THE JULIET INSTRUMENT FOR ALBEDO MEASUREMENTS

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ABSTRACT

The energy balance of Earth, i.e. the balance between the incoming short wave solar irradiation and the outgoing long-wave radiation is a crucial parameter in climate models. A fraction of the incoming radiation is reflected directly back into space and therefore does not contribute to the balance. Thus accurate determination of Earth albedo is of high importance when constructing climate models. Determining the albedo is not straightforward as it varies with Earth seasons, snow, ice and cloud cover.

Earth albedo may be determined by direct observing Earth using space based instruments in low-Earth orbit. However, this method requires long observing series which are subsequently stitched together to give an albedo measurement.

An alternative approach is to observe the bright and dark part of the lunar disk. The dark part of the disk is illuminated by the bright Earth. Provided that the orbital geometry is accounted for, the brightness ratio between the dark and bright part of the lunar disk contains directly the albedo for the part of Earth that illuminates the Moon.

Here we present the first space based earthshine telescope JULIET, the requirements for such an instrument and the expected results it will return.

1 INTRODUCTION

The largest driver of climate on Earth is the energy input from the Sun. In essence, the balance between the incoming short wave radiation from the Sun and the outgoing long wave radiation to space determines Earth temperature. While measuring the energy flux from the Sun at Earth orbit distance is relatively simple establishing Earth absorbance coefficient of short wave radiation is more involved. The main reason for this is the combination of the temporal variation of the absorbance coefficient and size of the Earth. It is possible to do measurements on the solar illuminated Earth disc from for instance L1 [1], however instrument calibration to mitigate sensor aging and/or drift remains challenging. Another approach is to do spot measurements from LEO and then stich the measurements together as done with e.g. the CERES instruments, the GCOM-C1 satellite and the upcoming Clarreo Pathfinder mission [2,3,4,5]. This method of direct Earth observation from LEO also has the calibration issue and the temporal resolution is less.

The method presented here eliminates the calibration issue by doing relative photometry. Further, it integrates larger part of the Earth disc offering better temporal resolution than the LEO direct observation approach.

Although the sought parameter is the Earth absorbance coefficient in reality, it is the reflectivity or albedo of Earth that is measured. Equation 1 gives the relation between the absorbance coefficient and albedo.

$$\boldsymbol{absorbed = 1 - albedo} \tag{1}$$

Thus, the absorbed energy from the Sun is calculated as eq. 2.

$$\boldsymbol{I_{absorbed} = I_{sun}(1 - a)} \tag{2}$$

Where a is the albedo of Earth.

2 THE JULIET MISSION

The juLIET instrument is based on the idea of applying relative photometry using the lunar disc to establish a value for Earth albedo. Leonardo da Vinci realized that the dark part of the lunar disc is illuminated by sunlight reflected off of Earth and back into space. Explaining why the dark part is sometimes visible to the naked eye. In 1925 André-Louis Danjon developed a method to measure the brightness of the earthshine [6].

A continuous registration of earthshine was commenced at the Big Bear Observatory in 1998 [7]. In 2008 a robotic earthshine telescope was proposed and described by a group of scientist at the Danish Meteorological Institute, the Tuorla Observatory, the Groove Creek Observatory and Lund University [8,9]. The telescope was constructed and operated at Mauna Loa Hawaii. Results revealed that Earth's atmosphere scatters light too much – even at 3397 m altitude – to obtain the desired accuracy of 0.1 W/m^2 (see 2.2). Recently experiments with the telescopes on-board Flying Laptop (FLP) have been conducted in order to gain a better understanding of the scattered light issue void of atmospheric contributions [10].

2.1 A protoflight instrument on-board ROMEO

The juLIET instrument will be built as a protoflight instrument intended to demonstrate the feasibility of a space based earthshine telescope. It will fly on-board the ROMEO satellite built by Institut für Raumfahrtsysteme (IRS) at Stuttgart University. The allotted mass for the system is 2.5 kg and the allowed maximum power consumption is 15 W. The ROMEO satellite will be launched to LEO at an altitude of 600 km for the first phase of the mission. First phase is expected to last three months after the completion of the LEOP. In the second phase of the mission an experimental propulsion system will raise ROMEO orbit apogee to ~2500 km at the same time lowering the perigee to 350 km. The second phase is expected to last 150 days. Operation of the juLIET instrument during the second mission phase is not prohibited but does not have priority.

2.2 Earthshine telescope

The basic principle of an earthshine telescope is depicted in figure 1. The Sun illuminates both the Moon and the Earth. A fraction of the sunlight hitting Earth is reflected back into space as earthshine. The earthshine illuminates the dark part of the lunar disc. The juLIET instrument will observe the Moon and measure light intensities from both the bright and the dark part of the lunar disc. The ratio between the two light intensities is determined by the albedo of Earth, when geometric factors are accounted for.

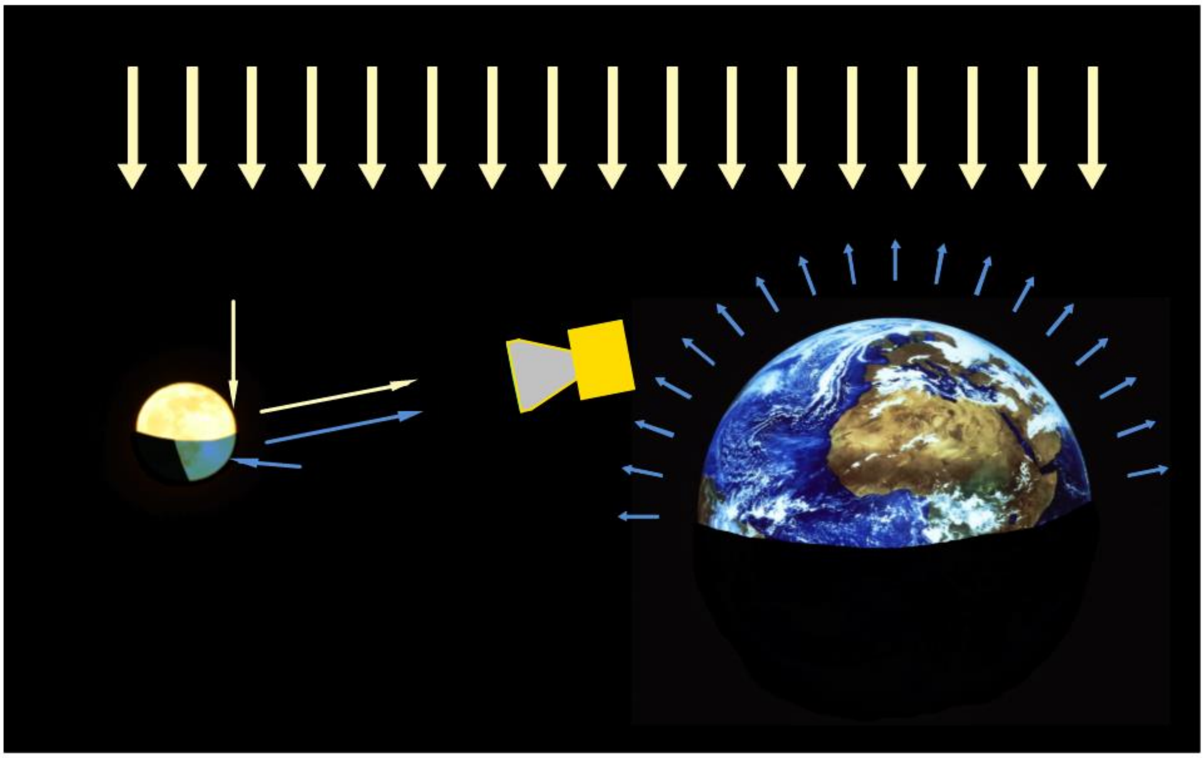

Figure 1. The basic principle of the earthshine telescope. Sun light illuminates both the Earth and the Moon. Except at full Moon the lunar disc has a bright and a dark part. The dark part of the disc is illuminated by earthshine. The earthshine flux equals the solar light flux times Earth albedo. Taking the ratio between the bright and dark part of the lunar disc reveals the Earth albedo, when geometric factors are accounted for.

2.3 Accuracy requirement and photometry

The relation between Earth albedo and Earth surface temperature is given by 3

$$\boldsymbol{T_s^4 = \frac{C}{4\sigma(1-g)}(1-a)} \tag{3}$$

Where C is the solar constant, σ is Stefan-Boltzmann constant and g is the normalized greenhouse effect [11]. Equation (3) may be used to set the sensitivity requirement for the juLIET instrument. Assuming that the Earth mean temperature is 288.15 K and that changes of 0.1 K should be detectable means that changes of the albedo of 0.00139 or ~0.14 % should be registered. Establishing a value for Earth albedo requires series of recorded data which is stitched together. However the accuracy of the albedo depends on the accuracy of the accumulated data, therefore the measurement accuracy requirement for the juLIET instrument is set to 0.1 %.

As the Moon orbits Earth the lunar phase changes as seen from Earth (see figure 2 left) with the phase change the lunar albedo also changes. The reason for this lies in the optical properties of the lunar surface. Reference [11] reported a model for the lunar albedo phase dependency. An approximated graph from [11] has been reproduced (see figure 2 middle) and wrapped onto the lunar phase map, figure 2 left. As the property stems from the lunar surface it also affects the reflectance of earthshine, however if the observing satellite is in LEO the phase angle of the earthshine is close to 0°. The ROMEO satellite orbit altitude starts at 600 km, yielding a maximum earthshine phase angle of 1°.

The lunar phase is opposite of Earth. This means that when we see a new Moon from Earth a full Earth is seen from the Moon. Thereby the lunar phase angle may be used to calculate the fraction of Earth that illuminates the dark part of the Moon. Figure 2 right shows how the lunar phase angle may be used to calculate the minor axis of an ellipse on the lunar disc. Half the ellipse area plus half the lunar disc area represents the solar illuminated area of the lunar disc – provided that the sign of the elliptic area is determined by the cosine function. In figure 2 right the elliptic area has a negative cosine and is therefore subtracted from half-circle area. Vice versa for lunar phase angles less than 90° the two areas are added. Subtracting the ratio of the solar illuminated area to the lunar disc area from one yields the ratio of the Earth illuminated area that shine onto the Moon, setting r_{moon} to unity yields equation 4. The calculation assumes that the lunar orbit lie in the ecliptic plane. As the lunar orbit is tilted with 5.145° to the ecliptic plane the calculations are only approximate.

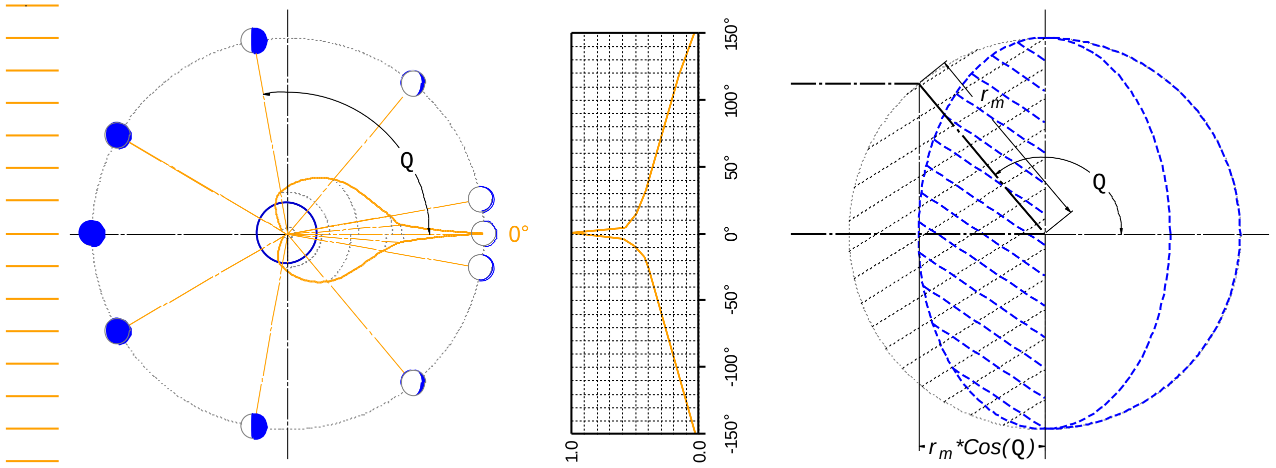

Figure 2. Left part illustrates how the lunar albedo changes with the lunar phase angle as described by [11]. Right illustrates how the lunar phase angle laid on top of a lunar disc may be used to calculate minor axis of an ellipse. Half the elliptic area (calculated with sign) added to half the lunar disc area gives the area of the solar illuminated part (bright side) of the Moon. The ratio of the illuminated area to the full disc area may be used to calculate the ratio of the Earth illuminated area seen from the Moon, i.e. give a quantity of how much of bright Earth is being measured by the juLIET instrument as a function of the lunar phase angle.

$$1-\left(\frac{{}^{1}/_{2}*\pi r_m^2+{}^{1}/_{2}*\pi r_m\cos(\theta) r_m}{\pi r_m^2}\right)=\frac{1-\cos(\theta)}{2} \qquad (4)$$

From figure 2 and equation 4 it is seen that it will not be possible to obtain data at all lunar phase angles. At small phase angles the observed Earth area is small or zero at the same time the full Moon brightness will generate maximum diffraction noise. For phase angles close to 180° it will be difficult not to be blinded by the nearby Sun at the same time the bright lunar disc, i.e. the reference area will be small or zero. For these reasons the requirements for observations has been limited to lunar phase angles of larger than +/- 30° and less than +/- 140°, meaning that the observed area of bright Earth varies between approximately 7% and 88%.

2.4 The juLIET instrument noise

Reference [8] reports of a ratio between the bright and dark side of the lunar disc of up to 1:10,000 from figure (2) it is clear that this situation occurs at low lunar phase angles. Thus the juLIET instrument should have a dynamic range of at least 1:10,000. A 14 bit ADC would just cover that range. To have some head-room the instrument will be equipped with an ADC of 16 bit. As the bright part of the lunar disc provides an amble amount of photons the challenge of reaching the desired dynamic range lies in obtaining sufficient low light sensitivity. Low light sensitivity may be obtained through signal amplification however this will be in vain if the system noise level is too high.

System noise contributions stems from light scattering in the telescope optical path and electrical noise generated in the detector and amplifier system. Moving the telescope to LEO will remove scattered light from the atmosphere. Scattered light due to aperture limitation and surface imperfection will still contribute light noise. At this point the telescope optics is not fully characterized.

The signal generated by the optical detector may be calculated as (5).

$$\boldsymbol{s = \alpha Q N} \tag{5}$$

Where α is the conversion efficiency of the electronics converting the incoming photons to electrons, Q is the quantum efficiency of the optical detector element and N is the number of photons. Noise in the detector system may arise from shot noise, dark current, read noise and bias noise. Here we will neglect the contributions from read and bias noise. The two remaining noise sources are expressed as (6) and (7).

$$\boldsymbol{n_{shot} = \alpha\sqrt{QN}} \tag{6}$$

$$\boldsymbol{n_{dark} = \alpha\sqrt{\beta(T)t}} \tag{7}$$

Where $\beta(T)$ is the dark current as a function of temperature and t is the measurement time. With no detector system to measure on yet estimates on the noise contributions are made instead.

The lowest photon flux stems from the dark part of the lunar disc at low lunar phase angles. As stated earlier empirical knowledge obtained by [8] revealed a photon flux 10,000 times weaker. Reference [12] reports a photon flux at Earth distance of 600 µW/m^2. The allotted surface area for the juLIET instrument on the ROMEO satellite is 100x150 mm^2. This allows an aperture diameter of ~70mm. Using a wavelength of 550 nm yields approximately 6.4*10^{12} photons/sec for the bright Moon and thereby roughly 6.4*10^8 photons/sec for the dark Moon.

Estimate of dark current is made using data from Thorlab photo-detectors. Thorlab state of the art detectors reaches I_{dark} ~2pA with a detector area of 1.21*10^{12} m^2 yielding 1.65 µA/m^2. As the detector area is not fixed yet the 2pA is assumed, yielding 12.5*10^6 electrons/sec.

The quantum efficiency Q is assumed to be 0.85.

With these numbers it is possible to estimate the signal to noise levels for the two noise sources (8) and (9).

$$\frac{s}{n_{shot}} = \frac{\alpha Q N}{\alpha\sqrt{QN}} = \frac{0.85 * 6.4 * 10^{8}}{\sqrt{0.85 * 6.4 * 10^{8}}} = \mathbf{2.3 * 10^{4}} \tag{8}$$

$$\frac{s}{n_{dark}} = \frac{\alpha Q N}{\alpha\sqrt{\beta(T)t}} = \frac{0.85 * 6.4 * 10^{8}}{12.5^{6}} = \mathbf{43.5} \tag{9}$$

With the requirement of 0.1% signal resolution it is clear that optimization on the detector dark current is necessary. As the dark current is temperature dependant one approach could be to lower the detector temperature.

3 SUMMARY

The juLIET is designed, developed and manufactured at the Technical University of Denmark under a PRODEX contract number 4000135179. The instrument is a pilot demonstrator built as a protoflight unit. It will be mounted on the small satellite ROMEO and launched to LEO no earlier than Q3 2025. The overall mission goal is to demonstrate the feasibility of an earthshine telescope as an instrument to determine Earth albedo and to achieve higher accuracy of the Earth albedo than present day (goal: +/-0.1%). The three major benefits of a space based earthshine telescope are:

- the relative photometry applied which eliminates the need for calibration due to instrument aging
- the large observation area reaching up to 88% of bright Earth area
- the elimination of light scattered from Earth atmosphere

The juLIET instrument specifications is listed in table 1.

Table 1. The juLIET mission specifications.

Available power, max	15	W
Maximum mass	2.5	kg
Aperture diameter	70	mm
Primary mission length	3	mnths
LEO altitude	600	km
Lunar observation phase angles	+/-30 to +/-140	°
Bright Earth observation ratio	7 to 88	%
Albedo measurement accuracy	+/-0.001	

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