L-1 and L-2 Observatories for Earth Science in the Post-2010 Era

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Abstract–**Twin observatories 1.5 million km from Earth along the Earth-Sun line offer revolutionary possibilities for Earth observation and scientific progress.**

INTRODUCTION

The L1 and L2 Lagrange points are 1.5 million km from Earth along the Earth-Sun line (Figs. 1, 2). Objects at L1 and L2 experience the same gravitational force as the Earth itself, and thus become new "planets" with the same orbital period as Earth. The points have saddle-point gravitational instabilities, but even current spacecraft have enough fuel and thruster authority to stationkeep for five years or more. From L1 or L2, the Earth occupies almost the same 0.5° FOV as the Sun does from Earth—although slightly smaller since the rim of the Sun is visible from L2 (an advantage for limb scanning!). The full-disk view of the Earth from L1 and L2 holds tremendous potential for Earth science. Both L1 and L2 have been occupied by space science missions, but not by any Earth science mission. NASA's $100M Triana (http://triana.gsfc.nasa.gov) was to be the first Earth observing platform at L–1, but became mired in political wrangling and now sits in storage with no scheduled launch date.

The L1 point is towards the Sun and provides a full-disk view of the sunlit half of the Earth; the L2 point is away from the Sun and provides a complementary view of the night side of the Earth. Twin observatories at L1 and L2 can observe every point on Earth once a minute—true synoptic coverage, the weather forecaster's dream! (Compare this with the five geostationary weather satellites which view the Earth to 60° latitude once every 15 min, or the 24 polar orbiting satellites required to obtain half-hourly coverage of the whole Earth.) This combination of global synoptic coverage and rapid temporal sampling allows the study of diurnal cycles and short-lived events. Precise long-term calibration using the Moon allows the measurement of delicate global changes unobservable with any current satellites.

Not everything can be done from L1 and L2, of course. The antennas required to do microwave or radar remote sensing, for example, would be immense. But ultraviolet, visible, near-IR and thermal-IR remote sensing from L1/L2, while extremely challenging, are all within current technological capabilities. (Indeed, the challenge of measuring from L1/L2 creates technical spinoffs that benefit all spaceborne Earth observation.) Thus, the view to take is that each vantage point will do what it does best: some remote sensing now done from low Earth (LEO) and

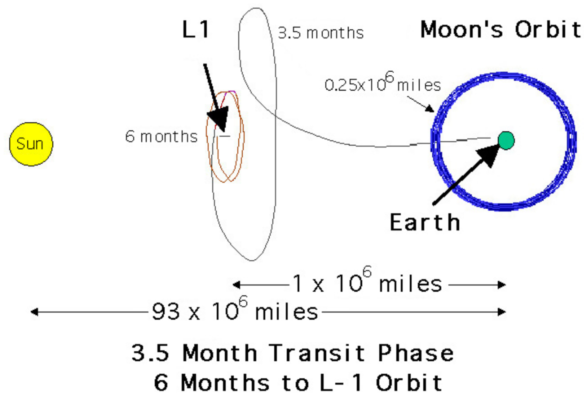

Fig. 1 The injection path for Triana showing the distances and time to reach the L1 halo orbit. Moon's orbit in blue. Sun distance not to scale.

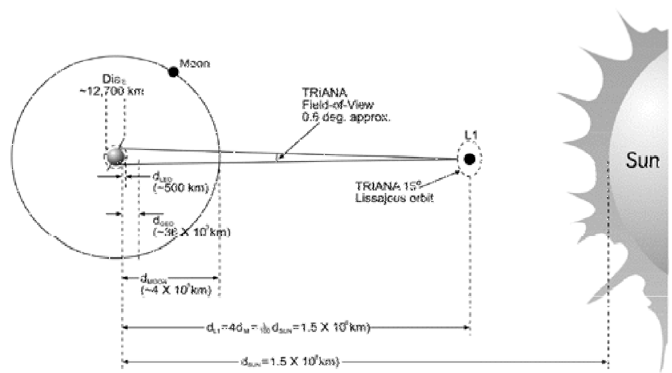

Fig. 2 Summary of major L1 orbital parameters and comparisons with the distances of conventional low Earth orbit (LEO) and geostationary (GEO) satellites. The Moon is approximately where it would be viewed for calibration purposes, with the Earth in a solstice configuration allowing a complete view of a polar region.

geostationary (GEO) orbits can better be done from L1/L2, while LEO and GEO are more appropriately used for complex instruments that may not work well so far from Earth. Moreover, some observing tasks are best done by constellations of robot aircraft and Ultra-Long Duration Balloons (ULDB's).

L1 and L2 observatories are essential components of an emerging integrated multi-perspective approach to observing all elements of the Earth system. These multiple perspectives range from at and below the Earth's surface, to robot aircraft, to ULDB's, to satellite formations in LEO and GEO, out to L1 and L2. The National Academy report [1] on Triana states: "Perhaps Triana's most important contribution ... is

Fig. 3 Galileo Earth flyby image of Pacific Ocean from close to L1 point. Note sunglint near center, Antarctica at bottom.

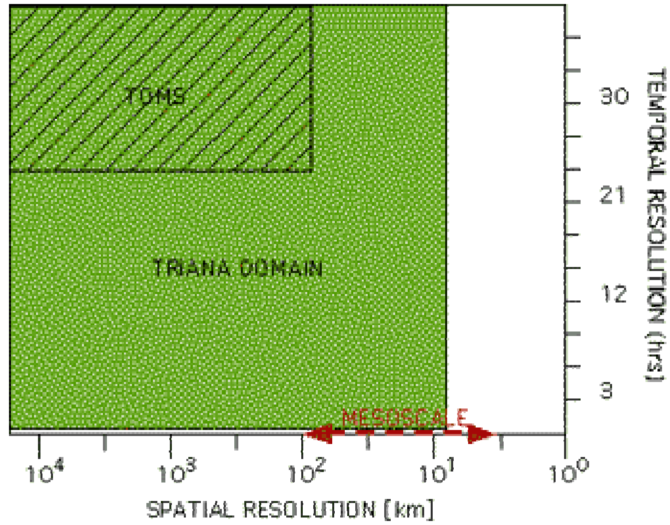

Fig. 4 The spatial and temporal resolutions of TOMS (a LEO ozone mission) compared to those of Triana at L1.

the potential for using L1 observations of Earth to integrate data from multiple spaceborne as well as surface and airborne platforms in a self-consistent global database... Data from L1 may be useful for *cross-calibrating* independent observations…(see Fig. 3). Moreover, because of its large spatial coverage and temporal continuity (Fig. 4), data from L1 can be used to *fill in data gaps* left by other networks and spaceborne platforms"

Scientific Applications

The L1/L2 vantage point offers several unprecedented opportunities for examining aspects of the Earth not presently accessible. Indeed, armed with traditional VIS/IR land-cover and atmospheric remote sensing instrumentation, L1/L2 could provide never-before available observations of, to name but a few: dynamical aspects of atmospheric aerosols and clouds, regional ecological responses on short time scales, and ocean color variabilities.

At L1/L2, we can begin making integrated measurements that have largely remained a dream for climate scientists. Several proposals for a truly integrative view of global change have come forward, like Walter Munk's for long-distance undersea sound propagation to measure integrated temperature, but none is yet implemented. We often speak of very small changes in "global temperature" or "global cloud albedo", but we don't truly measure these things to the very high precision that is required to understand seasonal or annual variations. We merely composite them from a few LEO satellites supplemented by inadequate surface networks and try not to make huge errors. From L1/L2, for the first time, we could measure such globally integrated variables to the accuracies needed using Moon calibration (Fig. 5).

The globally-integrated outgoing radiation (reflected sunlight and emitted thermal) from Earth is a key signature of global change. From L1 and L2, we can measure it without the present monumental difficulties forced by LEO observation. And we not only see all parts of the Earth at once, but with a small FOV ideal for current absolute radiometers. Furthermore, we can achieve about ten times better accuracy from L1/L2 than from the usual LEO orbits. With care, the absolute accuracy of the global radiation measurement from L1/L2 can be better than 0.2%, and the relative accuracy better than 0.03%, which is at the right level to actually observe annual global change. While these accuracies may sound phenomenal, they are routinely achieved by the spaceborne solar-constant radiometer ACRIM, and for similar reasons: a steady view of a stationary object with an angular size of 0.5° using self-calibrating electrical-compensation radiometric technology. It is not that we can magically field better radiometers at L1/L2; it is simply that the viewing conditions are so much better. Not only can the radiometers simply stare at the Earth without having to scan (which reduces error by radically simplifying the optics), but they can add up radiation for a whole minute rather than rushing on to view another place a tiny fraction of a second later, as in LEO and geostationary orbit. This addition process is one of the best ways we know to beat down random error in a radiation measurement.

L2 is an ideal location for measuring altitude profiles of trace gases using solar occultation in the near-IR. While LEO satellites can obtain 14 occultation measurements per day (2 per orbit), solar occultation observations from L2 can give *hourly measurements at all latitudes*. The expected spatial resolution is 2 km in altitude, 0.5 degrees in latitude, and 2 degrees in longitude. The result from 24 hours of observations will be a 3D map of atmospheric trace gas composition, something never before achieved.

Accomplishing this task from L2 requires the development of a moderate spectral resolution instrument whose entrance aperture is about 10 m. Use of a standard telescope design for such a large mirror would be prohibitively expensive and

Fig. 5 Simulated nearly instantaneous Triana view of clouds constructed from actual cloud observations seen by the Galileo spacecraft near L1. The Moon has been inserted from observations of the sunlit side using Clementine data. The Moon view will be used for in-flight calibration.

excessively massive. Instead, we are designing a Fizeau interferometer with a 10-m partially filled non-redundant mirror aperture coupled to a Fourier transform imaging spectrometer. The result would have sufficient sensitivity and sufficient spatial and spectral resolution to do the job. Preliminary calculations show that 7 species (CO_2, O_3, O_2, CH_4, H_2O, N_2O) have clearly separated spectral features in the 1–4 μm wavelength range with sufficient absorption to produce profile information from 8 km up to the middle stratosphere. (Ray-path bending determines the lower altitude limit.) For CO_2 the estimated sensitivity to change is 0.33% or 1 part in 330. This should be sufficient for many carbon cycle studies.

Initial instrument design studies are underway to determine the optimum optical design for the interferometer-spectrometer as well as the necessary highly stable mechanical designs. Separate design studies are being conducted for the spacecraft, shuttle launch facility, low-light solar power design, thermal control, and unique navigation requirements to reach and maintain the tight halo orbit about L-2. Work is being done on the concepts for the design of the mirrors, the mechanical support, active optics control, internal optics in the Fourier-Transform spectrometer, and the implementation of laser metrology for precise mirror position knowledge. Extensive retrieval algorithm design based on forward calculations is being conducted to determine sensitivity to concentration changes in realistic atmospheres.

There is much more scientific gold that can be mined from the L1/L2 vantage points, e.g.:

(1) long-term monitoring of very small changes in global ozone, aerosols, snow/ice cover, water vapor, clouds, surface temperature, and greenhouse gases;

(2) understanding diurnal change sensitivity as a stepping stone to understanding global climate sensitivity; unlike seasonal or interannual change, where our database is impoverished, one can quickly accumulate enough cases to have reasonable assurance of statistical significance;

(3) mimicking the high spectral resolution measurements needed to search for the signature of life on extra-solar planets; it would certainly make sense to prototype life-seeking methodology on a planet with known life forms;

(4) continually observing highly transient phenomena like incoming comets and asteroids, aurorae, airglow, cosmic rays, sprites, and lightning.

Other benefits of L1/L2 observations which there is no space to discuss here include: unique sunglint view (see Fig. 3); vegetation hotspot view; support for field programs; much less need for compositing because peeks through clouds are much more frequent; long exposure times for dramatically increasing signal-to-noise; monthly Moon views for calibration (Fig. 5); small FOV, simplifying optics dramatically; benign thermal and mechanical environment; simple attitude control; almost same fuel requirement as GEO. Some disadvantages include: radio interference from Sun (L1); halo orbits with unchangeable (6-month) period; limited view angle variation; no GPS; 5-sec communication delay; diminished solar power (L2); not shielded by Earth's magnetic field; Moon smaller than Earth so doesn't fill FOV of instruments; and long time (3–6 months) to reach orbit.

CONCLUSION

L1 and L2 observatories force a kind of intellectual transformation in how we look at the Earth—namely, as a single object obeying simple global laws, rather than a collection of pixels. Earth appears complex from a worm's-eye LEO view, and we reflect this seeming complexity in our models, but it must average out in the large to produce a planet satisfying some relatively simple thermodynamic-type laws. Few of these laws are known yet, for example those relating global cloudiness to global warming. Few even seek such laws. We are as unlikely to discover those laws from a worm's-eye view as to discover the perfect gas laws from tracking individual gas molecules.

This future path is more than just the dream of a few Lagrange-point enthusiasts. The whole-Earth view has been NASA policy since the famous Bretherton Committee first defined the concept of "Earth System Science" in the 1980's. Lagrange-point observatories make that concept incarnate. They are a tangible symbol of Earth System Science philosophy.

REFERENCES

[1] National Academy of Sciences, Review of Scientific Aspects of the NASA Triana Mission, Mar 2000.