

The Lunar Terrestrial Observatory: Observing the Earth using photometers on the Moon's surface.

E. Pallé¹, P. R. Goode²

¹*Instituto de Astrofísica de Canarias, Via Lactea s/n, E38205, La Laguna, Spain.*

²*Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City,
92314, USA.*

Abstract

1 The Earth's albedo is one of the least studied fundamental climate parameter.
2 The albedo is a bi-directional variable, and there is a high degree of anisotropy
3 in the light reflected from a given terrestrial surface. However, simultaneously ob-
4 serving from all points on Earth at all reflecting angles is a practical impossibility.
5 Therefore, all measurements from which albedo can be inferred require assumptions
6 and/or modeling to derive a good estimate. Nowadays, albedo measurements are
7 taken regularly either from low Earth orbit satellite platforms or from ground-based
8 measurements of the earthshine from the dark side of the Moon. But the results
9 from these different measurements are not in satisfactory agreement. Clearly, the
10 availability of different albedo databases and their inter-comparisons can help to
11 constrain the assumptions necessary to reduce the uncertainty of the albedo esti-
12 mates. In recent years, there has been a renewed interest in the development of
13 robotic and manned exploration missions to the Moon. Returning to the Moon will
14 enable diverse exploration and scientific opportunities. Here we discuss the possibil-
15 ity of a lunar-based Earth radiation budget monitoring experiment, the Lunar Ter-
16 restrial Observatory, and evaluate its scientific and practical advantages compared
17 to the other, more standard, observing platforms. We conclude that a lunar-based
18 terrestrial observatory can enable advances in Earth sciences, complementary to the
19 present efforts, and to our understanding of the Earth's climate.

20 *Key words:* albedo, climate, longwave radiation, satellites, earthshine

21 **1 Introduction**

22 In recent years, there has been a renewed interest in the development of robotic
23 and manned exploration missions to the Moon. Returning to the Moon will
24 enable diverse exploration and scientific opportunities. Here we propose to use

25 lunar exploration to set up a lunar observatory designed to better understand
26 our own planet, Earth. The first such observatory was brought to the moon
27 by Apollo 16, which deployed a small far-UV telescope in a shady area to
28 make spectral observations of the Earth's upper atmosphere. The astronauts
29 returned the film from the observations to Earth.

30 The Earth's climate is driven by the amount of energy absorbed from the Sun,
31 dominated by the solar luminosity and the Earth's albedo, and the amount of
32 energy emitted to space in the form of infrared radiation, mainly controlled
33 by atmospheric greenhouse gases. Considerable effort has been made in the
34 past to characterize and model both solar irradiance and greenhouse gases.
35 The Earth's albedo remains the least studied fundamental climate parameter.
36 Most climate studies assume the albedo to be nearly constant in time, but
37 recent monitoring of the albedo, from different techniques, show that this is
38 certainly not the case.

39 It is also important to notice that the albedo is a bi-directional property, and
40 there is a high degrees of anisotropy in the reflected light from a given surface.
41 Thus, to derive ideal estimates of the Earth's true Bond albedo (reflectance
42 at all wavelengths in all directions), it would be necessary to observe reflected
43 radiances from the Earth, from all points on the Earth and at all angles. There-
44 fore, all measurements from which albedo can be inferred require assumptions
45 and/or modeling to derive a meaningful estimate.

46 Nowadays, albedo measurements are taken regularly either from Low Earth
47 Orbit (LEO) satellite platforms or from ground-based measurements of the
48 earthshine on the dark side of the Moon. But the results from these different
49 measurements are not always in satisfactory agreement (Pallé et al, 2005;

50 Wielicki et al., 2002; Pinker et al., 2005; Pallé et al., 2004; Wild et al., 2005).
51 Further, there are discrepancies of up to 7% among the mean albedo estimates
52 of different global circulation models (Charlson et al., 2005).

53 Apart from these discrepancies, all the observational estimates of the Earth
54 reflectance are broadly consistent in suggesting changes in the Earth's short-
55 wave forcing, both at the surface and at the top of the atmosphere, that will
56 have a large impact on the planet's radiation budget (Gilgen et al., 1998;
57 Stanhill and Cohen, 2001; Liepert, 2002). Thus, the availability of different
58 albedo databases and their inter-comparisons are essential to constraining the
59 assumptions necessary to reduce the uncertainty of the albedo estimates.

60 Global measurements of the infrared radiation emitted from Earth are only
61 taken from LEO satellites, and are subject to the same limitations discussed
62 for the albedo.

63 Here we propose a lunar-based Earth radiation budget monitoring experiment,
64 and evaluate its scientific and practical advantages over other, in use or pro-
65 posed, techniques for Earth's Radiation Budget monitoring. Long-term moni-
66 toring of both variables (reflected shortwave and emitted longwave radiation),
67 with detailed geographical resolution, would provide valuable information for
68 the study of the Earth's global energy budget, cloud macro- and micro-physics,
69 the interactions of clouds and aerosols, and the role of greenhouse gases (espe-
70 cially those non-well mixed in the atmosphere such as water vapor) in climate
71 change.

72 2 A Moon-based Earth's radiation budget monitoring

73 The Lunar Terrestrial Observatory (LTO) proposed in this paper would consist
74 of a two (four) small telescopes, one (two) in the visible range and one (two)
75 in the infrared, continuously monitoring the Earth. Photometric images of the
76 full Earth disk would be taken continuously, and would provide a continuous
77 record of the reflected shortwave flux from the Earth's surface and atmosphere,
78 and the emitted flux of outgoing longwave radiation (OLR). In Figure 1, an
79 illustration is shown of the two views of the Earth (one in the visible and one
80 in the infrared) that LTO would continuously record. Note that the OLR flux
81 can be measured continuously over the full Earth disk.

82 Here we focus on the scientific value of the LTO, rather than its specific nature
83 (manned or robotic) or technical details, as they will be highly dependent on
84 the evolution of the diverse national space programs. Consider however, that
85 viewed from the Moon, the angular size of the Earth is large (about 2 degrees
86 in diameter). A fine geographical resolution will be needed to support the
87 science objectives of LTO, but as an example, suppose that we wish to image
88 the Earth in 100 x 100 pixels (equivalent to a geographical resolution of about
89 100km). Then, if each pixel is 25 microns in size, and the imaging beam
90 is $f/4$, conservation of etendue (geometric optical throughput) requires that
91 the telescope size be only about 2 cm in diameter. This illustrates that a very
92 modest (and low mass) LTO telescope is needed to completely capture the full
93 image of the Earth. Moreover, the flux rates are large: in the visible we expect
94 that the Earth at quadrature will produce about 10^5 electrons per second per
95 image pixel per 1000-Ångström band, making the exposure times very short.
96 Several feasibility studies and research proposals support the possibility of

97 such a low mass/size LTO (Smith et al., Ruzmaikin et al., Traub et al., priv.
98 comms.)

99 We note that LTO would benefit from the inclusion of a side-by-side solar
100 observatory to look for correlations between changes in the full solar radiation
101 spectrum and reflectance, for example. However, we will not further discuss
102 solar observations here.

103 *2.1 Scientific objectives*

104 There are several primary scientific objectives that could be met by measuring
105 the earthshine from the Moon:

- 106 • To monitor and characterize the diurnal, seasonal and inter-annual variabil-
107 ity of the Earth's reflectance. One of the most crucial climate parameters,
108 and at same time one of the least well-known.
- 109 • The Earth's reflectance and OLR are tightly related to cloud amount and
110 other cloud properties, and the high geographical resolution provided by
111 LTO would help to characterize the role of clouds in the Earth's radiation
112 balance. It will also help to constraint climate model parameterizations on
113 regional scales.
- 114 • To monitor and characterize the diurnal, seasonal and inter-annual variabil-
115 ity of the Earth's infrared emission.
- 116 • To obtain globally-integrated measurements, by degrading the detectors res-
117 olution to a single point, of the Earth's shortwave and longwave light curves.
118 This will serve as very valuable input for future missions aiming at the detec-
119 tion and characterization of extrasolar planets. Among the most interesting

120 things to study are: Determining the magnitude of the albedo changes on
121 global scales at all time scales; determining the changes in the observed
122 Earth's light curve as a function of phase; determining the photometrical
123 precision needed to retrieve the Earth's rotational rate; determining the im-
124 portance/detectability of glint scattering signaling the presence of oceans;
125 Trying to derive the presence of tracers (clouds) in the Earth's atmosphere
126 by observing changes in the rotational rate, etc.

127 **3 Inter-comparison of Earth's radiation budget observing plat-** 128 **forms**

129 There are five primary, distinct ways in which one can measure the Earth's
130 albedo: from a satellite(s) in LEO, from a satellite(s) in Geosynchronous Earth
131 Orbit (GEO), from a satellite sitting at the L1 Sun-Earth Lagrangian point,
132 from a telescope sitting on the Moon and from ground-based observations of
133 the earthshine in dark side of the Moon.

134 Currently LEO, GEO and earthshine observations are routinely carried out. In
135 LEO, the ERBE (Earth Radiation Budget Experiment) instrumentation, and
136 the more recent CERES (Clouds and the Earth's Radiant Energy System) in-
137 struments have monitored the Earth's reflectance and OLR since early 1980's
138 in the tropical regions (Chen et al, 2002), and globally since 2000 (Wielicki et
139 al, 2002). A more diversified set of experiments, including GERB (Geostation-
140 ary Earth Radiation Budget) and MODIS (The Moderate Resolution Imaging
141 Spectroradiometer), to cite some examples, are also currently gathering data.
142 The Earthshine Project, has continuous measurements of the earthshine since
143 1999 from BBSO in California, and is currently expanding to a global network

144 (Pallé et al., 2005).

145 Several proposals have been made to place an Earth observing satellite at the
146 Lagrange L1 point. The US-led TRIANA mission, lately renamed as DSCVR
147 (Valero et al, 2000), was built but never launched, and its European counter-
148 part, the Earth-Sun-Heliosphere Interactions Experiment (EARTHSHINE), is
149 still in its design phase (Wall et al., 2003).

150 In this section, we will review and compare the observing parameters and
151 retrieved information of the existing and planned albedo/OLR missions to
152 those of LTO.

153 3.1 Sampling

154 Observing all points on Earth from all reflecting angles is a practical impossi-
155 bility. Thus, for our purposes, we define a coverage, C , of 100% if all points on
156 Earth were observed from at a least one angle at all times. Thus, to compare
157 the spatial and temporal coverage of the different observing methodologies we
158 define our coverage factor, C , as

$$159 \quad C = \frac{\Delta T}{T} \frac{\Delta A}{A} = \frac{N_h}{12(24)} \frac{N_d}{365} \frac{\Delta A}{A} \quad (1)$$

160 where, $\frac{\Delta T}{T}$ and $\frac{\Delta A}{A}$ are the fractional temporal and geographical coverage of
161 the sunlit half of the Earth reflectance, respectively. As some of the observing
162 techniques cannot be used at all times, to do a fair comparison, we need to
163 estimate the coverage over a relatively long period of time (a year for example).
164 Thus, N_h and N_d are the number of hours per day and number of days per
165 year in which observations take place. For albedo the number of hours/day

166 is divided by 12 (average daylight duration), and for the OLR, it would be
167 divided by 24.

168 In the upper part of Table 1, the coverage is given for the several albedo
169 observing techniques that have been proposed. The calculated coverage omits,
170 in all cases, losses in duty cycle due to overhead time. The maximum coverage
171 (100%) is only achieved by locating a satellite at the Sun-Earth Lagrangian
172 point. This ensures that the whole sunlit half of the Earth faces the detector
173 at all times, and the telescope can be operated continuously.

174 A satellite in GEO and the LTO come in second and third place, with a cov-
175 erage of roughly 40 % and 25%, respectively. The abrupt decrease in coverage
176 from a Lagrangian observing system is due to the fact that, as seen from the
177 Moon (or from geosynchronous orbit), the Earth presents phases that occult
178 part of the sunlit Earth. Also LTO cannot operate if the Sun is above the hori-
179 zon, although it is not clear where the limiting angle would be if the telescope
180 is appropriately shielded (Smith, priv. comm.). If LTO could observe when the
181 Sun is lower than, for example, 45° above the horizon, the coverage would be
182 larger (as indicated within parentheses in Table 1). Coverage could be further
183 enlarged by locating LTO at a high lunar latitude, so that the Sun is always
184 relatively low on the horizon, inside a crater permanently in the shadows, or
185 even inside a pipe pointing to Earth.

186 A network of earthshine observatories, mainly limited by lunar phase and the
187 short duration of the observations, is fourth in coverage, followed by a LEO
188 satellite, with a very poor temporal sampling at each location.

190 The results in the previous paragraph are however misleading. Not only is
191 it essential to have a wide geographical coverage, but also the geographical
192 resolution of that coverage is critical for subsequent detailed climate studies.
193 A satellite in LEO fares quite poorly when the crude space/time coverage
194 of the observations, C , is considered. But at the same time the geographical
195 resolution of the satellite observations is unmatched.

196 A detailed geographical resolution is needed to establish the links between
197 surface and atmospheric small-scale components and their radiative proper-
198 ties. Resolution is also invaluable for the validation of the observations with
199 other complementary datasets (such as ground-based weather observatories or
200 balloon measurements), and the modeling of the results at regional scales.

201 Again LTO, with a resolution of about 10 km , features second place in ef-
202 fective geographical resolution, one order of magnitude worse than a LEO or
203 GEO satellite data (see Table 1), and similar to a satellite at L1. It is also
204 noteworthy that the ground-based earthshine observations have no geographi-
205 cal resolution. Although, in the case of a network of earthshine stations, a very
206 large-scale resolution (of a few hundred to a thousand km) could be achieved
207 with overlapping observations (Pallé et al, 2003 and 2005).

208 We note that the geographical resolution of 1 km is not met by all operating
209 LEO satellites, but it will probably be met routinely in future instrumentation.
210 The 10 km geographical resolution from L1 or the Moon, can be lowered down
211 to 1 km too, but it would require larger instrumentation (telescopes) and
212 substantially increase the cost of such missions, without providing a crucial

213 incremental scientific return. Thus, we select 10 *km* resolution as the most
214 probable scenario for such missions.

215 One can define what we call the “information content index”, I_c , as

$$216 \quad I_c = C / \frac{\Delta R}{R} \quad (2)$$

217 where $\frac{\Delta R}{R}$ is the angular fraction of the Earth’s radius resolved in any one ob-
218 servation. It is very similar to $\frac{\Delta A}{A}$ in equation 1, but here we are not considering
219 the amount of area covered over the course of one year of observations, but
220 the angular fraction of the Earth’s diameter covered by a single observation.

221 While the index I_c has no real physical meaning, it takes into account not
222 only the space/time coverage of the observations, but also their detailed res-
223 olution, and it serves to illustrate the amount of information that a given
224 technique produces. Information that can be used for inter-calibration with
225 other datasets, model validation, etc.

226 The information content index is very similar for all observing platforms, ex-
227 cept for ground-based earthshine. In the I_c index, the lower temporal coverage
228 of the whole sunlit Earth of LEO satellites, as compared to the other plat-
229 forms, is compensated by their very fine geographical resolution. Satellites
230 in GEO or at L1, with both fine geographical resolution and large coverage,
231 retrieve the most information without considering the scattering angle.

232 *3.3 Scattering angle*

233 As mentioned in the introductory section, the albedo is a bi-directional prop-
234 erty, and there is a high degrees of anisotropy in the reflected light from a

235 given terrestrial surface. Thus, radiance retrievals at different angles are crit-
 236 ical in order to retrieve the true Bond albedo of the Earth. To determine the
 237 Bond albedo, A , which is the fundamental reflection parameter for climate
 238 studies, one needs to integrate the measured radiances, or albedos, $p(\theta)$, over
 239 all observing angles,

$$240 \quad A = \frac{2}{3} \int_{-\pi}^{\pi} d\theta p(\theta) f_L(\theta) \sin \theta, \quad (3)$$

241 where θ is the observing (phase) angle, $f_L(\theta)$ is the Earth's Lambert phase
 242 function and p is the apparent albedo in one direction. The kernel of the
 243 integrand, $f_L(\theta) \sin \theta$, is plotted in Figure 2, and its coverage by the different
 244 observing platforms are compared.

245 LEO satellites have a fixed geometry in the sense that they measure every
 246 point of the Earth from a nadir point of view (perpendicular to each earth
 247 surface element), or, if several detectors are used, a limited set of angles can
 248 also be measured.

249 In this sense, DSCVR and LEO satellites are limited to a small range of
 250 scattering angles, which means one has to assume a linear relationship in the
 251 changes of reflectance properties at all scattering angles, or rely on modeling
 252 to derive estimates of changes in the Earth's Bond albedo. Contrariwise, the
 253 LTO observations would sample almost the full range of scattering angles, as
 254 the GEO satellites do, but for a more limited region of the Earth.

255 A further weight, that takes into account the angular coverage of the mea-
 256 surements, can be introduced in the I_c calculations, in the form of,

$$257 \quad I_{ck} = I_c / \frac{\Delta K}{K} \quad (4)$$

258 where $\frac{\Delta K}{K}$ is the fraction of the kernel covered by each method. This kernel-
259 weighted index is also given in Table 1.

260 3.4 *Observational Geometry and the Diurnal cycle*

261 The geometry of the observations is also an important parameter. Complete
262 longitudinal coverage of the Earth could be achieved using 5 of the current
263 GEO satellites, which would cover about 96% of the planet, leaving out the
264 polar regions. However, because of the curvature of the Earth, only data up
265 to latitudes of about $50 - 60^\circ$ are commonly used (Valero et al, 2000). LEO
266 satellites have a more homogenous sampling, as they have the same (nadir)
267 viewing geometry for each point of the Earth once a day.

268 Fullest longitudinal coverage is also a problem for observations from L1 or from
269 the Moon. Observations from an L1 satellite, will have a full hemispheric view
270 of the whole illuminated Earth. This geometry will change only slightly with
271 seasons, and because of the spherical shape of the Earth, the regions near
272 the center of the disk will be geographically better sampled than the outer
273 regions. For the tropical and inter-tropical regions, this differential sampling
274 becomes uniform as the Earth rotates, but it is never properly solved for the
275 polar regions.

276 This is important because, although the polar regions are small in area, they
277 are very susceptible to climate change, through changes in snow/ice thickness
278 and extent, leading to strong changes in albedo and OLR (Davies, 2007).
279 However, for the DSCOVR mission, algorithms have been developed to work
280 up to about 80° in either solar zenith angle or satellite viewing angle. Unlike

281 GEO satellites, for Triana the two angles would be approximately equal, which
282 permits viewing closer to the poles (Valero et al, 2000). From the Moon,
283 despite being four times closer to the Earth than the L1 point, the same
284 geometrical advantages hold, and retrieval algorithms such as those planned
285 for the TRIANA/DSCVR missions could be developed for LTO.

286 Thus, with respect to useful geographical coverage, an LEO satellite is the best
287 option for an homogeneous sampling, followed by LTO or an L1 satellite, with
288 GEO satellites having the worst “useful” coverage (Note that this “usefulness”
289 of the observations is not incorporated into Table 1).

290 Another key issue of Earth’s radiation measurements is for the collected data
291 to be able to characterize the diurnal cycle of reflected and emitted radiances.
292 LEO satellite cannot do that and must rely on modeling or inter-calibration
293 with other datasets to correct the data. One of the greatest advantages of
294 GEO is to be able to characterize this diurnal cycle, albeit only for part of the
295 planet. An L1 satellite or the suggested LTO would also be able to characterize
296 the diurnal cycle of the albedo for virtually each point on the planet, daily or
297 monthly.

298 *3.5 Calibration and instrument lifetime*

299 One of the most difficult problems in the study of climate variability is the
300 construction of long-term, well-calibrated time series of the essential climate
301 parameters. This is often the Achilles heel of satellite data compilations.

302 Because satellite observation have to rely on absolute measurements of ra-
303 diances from different points on Earth, they are bound to have calibration

304 errors. Space is an unforgiving environment, and compiling reliable long-term
305 observations is not an easy task. When observing from space, orbits and alti-
306 tudes change, instrumentation degenerates, and gaps in the observations are
307 inevitably produced because of the finite lifetime of the missions. Moreover,
308 when a new satellite is launched, it carries improved instrumentation yielding
309 data from which it is not easy to compare with data from previously launched
310 instrumentation, as the scientific goals change with time. This remains true
311 for all satellite data, whether at LEO, GEO or L1.

312 Moreover, satellites have a finite lifetime, sometimes very short. In the case
313 of DSCVR, for example, the nominal mission lifetime is two years (Valero et
314 al, 2000). Even though this missions would provide some unique climate data,
315 they are not so useful for decadal to centennial scale climate changes studies.
316 Thus, in order to compile a long-term series, one needs to link together data
317 from different satellites.

318 Observations from the Moon with LTO, offer some advantages for the long-
319 term calibration of the data, that are denied to LEO, GEO or L1 satellites.
320 A simple LTO can be developed as a robotic mission, but frequent manned
321 visits or settlements in the Moon may allow the recharging of dead batteries,
322 complex repairs and precise in-situ calibrations, as well as basic maintenance
323 that can substantially extend the lifetime of the instrumentation. Moreover,
324 the possibility exists for retrieving the instrumentation back to Earth where
325 post facto calibration tests can be performed. In-situ calibration is also possi-
326 ble using the well-known astronomical technique of observing standard stars.
327 The small size/mass of the instrumentation could also be used to argue for
328 redundant instrumentation, two visible and two infrared LTO telescopes, for
329 calibration purposes. With this continuous support, the lifetime of simple in-

330 strumentation can be extended for decades. And if new instrumentation is
331 developed, it can always be installed next to the old instrumentation, and
332 provide a smooth, well-calibrated, transition.

333 Ground-based observations of the earthshine are based on relative measure-
334 ments between the dark and bright sides of the Moon. Thus, they are insen-
335 sitive to systematic long-term changes in the instrumentation, and are also
336 insensitive to changes in solar irradiance or local atmospheric conditions. De-
337 spite the low information content of these kind of globally-integrated measure-
338 ments, their strength relies in their simplicity, and can provide a very useful
339 complement to satellite or LTO measurements. The cost of such ground-based
340 instrumentation, about two orders of magnitude cheaper than any of the al-
341 ternative methodologies, is also a good argument for continuing observations.

342 *3.6 Environment*

343 The lunar environment is much harsher than our normal environment below
344 the Earth's atmosphere. About 30,000 zap pits (micro-craters) per year will
345 be formed on a given square meter of the lunar surface (Taylor, 1989). The ex-
346 posed surfaces of any instrumentation placed on the Moon must be protected
347 from this type of bombardment for the duration of the mission. Moreover, the
348 electronic components must be able to withstand the high energy solar flare
349 particles with fluxes of about $100\text{cm}^{-2}\text{s}^{-1}$. This will be especially harsh if the
350 mission is being conducted, as it will be, for measurements lasting more than
351 a few years, and during periods of high solar flare activity. The instrumen-
352 tation will also need thermal protection to cope with extreme hot and cold
353 temperatures along a lunar day, and rapid change from one to the other.

354 Lunar dust is another potential danger for LTO. The lunar regolith is com-
355 posed largely of angular agglutinate fragments, which are highly abrasive
356 and adhere electrostatically. Deposited on optics, the dust would compromise
357 the imaging performance and increase the emissivity of the telescopes, which
358 would add background noise to thermal IR measurements (Lester, 2006). How-
359 ever, lunar robotic missions so far have not encountered this problem (Low-
360 man, 2006). The Apollo 12 mission retrieved components from the Surveyor 3
361 spacecraft that had been on the Moon for 31 months and operated with little
362 dust problems (NASA SP-284).

363 On the other hand, satellites in LEO do not find a more comfortable environ-
364 ment. Objects in LEO encounter atmospheric drag, from the thermosphere or
365 exosphere, depending on the orbital altitude. In LEO, the instrumentation is
366 exposed to a radiation field composed of galactic cosmic rays, solar particles,
367 particles in the Earth's radiation belts and neutrons and protons from the
368 Earth's atmosphere (Zhou et al, 2004; Shin and Kim, 2004). Higher orbits
369 are subject to early electronic failure because of intense radiation and charge
370 accumulation. Finally, orbital debris are also becoming a major concern for
371 those planning spacecraft missions in Earth orbit, either in low Earth orbit or
372 in higher geosynchronous orbits.

373 As a summary of all the previous discussions, a comparison of the strengths
374 of each Earth radiation budget observing technique is given in Table 2.

375 4 Conclusions

376 The principal advantage of observing the earthshine from the Moon is the com-
377 promise between the different measurements techniques. While the proposed
378 LTO may not have the high resolution of the LEO satellite instrumentation, a
379 resolution of tens of km, depending on the instrumentation, is good enough for
380 global climate models and regional climate changes assessments. The coverage,
381 C, is smaller than what a satellite in the Lagrangian point would have, but
382 it is larger than the retrieved coverage from any of the remaining techniques.
383 Observations from LTO will also sample a wide range of scattering angles
384 that will contribute to the determination of the Earth's Bond albedo. On top
385 of that, LTO has the potential for unprecedented precision for a calibrated
386 long-term time series, which is a crucial factor in climate change studies, and
387 depending on the intensity of future robotic and manned lunar expeditions, the
388 lifetime of such a mission could be extended for much longer than a satellite
389 mission either in LEO, GEO or L1.

390 Some authors have expressed their fears that the new NASA vision of lunar
391 exploration may divert resources from the Earth sciences (Leovy et al, 2006),
392 which are greatly needed for the characterization and evaluation of the current
393 global warming. It is not the authors suggestion in this paper that the LTO
394 should be implemented instead of any of the other Earth sciences missions.
395 However, if future, more intensive, lunar exploration and exploitation are to
396 take place regardless, the LTO can offer an invaluable contribution to Earth
397 sciences, by providing a better understanding of the Earth's radiation budget
398 and ultimately, Earth's climate. Most especially if the LTO data is combined
399 with other, independent, Earth radiation budget datasets.

400 **References**

- 401 [] Charlson, R. J., F. P. J. Valero, and J. H. Seinfeld (2005), In search of
402 balance. *Science* 308, 806.
- 403 [] Chen, J., B. E. Carlson, and A. D. Del Genio (2002) Evidence for Strength-
404 ening of the Tropical General Circulation in the 1990s. *Science* 295, 838-841.
- 405 [] Lester, D. (2006), Build astronomical observatories on the Moon? *Physics*
406 *Today*, 50-54.
- 407 [] Leovy, C., T. Anderson, D. Catling, and R. Charlson (2005), Moon-Mars:
408 The Elephant in the Attic. *Eos Trans. AGU*, 86(14), 143.
- 409 [] Lowman, P. (2006), Build astronomical observatories on the Moon? *Physics*
410 *Today*, 50-54.
- 411 Rodriguez, M.-C. Chu, E. Kolbe, C. T. Brown, and S. E. Koonin (2003),
412 Earthshine and the Earth's albedo: 2. Observations and simulations over 3
413 years, *J. Geophys. Res.*, 108(D22), 4710.
- 414 [] Pallé, E., P.R. Goode, P. Montañés-Rodríguez, and S.E. Koonin (2004),
415 Changes in the Earth's reflectance over the past two decades. *Science*, 304,
416 1299-1301.
- 417 [] Pallé, E., P.R. Goode, P. Montañés-Rodríguez, S.E. Koonin (2005), Toward
418 a global earthshine network: first results from two stations. *Geophysical*
419 *Research Letters*, 32, L11803.
- 420 [] Pallé, E., P. Montañés-Rodríguez, P.R. Goode, S.E. Koonin, M. Wild,
421 S. Casadio (2005), A multi-data comparison of shortwave climate forcing
422 changes. *Geophysical Research Letters*, 32, 21, L21702.
- 423 [] Shin, M., and M. Kim (2004), An evaluation of radiation damage to solid
424 state components flown in low Earth orbit satellites. *Radiation Protection*
425 *Dosimetry* 108:279-291.

- 426 [] Taylor, G. Jeffrey (1989), The Environment at the Lunar Surface. *Lunar*
427 *Base Agriculture: Soils for Plant Growth*, D. W. Ming and D. L. Henninger
428 (eds), Madison, WI, 37-44.
- 429 [] Valero, F.P.J., J. Herman, P. Minnis, W.D. Collins, R. Sadourny, W. Wis-
430 combe, D. Lubin, and K. Ogilvie (2000), Triana - a Deep Space Earth and
431 Solar Observatory Report num. 12.99, *National Academy of Sciences re-*
432 *ports*, Washington, DC.
- 433 [] Wall, R., M. Smith., R. Sides, M. Lockwood, N. Morris, N. Waltham, C.
434 Carr, C. Castelli, C. Eyles, D. Linder, C. Chaloner, L. Baldwin (2003),
435 EARTHSHINE: a deep-space small satellite to examine the sunearth con-
436 nection. *Proceedings of the 54th International Astronautical Congress of the*
437 *International Astronautical Federation*, 29, IAC-03-IAA.11.3.06.
- 438 [] Wielicki, B.A., T. Wong, R.P. Allan, A. Slingo, J.T. Kiehl, B.J. Soden, C.T.
439 Gordon, A.J. Miller, S. Yang, D.A. Randall, F. Robertson, J. Susskind, H.
440 Jacobowitz (2002), Evidence for Large Decadal Variability in the Tropical
441 Mean Radiative Energy Budget. *Science*, 295, 5556.
- 442 [] Zhou, D.; O'Sullivan, D.; Semones, E.; Heinrich, W. (2004), Radiation Field
443 of Cosmic Rays Measured in Low Earth Orbit by CR-39 Detectors. *Advances*
444 *in Space Research*, Vol. 37, 1764-1769, 2006.

Table 1

Comparison of the coverage parameters for different albedo measurements techniques. For OLR radiation measurements, the number will be the same, except for an L1 satellite where coverage C , I_c and I_{ck} would be half the values here. For earthshine observations OLR measurements are not possible.

	LEO Sat.	GEO Sat.	ES (8-stat.)	L1 Sat.	LTO
N_h	0.5	12	3.0	12	6.0
N_d	365	365	182	365	182 (273)
$\Delta A/A$	1	0.4	1	1	1
C	4.2	40.0	12.5	100.0	25 (37.5)
Geo. Resol.	1 <i>km</i>	1 <i>km</i>	Continental	10 <i>km</i>	10 <i>km</i>
$\Delta R/R$	2×10^{-9}	2×10^{-9}	0.3	2×10^{-8}	2×10^{-8}
I_c	2.1×10^9	2.0×10^{10}	45	5×10^9	1.25×10^9 (1.87×10^9)
$\Delta K/K$	0.15	1	0.8	0.05	0.9
I_{ck}	3.15×10^8	2.0×10^{10}	36	2.5×10^8	1.125×10^9 (1.68×10^9)

Table 2

A comparison table of the typical characteristics and advantages of each albedo/OLR observing platform. An 'x' symbol means that the particular technique meets the requirement formulated in the left column. The techniques that has the most “ideal” result for each requirement is marked with a bold capital **X**. Note that LTO does not meet this last case for any of the requirements. However it meets almost all the listed requirements, except for homogeneous latitudinal sampling and cheap cost.

Requiereement	LEO Sat.	GEO Sat.	ES (8-stat.)	L1 Sat.	LTO
Homog. sampl. long	x		x	x	x
Homog. sampl. long+lat	X				
Scattering angle sampling		X	x		x
Detailed Geo Res	X	x		x	x
Decadal lifetime			X		x
Diurnal cycle		X	x	x	x
Calibration			X		x
Low cost			X		

445 **Figure 1 Earth views from the Moon.** The picture illustrates a real
446 image of the Earth, in the visible, taken by the Apollo 11 astronauts
447 in 1969. Over-plotted is a global composite of the water vapor in
448 the atmosphere, mapped in the IR range, by the GOES satellites.
449 LTO would obtain continuous observations of the Earth both in
450 the visible and infrared. Note that the two images correspond to
451 different dates, seasons and geometries so the weather patterns do
452 not correspond to each other, but are plotted for illustration only.
453 In reality, the IR emission from the Earth as seen from the Moon,
454 will be slightly brighter from the sunlit part of the Earth than from
455 the night side.

456 **Figure 2** The kernel ($f_L(\theta)\sin(\theta)$) from which the Bond albedo is
457 determined, shown as a function of observing angle. Its behavior is
458 dominated by the Lambert phase function for small phase angles and
459 by $\sin(\theta)$ for large phase angles. The kernel coverage by the ground-
460 based earthshine observations (green), a satellite orbiting about L1
461 assuming the proposed orbit of Triana or DSCVR (red), a satellite
462 in LEO (yellow), a satellite in GEO (dark blue) and the proposed
463 LTO (light blue), is shown. Adapted from Palle et al. (2003)

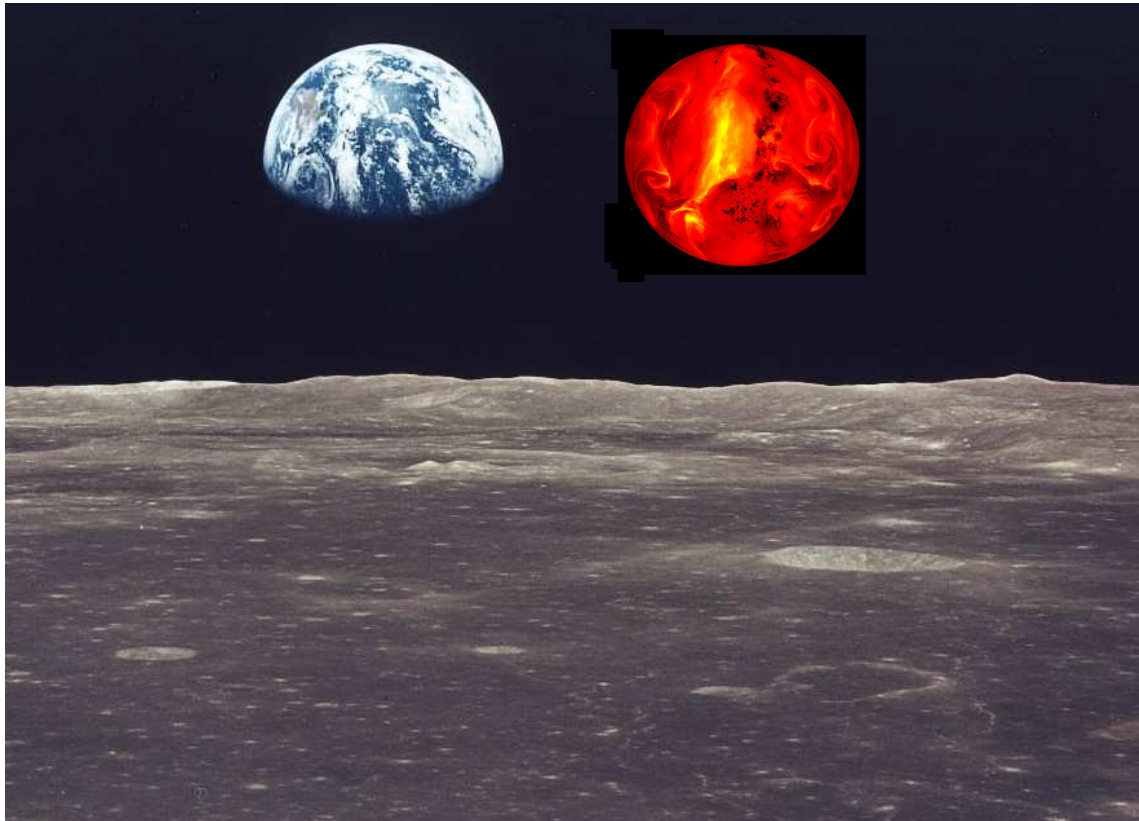


Fig. 1. Earth views from the Moon. The picture illustrates a real image of the Earth, in the visible, taken by the Apollo 11 astronauts in 1969. Over-plotted is a global composite of the water vapor in the atmosphere, mapped in the IR range, by the GOES satellites. LTO would obtain continuous observations of the Earth both in the visible and infrared. Note that the two images correspond to different dates, seasons and geometries so the weather patterns do not correspond to each other, but are plotted for illustration only. In reality, the IR emission from the Earth as seen from the Moon, will be slightly brighter from the sunlit part of the Earth than from the night side.

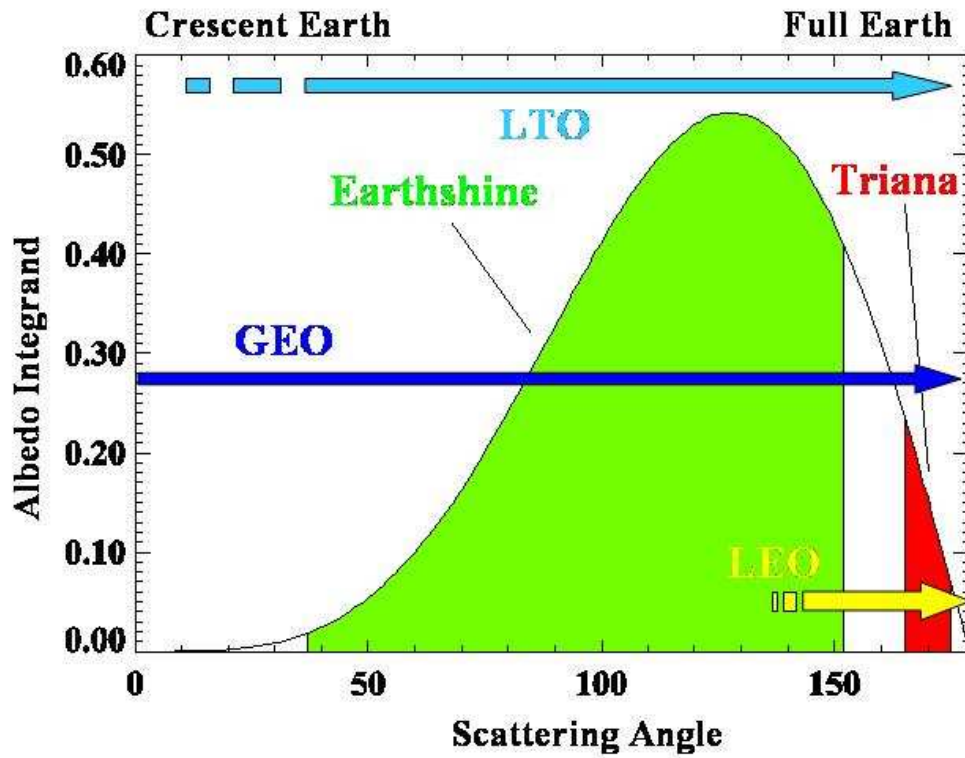


Fig. 2. The kernel ($f_L(\theta)\sin(\theta)$) from which the Bond albedo is determined, shown as a function of observing angle. Its behavior is dominated by the Lambert phase function for small phase angles and by $\sin(\theta)$ for large phase angles. The kernel coverage by the ground-based earthshine observations (green), a satellite orbiting about L1 assuming the proposed orbit of Triana or DSCVR (red), a satellite in LEO (yellow), a satellite in GEO (dark blue) and the proposed LTO (light blue), is shown. Adapted from Palle et al. (2003)