Century-long monitoring of solar irradiance and Earth’s albedo using a stable scattering target in space

Philip G. Judge* and Ricky Egeland†

High Altitude Observatory, National Center for Atmospheric Research†, PO Box 3000, Boulder, CO 80307-3000, USA

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ABSTRACT

An inert sphere of a few metres diameter, placed in a special stable geosynchronous orbit in perpetuo, can be used for a variety of scientific experiments. Ground-based observations of such a sphere, ‘GeoSphere’, can resolve very difficult problems in measuring the long-term solar irradiance. GeoSphere measurements will also help us understand the evolution of Earth’s albedo and climate over at least the next century.

Key words: techniques: photometric – Sun: activity – solar–terrestrial relations – zodiacal dust.

1 MOTIVATION

The Sun is a very stable object. The Sun’s ‘irradiance’ (bolometric flux measured since 1978 from above the Earth’s atmosphere) varies by 0.06–0.1 per cent peak to peak, on time-scales of 11 yr (see, for example, recent reviews by Fröhlich 2013; Willson 2014). This variation follows the well-known ‘sunspot cycle’ (Schwabe 1844). On shorter time-scales, the evolution and disc passage of sunspot groups produce variations that are often 0.2 per cent. Given that sunspots are magnetic (Hale 1908), these variations arise because of a variable solar magnetic field. While of small amplitude, these changes are far more rapid than expected from first principles. They are believed to be generated by a magneto-hydrodynamic dynamo, drawing energy from differential rotation and turbulence in the Sun’s interior. The dynamo engine changes the Sun from a benign object, stable over time-scales of 100 000 yr and radiating essentially as a blackbody near 6000 K, to a rapidly varying object. The dynamo also causes far more variable high-energy UV and X-ray photons (White 1977), wind variations, and intermittent energetic particles and magnetized plasma clouds.

The Earth’s climate is sensitive to several factors, the Sun is by far the largest external factor. Herein lies a problem. We have no physical explanation of the solar dynamo, thus our understanding of irradiance changes remains empirical. Nor do we have accurate measurements of solar variability on time-scales longer than decades. Long-term variability is a contentious and active research area, plagued by the absence of hard data (e.g. Judge et al. 2012). Irradiances have been measured from 1978 using radiometers in space (e.g. Willson 2014). Pre-flight calibration precisions of ≈500 parts per million (ppm), 0.05 per cent, have been achieved. But independent data from different space missions have failed to provide the needed long-term stability. First, the highly precise irradiances measured by different experiments differ by 0.5–1 per cent (see fig. 1 of Willson 2014), i.e. disagreements of 10σ–20σ, on time-scales longer than 11 yr. These systematic differences thwart attempts to measure variations longer than one satellite lifetime. Second, instrumental sensitivities change over mission lifetimes which are, unfortunately, rather close to 11 yr. Third, expensive new radiometers must be regularly launched.

We propose an alternative solution that can provide society with solar brightness measurements that are stable over centuries at a time when climate change is of first importance. Our long-term precision photometric goal is set to 0.01 per cent averaged over a week. This may not be achievable, thus our less stringent requirement is a 0.1 per cent precision over a century, which will uniquely constrain long-term solar variations at a level still of great interest (Shapiro et al. 2011; Lubin, Tytler & Kirkman 2012). The technique we suggest is to use high precision differential photometry of a target in space against stable ensembles of stars. Nightly precisions of stellar observations of ‘only’ 0.1 per cent are achieved with existing small telescopes (Young et al. 1991; Henry 1999), with seasonal averages precise to 0.01 per cent.

2 A SIMPLE SOLUTION

Photometry of planets, asteroids and the moon present difficulties when trying to extract solar variations near 0.01 per cent. Planets have atmosphere-related albedo variations (for Neptune, \( m_V \approx 8 \), they are \( \approx 4 \) per cent; Lockwood et al. 1991). Asteroids have variable brightnesses dependent on their rotational aspect and highly variable geocentric distances. The moon is so bright and extended, with diverse phase-dependent brightnesses of its features, that accurate relative photometry with standard stars is not possible.

We suggest that a diffuse object, ‘GeoSphere’, be placed in a stable geosynchronous orbit (GSO). The need for a high level of geometric symmetry argues strongly for an unencumbered sphere.

* E-mail: judge@ucar.edu
† Also affiliated with Montana State University.
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3 SOLAR BRIGHTNESS OBSERVATIONS

Narrow-band photometric measurements of solar-like stars are routinely made using small (<0.8) Automated Photoelectric Telescopes (APTs; Henry 1999; Hall et al. 2009). In practice, combining all sources of error, those brighter than $m_v = 8$ have a daily rms precision of 1 mmag in $b$ and $y$. Scaling to the brightness of GeoSphere, telescopes of 1.5 m diameter are needed to measure the brightness of a 4 m diameter GeoSphere at the same daily level of precision.

With telescope time devoted exclusively to GeoSphere, the precision will improve over the 0.1 per cent nightly means reported in the stellar APT programmes.

However, qualitatively different observations must be made to permit differential photometry of GeoSphere against stars. Objects in GSO are observed most simply by switching off a telescope’s astronomical drive. In time $t$, the Earth’s rotation sweeps out 15 arcsec $(\cos \delta) \cdot t$ of sky, where $\delta$ is the object’s declination. As a result, background stars passing near to GeoSphere will contribute to the integrated flux. Consider a photometer fed from an aperture in the telescope’s focal plane of 5 arcsec diameter, $\delta = 0^\circ$, and $t = 100$ s. The area covered is $6 \times 10^{-4}$ square degrees. If the average number of stars with visual magnitude $>m$ is $N(m, b)$ per degree square at Galactic longitude $b$, then the number of stars crossing the field per 100 s observation is

$$n = 6 \times 10^{-4} N(m_v, b).$$

Using data from (Allen 1973, section 117), for $m_v = 10$, $\log_{10} N(m_v, b)$ varies between 1.25 (Galactic latitude $b = 0^\circ$) and 0.55 ($b = 90^\circ$); for $m_v = 20$ we find $\log_{10}N(m_v, b = 0, 90) = 5.0$ and 3.4, respectively. For $b = 0$ (worst case), 60 stars of magnitude 20 or brighter will cross the aperture; for $m_v \leq 10$, on average 1 in 100 such integrations will have one star of brightness similar to GeoSphere affecting the integrations. One solution might be to feed three mutually calibrated photometers from the focal plane of the telescope, offset along a line of constant declination. With GeoSphere measured from one part of the focal plane, the same stars can be measured within a second before and after the target in the other photometers, allowing subtraction of their contribution.

4 EARTH ALBEDO VARIATIONS

Changes in Earth’s albedo might be monitored observing GeoSphere close to quadrature, where it is illuminated by the Earth’s sunlit hemisphere. Then $\alpha_0 \approx \pi/2$, $\phi(\alpha_0) \approx \pi$ and the brightness of GeoSphere from direct sunlight is $m_v \approx 10.96$. Using mean Earth albedo data (Allen 1973), scattered light from the Earth adds $\approx 0.4$ per cent of the direct solar flux to the GeoSphere at quadrature. By measuring GeoSphere’s differential brightness as it crosses the sky, with statistical averaging, the goal of 0.01 per cent precision might be achieved. Long-term relative changes in Earth’s albedo greater than 2.5 per cent should be measurable by GeoSphere.

5 TECHNICAL CHALLENGES

5.1 Orbital stability

The orbits of GSO satellites are perturbed by non-spherical components of the Earth’s gravitational field, by lunar influences and by momentum transfer from solar radiation. Even so, certain orbits are stable enough over decades, for the purposes discussed here. Orbital drift through the Poynting–Robertson effect is unimportant for conceivable area-to-mass ratios for a sphere. Quoting from the

Table 1. Conditions for a 4 m geostationary sphere.

| Parameter                  | Value |
|----------------------------|-------|
| Geocentric distance $r_s$ km | 42 164 |
| Solar $m_v$                | −26.74 |
| Earth $m_v$ ($\beta = 90^\circ$, quadrature) | −20.6 |
| Earth $m_v$ ($\beta = 20^\circ$)     | −16.0 |
| Moon $m_v$                 | $\gtrsim$ −12.74 |

Notes. "Lambert’s law" for scattered radiation is assumed, corresponding to a perfectly diffusing sphere. Magnitudes were computed assuming the distance to the sphere is $r_s = r_0$, $\beta$ is the angle between the geocenter–GeoSphere line and geocenter–Sun line.

A sphere of a few metres diameter has $m_v \approx 10$ at opposition independent of orientation, and the optical appearance of a star (Table 1, placed at $L_2$, $m_v \approx 18$). Photometric observations of GeoSphere with ground-based telescopes can in principle provide century-long monitoring of GeoSphere’s brightness at 0.01 per cent precision (Young et al. 1991; Henry 1999) using statistical averages of many ($\approx 20$), nightly observations. If the scattering properties of the sphere in orbit can be measured, calibrated and/or modelled at the same level of precision, solar brightness variations will follow. GeoSphere should spin with a period of a few seconds, less than a typical integration time of precision photometry (a minute).

Table 1 lists conditions for a 4 m sphere as seen from Earth. We adopt a 4 m diameter only because fairings of large launch vehicles extend to 5 m. Smaller vehicles might be used with on-orbit expansion of a pre-compacted sphere (e.g. a ‘Hoberman sphere’).

Using data from Allen (1973), the Johnson $m_v$-magnitude when the sphere is at angle $\alpha$ from the anti-Sun point, is, with radius $r_s = d_s/2$:

$$m_v(\alpha) \approx −26.74 − 2.5 \log_{10} \left( \frac{r_s^2}{r_0^2} - \frac{a}{q} \phi(\alpha) \right).$$

Here, we use a perfectly diffusing sphere whose phase function $\phi(\alpha)$ obeys Lambert’s law:

$$\phi(\alpha) = \sin \alpha + (\pi - \alpha) \cos \alpha \right) / \pi$$

for which $q = 1.5$. Observing GeoSphere close to opposition gives $\phi(\alpha \ll 1) \approx 1$, and $m_v \approx 10.08$.

Young et al. (1991), their table 1 calculate exposure times needed to achieve 0.05 per cent rms photon noise in the Strömgren $b$ and $y$ filters at 4670 and 5470 Å, with widths of 160 and 240 Å, respectively. Assuming $m_v(\text{GeoSphere}) = 10.08$, an integration time of $\lesssim 100$ s, we find that telescope aperture $D$ and GeoSphere diameter $d_s$ must satisfy

$$(d_s/D)^2 \gtrsim 36 \text{ m}^2$$

(Stromgren by at opposition).

In the general case of a spectral sampling of $w$ Å,

$$(d_s/D)^2 \gtrsim 5800/w \text{ m}^2.$$  

For observations with the $w = 10$ Å sampling of the SORCE-SIM instrument (Harder et al. 2000) for example, then $d_s = 4$ m and $D \gtrsim 6$ m.
conclusions of Friesen et al. (1992): ‘Orbits of large satellites are radially stable throughout the region within 2000 km above and below the geosynchronous radius. Satellites placed in such orbits can be expected to go no more than 50 km above their original apogees or more than 50 km below their perigees for at least several centuries, barring collisions...’ A stable plane’ exists at the GSO distance, for which orbit plane motion is quite limited... if the initial angular momentum vector of a circular GSO is aligned with the 7:3 displaced axis about which precession takes place for the initially equatorial case, orbit plane motion will be limited to 1:2 of the initial plane.’

A 50 km change in orbital radius gives a 1 mmag change in brightness. These theoretical considerations are borne out in part by measurements of the orbits of abandoned satellites. INTELSAT 1, abandoned on 1969 December 2, has remained in an orbit with semidiameter between 42 130 and 42 200 km with eccentricity between 0 and 1.6 × 10^{-3} (e.g. Ulivieri et al. 2013) for over 41 yr. There are two longitudes of orbital stability arising from higher order terms in the dynamic equations (Friesen et al. 1992), 105W and 75E, running through western North America and the middle of Asia, respectively. These would be the desired orbits for GeoSphere.

5.2 Collision hazard
Friesen et al. (1992) compute the ‘collision hazard’ for orbits of small inclination (closing speed of two objects in GSO being v_c sin i with v_c the orbital speed of 3 km s^{-1}):

\[ C H = \frac{v_c \sigma}{2\pi R^2 \Delta R} \text{s}^{-1}, \]  

(5)

where \( \sigma \approx \pi d_i^2 / 2 \) is the geometric cross-section of the colliding objects, \( R \) is the GSO radius and \( \Delta R \) the rms altitude range of the object, \(-50\text{ km. Per impacting object, this becomes 1 impact in 10^9 yr. There are only of the order of 400 satellites in GSO around Earth, and } \leq 300 \text{ other small detected objects large enough for concern (Kessler et al. 2011, fig. 2.2). The largest threat to GeoSphere is from smaller natural micrometeoroids (MMs).}

Conversely, a non-powered GeoSphere represents a collision hazard to other spacecraft in GSO. The International Telecommunication Union (ITU) has mandated an end-of-life strategy for GSO objects, with ability to move out of the GSO region a requirement for new satellites. The science goals of GeoSphere are to remain in orbit for perpetuity, with no pre-planned end-of-life anticipated. The ‘stable plane’ solutions found by Friesen et al. (1992) minimize relative speeds between objects in these orbits, and reduce space debris by reducing both impact rate and debris scatter. If these orbits are adopted as ‘graveyard orbits’, there will be no ITU problem.

5.3 Secular changes in scattering properties
The GSO space environment is not ‘clean’. Surfaces exposed to propellant, silicone, and/or exposed to the solar UV flux and ionizing radiation, change their reflective properties (Dever et al. 2012). Oxidation is a serious issue in low Earth orbit (LEO) where oxygen densities are 10^{5-6} cm^{-3} in typical models, but oxygen concentrations in GSO are some 10^5 times smaller. Instead, in GSO, high energy particles and photons are the larger concern. For example, the absorbance (1 minus albedo) of white paints commonly used on spacecraft increases by factors of 1.3–2.8 after \( \approx 100 \text{ d exposure to solar-like UV and energetic electrons in LEO (Dever et al. 2012, table 4). To achieve an albedo stability over a century, GeoSphere’s surface should be a simple metal, alloy, or crystalline material not susceptible to such changes, like telescope optics in space. Such substances would need testing before launch, and perhaps ‘pre-aged’ by deep exposure to energetic ions, electrons and photons.}

All objects in GSO develop craters, punctures and chemical contamination from MM impact. Man-made orbital debris is less important in GSO orbits and is neglected here (Kessler et al. 2011). We consider particles mostly in excess of 1 \mu m size, those that are smaller being expected to exhibit unbound orbits because of the strong solar radiation pressure.

As damage accumulates the phase function of GeoSphere will evolve from, for example, Lambertian to cratered, or lunar-like. Diverse data sets collected from extended space missions indicate the effects of MM impacts on surfaces. The large solar cells on space station MIR indicated an accumulated surface coverage of MM damage of 0.045 per cent in 10 yr of exposure in LEO (Smirnov et al. 2000). Measurements in GSO are rarer. But the gravitational focusing for typical MMs is modest (\( v \sim 20 \text{ km} \cdot \text{s}^{-1} \)) compared with Earth escape speed (\( v_{\text{esc}} = 11-4 \text{ km} \cdot \text{s}^{-1} \) in LEO and GSO, respectively) and so fluxes will be similar. GeoSphere will accumulate MM surface damage that covers \( \approx 0.45 \text{ per cent per century, a fractional rate } k = 4.5 \times 10^{-5} \text{ year}^{-1}. \) Like the moon, cratering enhances 180° scattering at the expense of scattering at smaller angles. Changes to the geometric albedo may be smaller, depending on the surface material used and the surface optical contamination. Spillover of impact debris beyond the craters’ areas should be negligible if electrical potentials of attraction (polarization or net charge) are less than the kinetic energy of any charged exploding debris ejected outwards from the sphere.

Damage of 0.45 per cent in area translates to smaller than 0.45 per cent changes in scattered light. The albedo after time \( t \) in yr is

\[ a_t = (1 - kt)a_0 + (kt)b = a_0 - kt(a_0 - b), \]  

(6)

where \( a_0 \) is the initial albedo and \( b \) the albedo of damaged areas. Since \( b > 0 \) MM-induced degradation in albedo occurs slower than \( (1 - kt)a_0. \) Nevertheless, it should be mitigated, modelled and/or measured. One solution might be to expose GeoSphere to cosmic-like dust particles to mimic a sufficiently long exposure \( (>1 \text{ kyr}) \) in GSO, such that the phase function remains constant.

A hypervelocity gun^1 might be used. Another might be to calibrate the scattering properties of GeoSphere using future ground-based stable laser sources.

5.4 Comparison stars
To achieve long term precisions of fractions of millimagitudes, a GeoSphere observing program would have to devote effort to identifying suitably non-varying comparison stars. This is not a trivial task (Henry 1999; Hall et al. 2009). Geosynchronous objects circumnavigate the celestial equator once per day, the right ascension at opposition drifting about 1° d^{-1}. GeoSphere would therefore require a significant number of cross-calibrated comparison stars in order to place its differential magnitude on a uniform scale throughout the year. Typical separations within photometric standard groups of three stars are near 3° and always less than 13° (Hall, Henry & Lockwood 2007; Lockwood et al. 2007). As a rough estimate, for a maximum intragroup separation of 4°, we find that 345 highly stable stars distributed along the celestial equator would need to be identified, with magnitudes near that of GeoSphere.

^1 For example, The White Sands Test Facility Remote Hypervelocity Test Laboratory, http://www.nasa.gov/centers/wstf/laboratories/hypervelocity.
Henry (1999) found that stars of spectral class F0–F3 and A8–A9 have rms probabilities of long-term (seasonal) stability better than 0.0005 mag of 63.3 and 87.5 per cent, respectively, and that short-term photometric stability tends to correlate with long-term stability. These findings should be used in any comparison star search. The observing program of the current Kepler K2 Mission schedules two ≈75 d pointings falling within ±10° of the celestial equator, and will obtain precise photometric light curves for thousands of stars covering about 10 percent of the region of interest. The planned Transiting Exoplanet Survey Satellite (TESS) will obtain precise photometric timeseries of 27-d duration for bright FGK-type stars in the entire equatorial region. These surveys will allow refinement of a list of candidates for GeoSphere comparison stars.

5.5 Other problems

In GSO, thermally induced geometric changes are dominated by eclipses at equinoxes. We find such orbital changes to be important at the level of 0.001 per cent only for a few minutes as GeoSphere enters and exits the Earth’s shadow.

GeoSphere will be measured only when out of eclipse (α > 10.9°) not at opposition. A thin Earth crescent is always visible. Table 1 shows that when separations β of the Sun and Earth are 20°, the using Lambertian scattering, the Earth is 10.8 magnitudes dimmer than the Sun (a flux ratio of 2×10^4). While below our target precision, this extra light is something to be considered in analysing GeoSphere data. Most likely one will solve for the sun’s brightness and suitable parameterizations of albedo and phase functions of GeoSphere and Earth in the analysis.

For a GSO, GeoSphere observations are best made within a few hours of midnight, daily. Irradiance variation data show significant power (excluding flares which can be identified and removed) on time-scales of hours and days, that is related in both phase and amplitude to the decadal variations. Using hourly irradiance data from the VIRGO instrument (Fröhlich et al. 1997), we find that sampling every 3 d suffices to reduce high frequency aliasing to 10 per cent of the total variance.

Lastly, care should be taken to determine the polarization properties of a GeoSphere which is always irradiated anisotropically. This can be determined prior to flight and using laboratory models, as well as measured directly during from telescopes on the ground.

6 CONCLUSIONS

We have suggested that an inert scattering sphere be placed in a very stable GSO in order to make measurements of the solar flux variations, and measurements of the Earth’s changing albedo. There are technical challenges but no fundamental show-stoppers in making these measurements. To achieve a precision better than 0.1 per cent over centuries, micrometeoroid-induced surface degradation must be mitigated, modelled and/or measured. Such precisions are of great interest to both solar and terrestrial climate change physics.

There is perhaps a direct conflict with ITU’s requirement for exit strategies on GSO spacecraft. But if the community adopts the ‘stable plane’ orbits identified by Friesen et al. (1992) as ‘graveyard orbits’, the ITU mandate will not be applicable with a GeoSphere placed in such an orbit.

Finally, 1 yr of ab photometric observations of GeoSphere should reveal phase relationships in spectral irradiance changes above and below 400 nm, resolving a debate of importance to climate science (Harder et al. 2009).

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