ATMOSPHERIC OBSERVATIONS FROM THE MOON: A LUNAR EARTH-OBSERVATORY

Patrick Hamill

Department of Physics and Astronomy
San Jose State University, San Jose, California, USA
NASA Ames Research Center
Moffett Field, California, USA

ABSTRACT

A telescope placed on the Moon would be valuable tool for studies of the atmosphere and climate. In this paper, we consider an observatory placed on the Moon to make observations of the Earth's atmosphere. We discuss the properties of such a telescope, the types of observations to be made, the benefits of having a telescope on the lunar surface and difficulties that may be encountered.

Index Terms— Lunar Telescope, Atmospheric Science, Climate Studies, Earth Observatory

1. INTRODUCTION

Measurements made by a telescope looking at Earth from the surface of the Moon would be beneficial to atmospheric scientists studying weather, atmospheric composition and the climate. Due to the geometry of the system, the entire disk of Earth is always visible from most locations on the Earth-facing side of the Moon. During the 28 day orbital period of the Moon, both the daylight and dark sides of Earth are visible. This allows one to observe the entire disk of the Earth (half of the surface) at any given time, and during one orbital period of the Moon, to observe both the day and night sides. Since the Earth's rotation rate is much faster than the Moon's orbital motion, nearly every point on the surface of Earth is in sight during each 24 hour period.

It should be noted that a telescope has already been placed on the surface of the Moon, namely, the 15-centimeter UV telescope on Chang'e 3, the Chinese lander that touched down on the lunar surface on December 14, 2013. (See Figure 1.) The telescope was still operational by early 2016. This telescope was designed to monitor bright variable stars in the near UV for periods of up to 12 days and to carry out a near UV sky survey at low Galactic latitude [1].

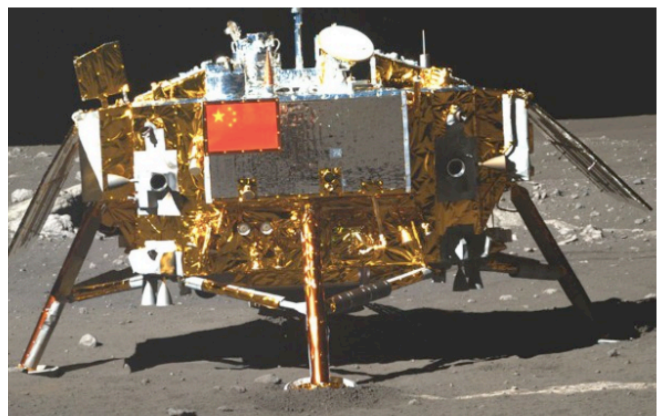

Figure 1. Photograph of the lander of Chang'e-3 taken from the Yutu rover.

The DSCOVR satellite (previously known as TRIANA) was placed at the Lagrange L1 point and observes the entire disk of Earth with a 30.5 cm telescope. The primary objective of the DSCOVR mission is to study "space weather," i.e., the properties of the solar wind and the interplanetary magnetic fields. A secondary objective is to generate data for atmospheric science and climate studies. To accomplish these goals it not only has an optical telescope, but also a cavity radiometer to measure the irradiance reflected and emitted from the face of the Earth. Due to its location in space, between the Sun and Earth, DSCOVR at all times observes the illuminated face of Earth.

In 2007 NASA considered sending astronauts to the Moon to establish a moon base and requested that the scientific community suggest scientifically valuable activities. A meeting of the NASA Advisory Council (NAC) in February 2007 considered a variety of suggestions, including proposals for a lunar telescope. However, the idea of manned flights to the Moon and the establishment of a lunar base were later abandoned. Many of the ideas described in this paper are based on concepts described at the NAC meeting [2].

As mentioned, a telescope placed on the near side of the Moon can observe the entire disk of Earth. No satellite in low Earth orbit can do this. A satellite in geosynchronous orbit observes one third of the total area, but is limited to the same view at all times. A satellite at the unstable Lagrange point between Earth and Sun (L1) only sees the sunlit side of Earth and cannot be permanent because of the need for continuous orbital corrections leading to the eventual depletion of fuel. L1 is about a million miles from Earth. The Earth-Moon distance is somewhat less than one fourth of this value.

From the Moon, over the course of a day as the Earth rotates, all sublunar points are visible. During the course of a month, due to the tilt of the Moon's orbit by about 5 degrees relative to Earth's equator, the two poles alternately point towards the Moon, giving excellent coverage of these important regions every 14 days. (As seen from the Moon, Earth exhibits phases, from "new Earth" through "full Earth" to "waning Earth" until it presents its dark side to the Moon. For example, in late spring, an observatory on the Moon would be looking "up" at the Antarctic region during "new" Earth; at "full Earth" it would be over the equator, and as the Earth wanes, the observatory would be looking "down" on the Arctic region.)

An interesting feature of the observations of Earth's night side will be the quantification of artificial illumination related to population growth and industrialization.

Over the course of a year, the view of Earth varies in an interesting way as the Sun illuminates the Earth from different angles, due to the 23.5 degree tilt of Earth's axis of rotation relative to the ecliptic.

The varying views of Earth, the visibility of the entire disk, the relatively rapid rotation of Earth and the stability of the lunar surface make the Moon an ideal location for long-term monitoring of the Earth.

In Section 2 we consider the expected characteristics of the lunar telescope and the associated sensors, in Section 3 we discuss the benefits that are expected from placing an Earth Observing telescope on the Moon and in Section 4 we consider some difficulties and problems associated with this proposed project.

2. THE INSTRUMENT

The Lunar Earth-Observatory is essentially a telescope placed somewhere on the surface of the Moon and focused on the Earth. The observatory would consist of a telescope and a number of standard instruments such as a diffraction grating with an associated CCD array, a CCD camera, a radiometer, and the associated telemetry. The telescope diameter should be between 0.5 and 0.75 meters, this being a compromise between the desire for a small instrument and the desire of high resolution. For the sake of comparison, a telescope with a diameter of only 0.25 meters has a theoretical resolution of about 1km X 1km on the Earth's surface. The Ozone Measurement Instrument [3] (OMI on AURA) has a nadir pixel of 13km X 24km and it scans the entire Earth once per day. If the Lunar telescope had a resolution of 100km X 100km, and the CCD array were integrated over 1 sec, the entire disk of Earth, could be scanned in about 3.5 hours.

The telescope would scan the disk of the Earth and the light from different points on the Earth would be sent through a diffraction grating onto the CCD array. This allows one to determine the column amounts of various atmospheric gases, such as ozone, CO_2, SO_2, NO_2, as well as aerosols. When the opportunity arises, the telescope could be used to track the image of a bright star as it is occulted by Earth [4]. Such scans are best carried out as the star descends onto the dark limb of Earth to avoid "earthshine" and to obtain maximum contrast. From the vantage point of a satellite in a 500 km orbit, a star descends through the atmosphere at a speed of about 8 km/sec. From the vantage point of the Moon, a star descends at about 1 km/sec, that is, eight times slower. Thus since stellar occultation is possible from artificial satellites (the GOMOS instrument on ENVISAT [5], for example), it will be even easier from the surface of the Moon. Note that a star is always a point source, so scanning is not required, as in most solar occultation measurements. (One cannot carry out solar occultation from the Moon because it only occurs during "Earth eclipses.")

Infrared measurements usually require cooling instruments with cryogens, but on the lunar surface extremely low temperatures are obtainable by simply shading the instrument during the day. Furthermore, the side of the Moon facing Earth is dark for half of the month, so cycling between extreme cold and extreme heat allows one to consider the possibility of some sort of heat engine operating in (perhaps) a Stirling cycle to power various components.

The surface of the Moon is a highly stable platform, so the observatory should be built to operate for a very long time (decades rather than years). This is reasonable when one considers that many satellite observing systems have lasted much longer than their expected lifetimes. (For example, the SAM II system lasted 15 years before it was turned off due to orbit degradation. The instrument was still operational.) Therefore, the instrumentation of the observatory should be standard and well developed rather than innovative.

Although the surface of the Moon is certainly a difficult environment, it is perhaps more benign that the environment of an artificial satellite. The Moon is a stable platform not requiring corrections for drift nor subject to the vibrations of satellites. The temperature extremes on the Moon have a periodicity of a month rather than several hours.

3. BENEFITS

There are many reasons for placing an Earth atmospheric observatory on the Moon. Perhaps the most obvious reason is that from the Moon one can observe a single location on Earth for a relatively long period of time (hours, rather than seconds for a satellite in LEO). During a 24 hour period, nearly every point on the surface of Earth can be monitored, and during one month, both the sunlit and night sides of the Earth will have been observed. Further, there will have been excellent views of the polar regions.

The visible images of the entire illuminated surface of Earth will allow one to evaluate in an unambiguous manner the total cloud fraction of Earth's atmosphere. The scans will allow one to determine the composition of the Earth's atmosphere in terms of the major trace gases and aerosols. The polarization of the scattered light will also yield information on the aerosol type.

Stellar occultation allows one to determine profiles of extinction from aerosol particles, and the altitude dependence of concentrations of gas species such as O_3, CO_2, etc. Profiles of stratospheric particle extinctions are of particular interest following energetic volcanic eruptions that inject large amounts of SO_2 into the stratosphere. Profiles of O_3 allow one to determine the vertical structure of the Antarctic ozone hole and "mini ozone holes" in the Arctic. Stellar occultation is a valuable technique for studying the formation and structure of polar stratospheric clouds. The GOMOS instrument on ENVISAT was operational from 2002 to 2012 and during that time it observed well over 10,000 stellar occultations. Perot et al. [6] present a polar mesospheric climatology based on these measurements.

The formation of dust clouds, particularly from regions such as the deserts in Northern Africa and Central Asia, and their atmospheric dispersion is an important scientific and environmental problem. The lunar observations could shed light on the relationship between the presence of dust and the formation of hurricanes in the Atlantic Ocean.

The fact that the entire disk of the Earth is visible from the Moon make it an excellent location to measure the radiation balance of the Earth. Consequently, a component of the observatory would be an ERBE/CERES type of radiometer to measure short and longwave radiation [7]. The goal would be to monitor, on a continuous basis, the global energy balance, planetary brightness, regional forcings and the net radiative effect of clouds [8]. The fact that during the course of a month Earth presents both day and night faces to the Moon allows one to determine emitted and reflected radiation under a variety of solar illuminations.

Volcanic plumes are a well-known danger to aircraft. Some regions of Earth that are not well monitored, such as the Arctic regions between North America and Asia, are locations of frequently occurring volcanic eruptions. Monitoring of the Earth from the Moon would offer an early warning system for volcanic plumes reaching aircraft altitudes.

The atmosphere above a low earth orbit satellite is tenuous but not entirely negligible. The fact that the Moon has essentially no atmosphere, means there is no interference of measurements of the radiation emitted from the surface of Earth.

It should be mentioned that the lunar observatory presents a great opportunity for education, allowing students to access "real time" pictures of Earth and to carry out analyses with the data obtained.

4. PROBLEMS TO BE OVERCOME

There are a number of problems associated with placing an observatory on the Moon. We will consider a few of them.

As alluded to above, the surface of the Moon is a harsh environment. During the sunlit period, the temperature ranges from as low as 120 K during the lunar night to nearly 400 K during the day in direct sunlight. It would be beneficial to place the observatory in a deep crater, shielded from the direct rays of the sun and thus maintained at a nearly constant very cold temperature. In the absence of an appropriate cavity, it might be possible to shield the observatory artificially by erecting tall walls around it, so that it would be shaded from the sun except during short intervals.

The lunar surface is covered in electrostatically charged fine dust particles of diameter 70 μm. This dust has sharp edges (not having been exposed to weathering) and is expected to cling to surfaces to which it is exposed. It is believed that the dust is disturbed by the changing electric field at the terminator and rises to heights of several meters [9]. This effect may have been observed by the Apollo astronauts. The dust may damage unshielded equipment [10]. Some investigators have even suggested that the presence of dust would make telescopic observations impossible, but the evidence from Chang'e 3 shows that this is not the case. (It might be mentioned that the Chang'e 3 instrumentation is protected during sunrise and sunset.) Furthermore, the retroreflectors placed on the lunar surface by NASA Astronauts and Soviet robotic rovers over forty years ago still reflect laser beams, indicating that even over long periods of time optical surfaces are not completely degraded by the lunar dust [11].

The difficulties and problems in the construction of a large lunar telescope were considered by Van Susante [12]. These can be alleviated by constructing the entire observatory on Earth and enclosing it in a single package. This is sometime referred to as "suitcase science."

In considering telescopes on the Moon it is often assumed that they will be placed in the Malapert Mountain region near the South Pole, as the NAC committee deemed the nearby rim of the Shakelton Crater to be the preferred site for a manned lunar outpost [2]. However, at this location the Earth is not visible at all times. The optimal location of the observatory would be in a deep crater near the Earth-facing equatorial region of the Moon.

5. CONCLUSION

We have outlined some of the benefits and some of the difficulties of placing an Earth-observing telescope on the Moon. The benefits are the ability to view the full face of Earth both during day and night. The radiation emitted from the total disk of Earth can be measured at one instant of time, and the visible image will give information on clouds and desert dust plumes. Stellar occultation will allow one to determine atmospheric composition as a function of altitude. As the concept is more fully developed many more benefits will surely be appreciated, and solutions will be found for the problems we have mentioned. The feasibility of such a project has been demonstrated by the performance of the Chang'e 3 telescope.

6. REFERENCES

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