A LUNAR EARTH OBSERVATORY
Patrick Hamill
San Jose State University and NASA Ames Research Center
The psychological impact of seeing Earth from Space should not be underestimated. Imagine real time pictures of Earth from the Moon as seen on “Google Earth.”

(Picture of Earth taken by the Apollo Astronauts on their way to the Moon)
EARTH AT NIGHT
From “La Voyage dans la Lune” a 1902 film by Georges Melies based on the novel by Jules Verne.
Brave blue world

Human spaceflight is no excuse for ignoring the home planet, which needs constant monitoring from space.

It is commonplace to dismiss NASA’s human spaceflight efforts as a waste of money and expertise. For a country with an alarming budget deficit to devote tens of billions of dollars to a project with so little prospect of palpable returns is hard to justify. Certainly, science does not come close to offering a justification.

But arguments against this peculiarly pricey form of showing off, however strong, will not prevail in the foreseeable future. Space exploration resonates with the expectations many Americans have of their country as a home to the exceptional, a conqueror of frontiers and a leader of the world.

Furthermore, the inspiring, potentially transcendent impact of human spaceflight on the imagination should not be lightly dismissed. In the words of one uplifted pioneer: “In that instant I could feel no doubt of man’s oneness with the universe... it was a feeling that transcended reason; that went to the heart of man’s despair and found it groundless. The universe was a cosmos, not a chaos; man was rightfully a part of that cosmos as were the day and night.”

The pioneer quoted above was not an astronaut, although he got as close to the alien isolation of space as any man could at the time. He was the US Antarctic explorer Richard Byrd. As NASA administrator Michael Griffin has argued, there are some interesting parallels to be drawn between the history of Antarctic exploration and the possible future for American spaceflight. But there are differences, too, which NASA, the Bush administration and Congress should pay careful attention.

Griffin points out that after the South Pole was first explored, it was largely ignored for decades before an eventual return in the 1957 International Geophysical Year led to a continuous presence. Similarly, NASA’s plans now call for ending the post-Apollo hiatus by setting up a permanent lunar base — probably at the south pole. But there the comparisons end. For one thing, the renewal of Antarctic exploration was empowered by new technologies, notably reliable diesel engines, capable aircraft and portable radios. But the technologies that NASA plans to implement on its return to the Moon look remarkably similar to those it used the first time (see page 474).

Another difference is that ever since humanity’s return to the South Pole, Antarctic science has been central to the great project of understanding the changes that humans are inflicting on the Earth. An Antarctic component to the nascent global carbon dioxide monitoring effort was established in 1957. Since then the contributions have been legion: discovery of the Antarctic ozone hole; the extraction of greenhouse-gas records and climate data reaching back more than half-a-million years from ice cores; the study of the anomalous warming of the Antarctic peninsula; and so on.

Although lunar research may illuminate some far deeper recesses of Earth’s history, the Moon is no Antarctica: the only input that lunar activity will provide for the study of Earth is the iconic and inspiring sight of a blue planet in a black sky over a grey desert.

The human exploration of new worlds may well be important, as inspiration and even, eventually, as something more. But it is not urgent in the same way as understanding and monitoring the Earth system. This is why, as the amount NASA spends on its new vision of exploration increases, it is vital that the resources needed to monitor and study Earth are brought up to the levels required, from which funding currently falls short. As a report by the National Academy of Science recently pointed out, some of this remediation needs to take place at the National Oceanic and Atmospheric Administration, where various instruments need to be placed on future weather satellites or flown on other platforms. But there are also challenges for NASA, notably in studying land-use change and global precipitation, that need to be seen as high priorities for the immediate future.

Mapping the march of global change and exploring possible futures have an urgency that the study of eternal verities and ancient deserts cannot match. The Moon is not going anywhere; Earth is.
“The only input that lunar activity will provide for the study of Earth is the iconic sight of a blue planet in a black sky over a grey desert.”
Chairman Boehlert’s Opening Statement:

“The Earth science program doesn’t exist as some secondary adjunct of the exploration program…there’s no reason that NASA can’t robustly carry out the President’s vision for Space Exploration while conducting vital Earth science research.”

WHAT WE ARE PROPOSING

A robotic Lunar Observatory consisting of a 20 to 30 cm telescope, a diffraction grating and a CCD array to observe Earth at wavelengths from far IR to UV (a hyperspectral imager). A camera for visible pictures of Earth. A radiometer to measure IR radiation from Earth.

This should be long-term monitoring of Earth’s atmosphere, lasting twenty to forty years. It must be simple, rugged, and based on well developed technology.
Telescope scans across disk of Earth. Light passes through diffraction grating and measurements are made at many wavelengths from UV to IR. (Column measurements) Or we could use an “image slicer.”

Telescope can be diverted to follow the occultation of a bright star as its light passes through Earth’s atmosphere. (Profiles)

Radiometers obtain longwave energy radiated by Earth (day and night sides) on a near continuous basis.

Camera takes high resolution pictures of Earth that are instantaneously put on internet.
OBVIOUS PROBLEM # 1: THERMAL STRESS. (DAY/NIGHT TEMPERATURE VARIATION IS FROM 390 K TO 120K)

WOULD SHADING THE TELESCOPE SOLVE THE PROBLEM?
Temperature Variations

In permanently shadowed regions (at bottom of a crater) the temperature is believed to drop to a permanent 40 to 70 K and even to 30 K if shaded from reflected sunlight.

Should we place the telescope in a shadowed crater?
Maximum change in angular position of Earth is 8 degrees.

Temperature 40 to 70 K

Other components require higher temperatures.
OBVIOUS PROBLEM # 2: PHASES OF THE EARTH.
OBVIOUS PROBLEM # 3: LUNAR DUST

MAY NOT BE A SERIOUS PROBLEM (LUNAR RETROREFLECTORS HAVE BEEN OPERATIONAL FOR ≈ 40 YEARS)
The Dust Problem

Dust has been observed at the lunar terminator. It is believed that dust particles of < 0.01 cm to 5 cm in radius are elevated up to 30 cm at the terminator and is due to contracting sunlit areas during sunset. The problem is probably much less serious in permanently shadowed regions.

Properties of the dust:

• Size range = mean diameter of 70 microns, about 20% smaller than 20 microns

• Electrically charged and sticks to any surface

• Coarse, sharp dust particles can degrade bearings, seals and other moving parts.

• Did not affect performance of rovers although covered in dust
SCIENTIFIC OBJECTIVES

1. Routine Measurements of
   - Column Ozone
   - Column trace gases such as SO$_2$, NO$_2$, CO$_2$ etc.
   - Aerosol optical depth
   - Cloud heights, cloud reflectivity, precipitable water

2. Stellar Occultation allows for determination of profiles of
   - Aerosol extinction
   - Ozone concentration
   - Other trace gases
SCIENTIFIC OBJECTIVES

3. Visible (photographs)
   • Weather prediction, Polar Sea Ice. Hurricane tracking.
   • Forest Fires, Early warning of volcanic plumes.
   • Industrialization as characterized by lights at night.
   • Dust storms, Asian pollution plumes.

4. Radiometer measurements
   • Earth brightness, global dimming
   • Global energy balance, albedo.
   • Regional forcings, Radiative effects of clouds.
SCIENTIFIC OBJECTIVES

5. More speculative objectives

- Cross calibration of instruments in low Earth orbit satellites
- Monitor the rapidly changing 11 micron radiation that may be a signature of impending earthquakes
- Observation of (say) Los Angeles pollution over a time period of several hours.
SOME EXAMPLES OF THE SORT OF DATA PRODUCT ONE COULD EXPECT FROM THE PROPOSED LUNAR EARTH OBSERVATORY

1. From stellar occultation
2. From hyper-spectral imager
3. From the visible camera
4. From the radiometer
From Stellar Occultations

Stellar occultation will yield the same sort of information that has been obtained from satellite-borne instruments using the solar occultation technique. This technique yields profiles of various quantities, including aerosol extinction, ozone concentration, etc.

We show some results obtained from the SAM/SAGE instruments
The Solar/Stellar Occultation Technique

To Sun (or Star)
What you get

From SAM II...the discovery of Polar Stratospheric Clouds
Aerosol Extinction as function of Latitude and Altitude at 4 different wavelengths

Figure 4.2: Zonal depictions of $\log_{10}$ aerosol extinction at (a) 386, (b) 452, (c) 525, and (d) 1020 nm measured by SAGE II during January 1994. The crosses represent the average tropopause altitude.
Stellar Occultation from Moon

The “descent” of a star through Earth’s atmosphere is much slower as seen from the Moon than as seen by a Low Earth Orbit satellite (by a factor of 8). Therefore integration times are greater. However, vertical resolution is limited by telescope diameter. Stellar occultation has been used by GOME and other LEO satellites.
From hyperspectral imagers such as OMI, GOME, SCIAMACHY, etc.
OMI Measurement Principle
WE CAN SCAN THE SURFACE OF EARTH OR USE A MORE ADVANCED TECHNOLOGY: AN INTEGRAL FIELD UNIT OR “IMAGE SLICER”

THIS YIELDS A THREE DIMENSIONAL IMAGE, THE FIRST TWO DIMENSIONS ARE LATITUDE AND LONGITUDE AND THE THIRD DIMENSION IS WAVELENGTH

Instead of the usual two dimensions of a normal image the IFU also records the spectrum of each point in the image
GMOS Integral Field Unit observes NGC1068

Image taken by GMOS without using the IFU

The GMOS IFU records a spectrum for each pixel

One image at each wavelength

One spectrum for each pixel in the image
EXAMPLES OF IMAGES PRODUCED BY HYPERSPECTRAL IMAGERS IN LOW EARTH ORBIT
SCIAMACHY: Anthropogenic SO$_2$ in China (2003)

Image: M. Van Roozendael (IASB-BIRA)
Aura/OMI - 05/20/2006 17:00-18:41 UT

Mass: 135.133 kt; Area: 2024.57 km$^2$; SO$_2$ max: 146.85 DU at lon: -64.79 lat: 15.72

Normalised SO$_2$ column
Visible Images of Earth
Modis: Fires in Northwestern USA
Infrared
2001 Mars Odyssey's Thermal Emission Imaging System (THEMIS) acquired these images of the Earth in visible and IR at the same time.
Pre-earthquake IR emission.
MODIS data.

after
Ouzounov & Freund
Adv. Space Sci. 2004

M=7.6
Gujarat EQ
NW-India
Jan. 26, 2001
WHERE ON THE MOON?

Any location on the side facing Earth is acceptable as long as the Earth is visible. A polar location is not optimal because the Earth will be below the lunar horizon about 50% of the time. However, a lunar observatory on a mountain near the pole would be quite satisfactory.
A simulation showing Earth as seen from Crater Bruce from May 15 to May 30, 2006.

Note that Moon’s orbit is tilted relative to Earth’s equator by 18.5 to 28.5 degrees depending on time of year. In the following simulation initially we look up at the Antarctic, then we are over the Equator, and finally we look down on the Arctic.
INSTRUMENTATION

Possible instrument types include

a) An ERBE/CERES type of radiometer to monitor radiation from Earth.

b) A TRIANA-like camera to photograph whole Earth in visible and also in specific wavelengths.

c) A SAGE/HALOE/GOMOS type of solar/stellar occultation instrument. (Stellar occultation takes eight times longer from Moon than from an artificial satellite).

d) A SCIAMACHY/OMI type of hyperspectral imager
TRIANA: Now Deep Space
Climate Observatory (DSCOVR)

The Triana Instruments are a camera, a single pixel radiometer and an instrument to measure solar wind. It is to be placed at L1. The camera has a 30.5 cm aperture telescope, a 2048X2048 pixel CCD array giving 8X8 km spatial resolution. It records images of Earth in 10 spectral bands.

Four radiation detectors (3 active cavity radiometers, 1 photodiode) measure radiation from entire disk (.2 to 4 μm).

Since Triana at L1 views the full sunlit disk of the Earth, it cannot determine the thermal budget of the planet as a whole.

The “close to backscatter” geometry complicates analysis.
WHY ON THE MOON?

Advantages of being on the Moon:

a) The Moon is a very stable platform

b) Temperature variation (day/night) allows us to use cryogen on a long-term basis or do without

c) Entire Earth is visible (Phases of Earth introduce interesting opportunities)

d) A location on Earth can be followed over many hours. (Example: Air pollution episodes in LA or Earthquake precursors)

e) Excellent coverage of polar regions (important for ozone hole and PSC studies)
WHY ON THE MOON?

Advantages of being on the Moon (continued):

e) The Moon has no radiation belts (long exposures in LEO generate “hot pixels” due to impacts with charged particles)

f) No residual atmosphere (residual oxygen molecule impacts excite faint emissions. Effect of residual atmosphere needs to be subtracted to determine radiation from Earth)

g) No orbital debris

h) Thermal environment is stable compared to the rapid changes in temperature in LEO

i) Can do without cryogens (expendable cryogen lifetime is serious design issue in LEO)
• Power when instrument is on “night” side of Moon
• Cooling IR instruments
• Thermal stress as temperature on lunar surface varies from 120 K to 390 K.
• Is stellar occultation feasible?
• Will lunar dust affect the observatory?
• Instrumentation to determine total radiation emitted from Earth?
• Where on Moon to locate observatory?
Where do we go from here?

- Decide what measurements are most useful
- Determine the instruments needed to make the measurements
- Calculate the wavelength ranges required
- Determine the instrument characteristics
- Obtain funding for feasibility studies
- Design and build instruments
- Find a Science Team
- Get an acronym (AMBEO = Autonomous Moon Based Earth Observatory)
Practicalities

• Want 2km resolution
• Need a telescope of about 30 cm diameter
• Power requirements: < 1kW
• Cost without launch/landing: < 100 million dollars
• Mass involved: Radiometers ~ 25 kg
  Telescope ~ 30 kg
  Spectrometer ~ 10 kg
  Camera ~ 20 kg

[For Comparison: Mars Observer Camera: Total payload 85 kg, total power 90 Watts, data rate 1.5 Kbps]
A Lunar Earth Observatory allows us to:

- View entire Earth, pole to pole, continuously
- View any point on Earth over fairly long periods
- Calibrate Low Earth Orbit satellites
- Measure total Earth radiation from day and night sides on a continuous basis
- Generate a long-term “Standard Earth Atmosphere”
CONCLUSION

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.
Bumper Sticker

ALL THE EARTH ALL THE TIME
Bumper Sticker

IT WOULD BE DUMB NOT TO DO IT!
The End