometric observations will be accessible. The photometric filters used in the system cover the range from blue to near-IR and have been chosen to allow observation of the "red edge vegetation index" near 750 nm. The span of colors available allows monitoring of the scattering properties of the atmospheric contribution to the albedo, while the special filters near 750 nm will be used to look for changes in the contribution from vegetation on cloud-free land and plankton in cloud-free oceans[2].

It is presently the intention to mount the telescope in one end of a 20' standard shipping container. A small commercially available dome will be mounted on the top of the container. The width of the dome aperture is going to be reduced to about 15cm for further straylight suppression and protection of the inside of the enclosure. Also, it has been planned to install an anemometer, an IR cloud sensor and a hygrometer for equipment safety on top of the container. For transport, the dome will be removed and placed inside the container. A combined control room, office, and small workshop will be installed in the other end of the container. There are two reasons for choosing a container solution. Firstly, it becomes possible to test the complete system at our institute with all installations, thereby reducing costly installation time at the observatory site. Secondly, the system can be shipped to almost any site in the world with little effort.

Table 1. Optical configurations for the four operating modes of LO/DMI RET, hard knife edge (HKE), neutral density filter (NDF), Color filter (CF), filter wheel (FW), Lyot stop (LS).

Configurations / Operation Modes			FW at first the image plane			FW before the LS		FW after the LS	
			KEDF	HKE	Clear	NDF	Clear	CF	Clear
BBSO	White Light	BS			√		√		√
		DS		√			√		√
	Band pass	BS			√		√	√	
		DS		√			√	√	
Modified BBSO	White Light	BS			√	√			√
		DS		√			√		√
	Band pass	BS			√		√	√	
		DS		√			√	√	
Co-Add	White Light	—			√	√			√
	Band pass	—			√		√	√	
Lund	White Light	—	√				√		√
	Band pass	—	√				√	√	

2.2 Optical design

The optical layout of the earthshine telescope is shown in Figure 1. The optics consist of a 250mm objective (Edmund 49393 250mm f/5 VIS-NIR AR coating) followed by an afocal 1:2 relay optics consisting of a 76.2mm and a 150mm lens (Edmund 49794 76.2mm f/3 VIS-NIR AR coating and an Edmund 47718 150mm f/5 VIS-0˚ AR coating). The VIS-0˚ coating is optimized for 0˚ angle of incidence and visible spectral range, and the VIS-NIR coating is specially optimized for visible and near infrared range. The transmission profiles as a function of the wavelength of both coatings are illustrated in Figure 2.a and b [6]. All lenses are achromatic doublets. In front of the telescope, a UV cut-off filter is mounted. The telescope has a mechanism for choosing between several different knife edges, which are located in the first image plane after a field stop aperture. One of the knife edges is an occulter and the rest are KEDFs with different densities. There are two filter wheels mounted to the right and left of the Lyot stop, see Figure 1, which each have six positions for one-inch filters. One of the filter wheels is used for color filters plus an IR cut off filter, and the other filter wheel is dedicated to neutral density filters. An adjustable iris diaphragm is used as a Lyot stop in the aperture stop image plane. A fast shutter from Uniblitz is mounted to the right of the iris diaphragm.

In the Lund mode of operation, a KEDF covers the bright side of the Moon image. ZEMAX simulations show that the optical performance is reasonably well matched to the pixel sampling (16μm results in slight under-sampling). Figure 3 shows encircled energy plots for the Lund mode.

2.3 Mechanical design

All workshop drawings have been made using CAD Inventor software. A steel base table is used as support for the components of the telescope. Four steel rods from Linos are used for mounting the standard components. Due to their stiffness, the vibration sensitivity of the system is reduced. Most mechanical components have been manufactured of aluminum and all components are black anodized or black chromated, as can be seen in Figure 4. In addition, some standard commercial electro-mechanical components have been used; e.g. a linear stage for adjusting the focus of the telescope, two filter wheels, a fast electromechanical shutter from Uniblitz, and two rotary tables to position the knife edge.

An electro-mechanical system was designed for selecting between hard knife edge and KEDFs of different density. Figure 5 shows a schematic drawing of the system, which has two rotary stages, one that rotates around the optical axis and another that rotates around an axis parallel to the optical axis. The knife edge angle and location are adjusted by both rotary stages and selection of the right knife edge is done with the off axis rotary stage.

2.4 The RET control system and hardware

The Earthshine telescope control system was built on a National Instruments PXI chassis running a dual core processor under the Windows 7 operating system and LabVIEW 2009. The PXI system is populated with a NI-6229 data acquisition card for system monitoring functions and an NI-7358 eight axis motion control card controlling the optics positioning stages inside the telescope. These stages are supplied by National Aperture Incorporated and are driven through their M4-CSA amplifier.

The software was built using the native LabVIEW functions. This minimizes the need to interface to multiple vendor proprietary tools and minimizes the likelihood of glitches in these outside tools. The control system architecture is structured as a group of independent parallel functions running at different rates and priority.
The heart of the system is a large state machine to handle task sequencing. Tasks will range from telescope configuration, to system timing, power phasing, and protocol execution, and other functions. In this context, the term "protocol" refers to a custom script that will be created by the scientific users and then downloaded to the system for automatic execution. Three other processes will be running in parallel with the sequencer. In order of importance, there are an error and exception handler, a data acquisition system, and an external event handler to deal with the remote and manual telescope control.

The error and exception handler receives input from all the other loops and determines how the system will respond to various failures and warnings. Possible outcomes will be holds on observations, system shutdowns, attempts to clear faults, etc. It will also handle operator requests for system control over the Internet and create a data log of faults. The data acquisition system will gather information from a weather station, thermal monitors, position indicators, and other sensors. It will do limit checking on inputs and pass critical information to the error and exception handler as necessary. The primary function of the event handler will be to act as an interface to a remote operator. The operator may chose to put the system into an engineering mode for manual control or merely to monitor current operations.

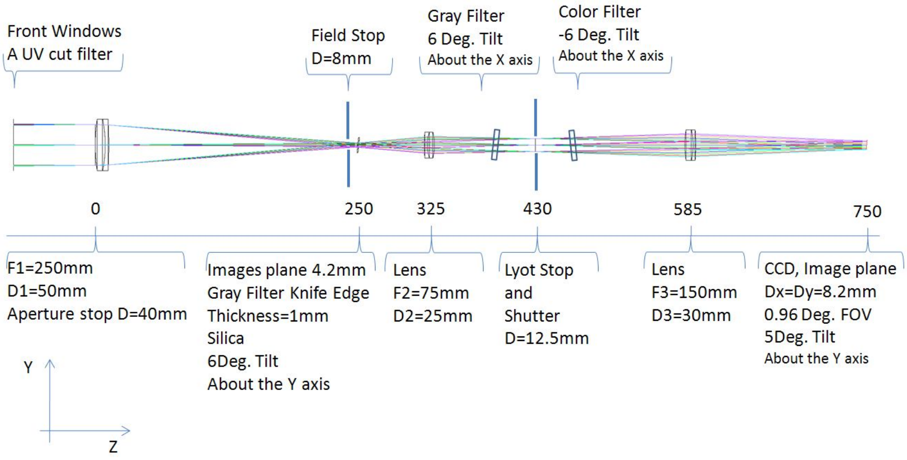
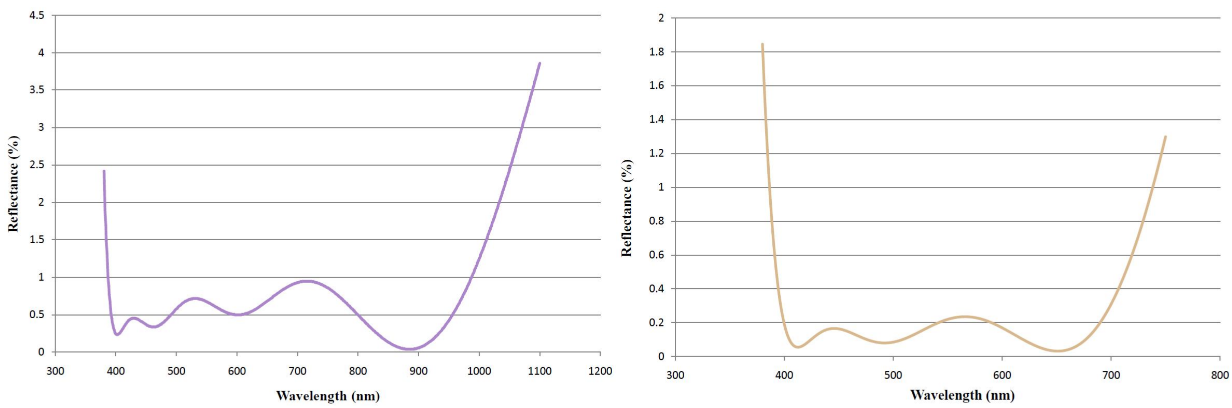


Figure 1. The optical layout of the telescope.



(a) (b)

Figure 2.a) VIS-NIR and b) VIS-0˚ coating performance curves.

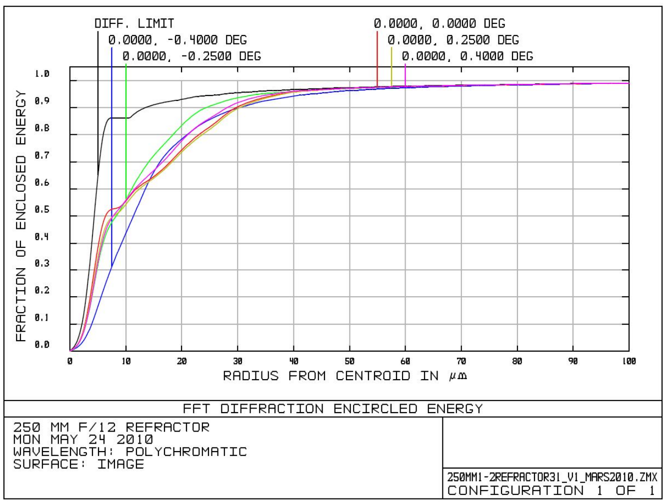


Figure 3. Encircled energy for the LO/DMI Earthshine telescope in the Lund mode operation.

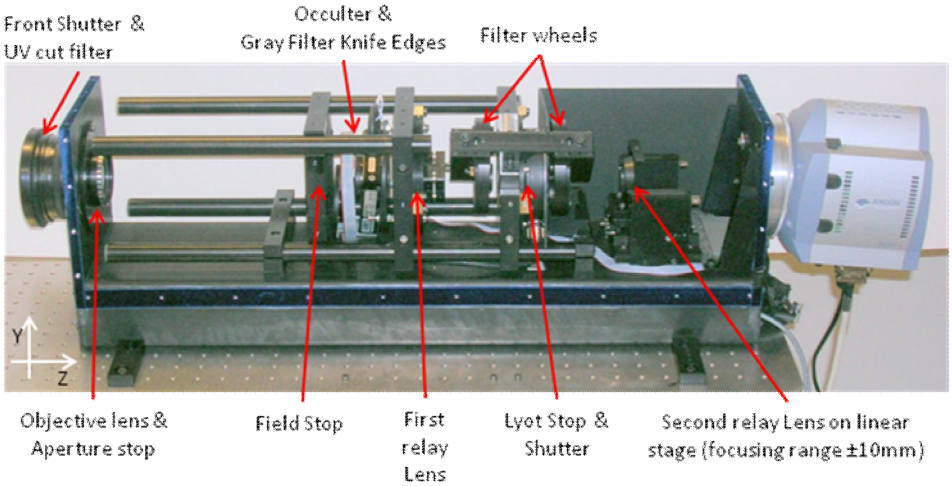


Figure 4. Photo of the Lund Earthshine telescope without cover.

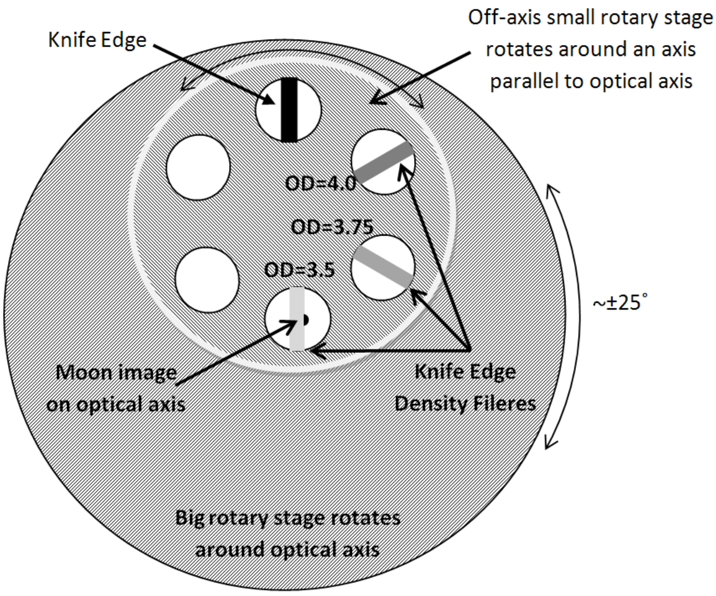


Figure 5. Diagram of the electro-mechanical system for selecting the knife edges using two rotary stages.

3. LABORATORY EVALUATIONS RESULTS

The RET has been assembled and tested in the laboratory in order to verify the optical performance, in particular to detect and quantify image artifacts due to inadequate stray light rejection. Such artifacts include "ghosts" from the detector window and filter reflections, glints from baffle or mask edges and other spurious light paths that produce undesired illumination of the detector. The ghost images have been moved away from the CCD by appropriate adjustment of components, e.g, tilting the occulter, knifes, the filter wheels and the CCD camera. Since a low stray-light level is crucial for albedo measurements, a separate experiment was carried out in laboratory. Figure 6 shows a diagram of the experimental setup. A high power tungsten light source, a neutral density filter OD=3 and a 0.3mm pinhole were placed in series to simulate a point light source. The distance between the point source and the telescope was about 16m.

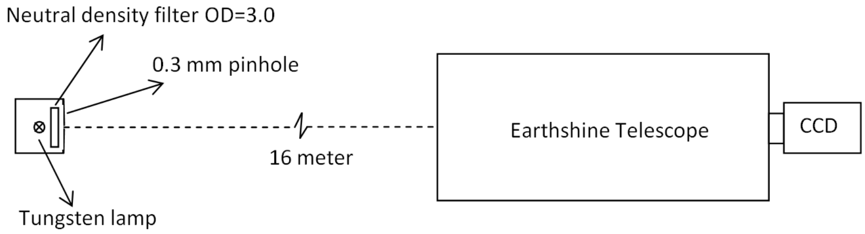
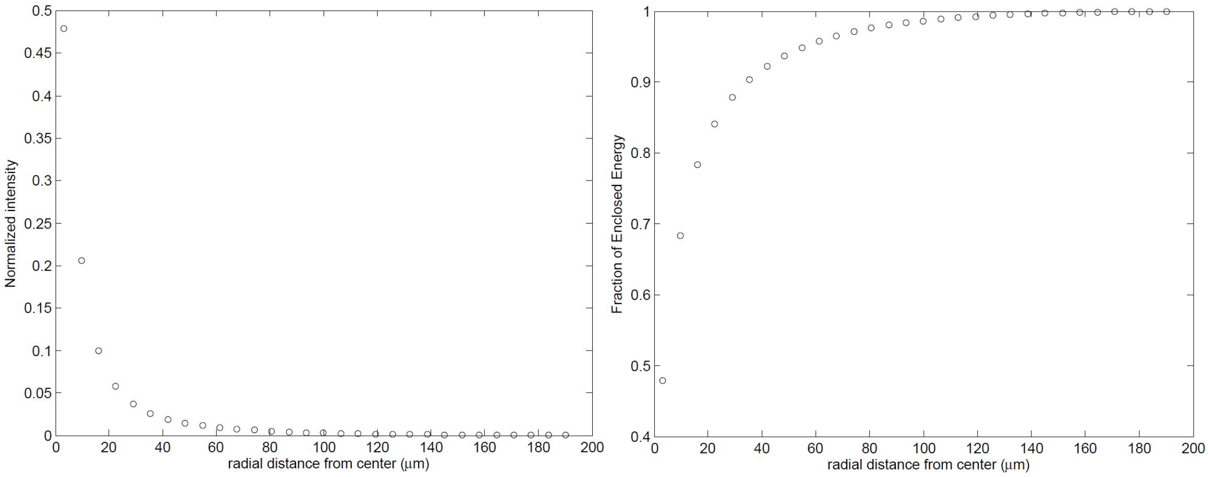


Figure 6. Experimental setup for stray light measurement.

During the first laboratory test, a CCD model Starlight SXV-H9 CCD with higher resolution than the iXon897 was used. The Camera has a progressive scan CCD chip from Sony with 1392×1040 pixels, 6.45µm×6.45µm pixel size and a good dynamic range around 10000 using 2×2 binning.
In the beginning, the brightness of the light source was adjusted to provide enough photo-electrons on the CCD camera at 10 millisecond exposure times and several images were recorded and averaged. Then, the dark field was subtracted and the exposures were flat field corrected to remove instrumental effects. The pixel size of the SXV-H9 camera was 2.48 times smaller than the iXon897 which makes it possible to quantify the PSF of the telescope.

Figure **7**a shows the intensity profile of the PSF and documents that the size of the FWHM of the profile is around the pixel size of the iXon897. Figure 7b shows the fraction of encircled energy versus radius from centroid, calculated from the data on Figure 7a. The result agrees well with the design simulation shown in Figure 3.



(a) (b)

Figure 7. a) Intensity profile of image of a point source on the CCD camera (PSF) and b) Fraction of encircled energy.

For measuring the amount of stray light for the BBSO mode, the Starlight camera was replaced with the Andor camera and the intensity of the light source was measured with a 10ms exposure time and the OD=3 ND filter. Then the filter was removed and the image of the point source was masked by an occulter in the first focus of the telescope. In order to improve the sensitivity of the stray light measurement, the exposure time was increased to 10s resulting in an overall increase of 10^6 times of the sensitivity. Several images were recorded and analyzed. The intensity distribution was normalized by dividing by the PSF peak intensity. The intensity distribution for an on-axis point source is illustrated in Figure 8a. The same procedure has been used for the Lund mode in which the occulter was replaced by a KEDF OD= 4.0 masking the on axis-field point. The 2D normalized color plots of the results are shown in Figure 8b. The figures show a level of about 10^{-6} of scattered and straylight in the unmasked region of the CCD. Further attempt to reduce this level will take place by proper baffeling of the telescope.

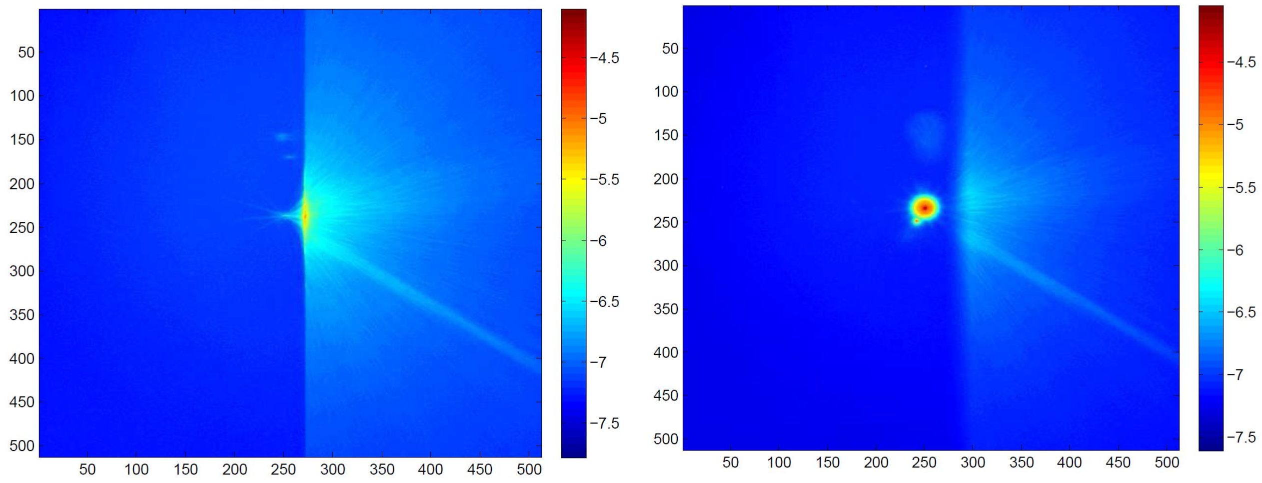


Figure 8 Normalized stray light a)BBSO b)Lund mode for KEDF density 4.0.

4. DISCUSSION

Achieving a precision of around 0.1% for albedo measurements poses serious technical challenges, which fall in two categories: instrumental design and data reduction. Optical simulations of the telescope have demonstrated promising result with respect to aberrations, straylight and ghost images[3]. However the laboratory test results show that the instrument does not yet meet the needed low level of straylight (around 10^{-9}). More investigations for selecting adequate shape and material of baffles for better rejection of straylight, in particular between the objective lens and the field stop, will be needed. Correction for atmospheric scattering by post-processing poses several problems, comprising dark current removal, flat field correction, scattered light removal and differential extinction correction, of which flat field correction and scattered light removal are the most challenging issues currently under investigation. Selection of a site at high altitude with fewer aerosols will reduce scattered light contribution to the intensity of the disk of the Moon and allow high quality data reduction.

In addition to the requirement for high precision, the instrument needs to be stable for long-term monitoring of the Earth’s albedo. Provisions for high precision and stability put heavy demands on calibration of the camera gain factor, the filters and the KEDFs. It will probably also be necessary to clean the front window with regular intervals.

As soon as some laboratory test and photometric calibration of the telescope are finalized, the RET will be ready for operation, development of the control program and software debugging. On the software side much work was done to provide a smooth interface to scientific users. LabVIEW was used for programming, yet the operator will need no knowledge of LabVIEW. It is planned that the LO/DMI RET will go into operation in the first half of 2011.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Pallé E., Goode P.R., Montañés-Rodriguez P. and Koonin S.E., "Earthshine and Earth’s reflectivity," Bulletin of the American Astronomical Scociety 32, p833 (2000).
[2] Thejll P.,Flynn C., Gleisner H. and Mattingly A., "Earthshine: Not just for romantics," A&G 49, 315-320 (2008).
[3] Owner-Petersen M., Andersen T., Ardeberg A., Thejll P., Gleisner H., The Earthshine Telescope Project, SPIE V.7012, 2008.
[4] Pallé E., Goode P.R., Montañés-Rodriguez P. and Koonin S.E., "Changes in Earth’s reflectance over the past two decades," Science 304, 1299-1301 (2004)

[5] Pallé E., Goode P.R., Montañés-Rodriguez P. and Koonin S.E., "Can Earth's albedo and surface temperatures increase together?," EOS, Transactions American Geophysical Union 87, p37 (2006).
[6] Edmund optics, http://www.edmundoptics.com/technical-support/optics/anti-reflection-coatings