Review of Scientific Aspects of the NASA Triana Mission: Letter Report

Task Group on the Review of Scientific Aspects of the NASA Triana Mission, Commission on Physical Sciences, Mathematics and Applications, National Research Council

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March 3, 2000

Dr. Ghassem R. Asrar
Associate Administrator for Earth Science
Code Y
NASA Headquarters
Washington, D.C. 20546

Dear Dr. Asrar:

At your request the National Research Council established a task group to evaluate the scientific aspects of the Triana mission. The charge to the Task Group on the Review of Scientific Aspects of the NASA Triana Mission was to review (1) the extent to which the mission's goals and objectives are consonant with published science strategies and priorities, (2) the likelihood that the planned measurements can contribute to achieving the stated goals and objectives, and (3) the extent to which the mission can enhance or complement other missions now in operation or in development.

Triana is a mission designed to be deployed into a stable orbit, at roughly a million miles from Earth in the direction of the Sun. An orbit at this location, known as Lagrangian point 1 (L1), is stable in the sense that the satellite remains on the Sun-Earth line and views the full sunlit disk of Earth continuously. From L1 Triana will observe Earth with two instruments, and a third will monitor the space environment in the direction of the Sun. Observed data are expected to be delivered in near real time to ground stations.

As proposed, Triana is an exploratory mission to investigate the scientific and technical advantages of L1 for Earth observations. The continuous view of the full sunlit disk of Earth will complement and extend observations from low Earth orbit (LEO) or geostationary Earth orbit (GEO) satellites. Triana will provide a global synoptic view (a continuous, from sunrise to sunset, simultaneous view of the sunlit side) of Earth in a range of wavelengths including ultraviolet, visible, and infrared to observe variations in ozone, aerosols, clouds, and surface ultraviolet radiation and vegetation. Triana is a flight opportunity to extend and improve observation of the solar wind and space weather at a most meaningful site, supplementing the data from the Advanced Composition Explorer satellite.

A detailed analysis of instrumentation, data collection and reduction, systems operation, and management was beyond the scope of the task group's effort and was precluded by the time and budgetary constraints placed on the preparation of this report Nevertheless, the task group agreed on a number of general issues related to the likely scientific success of the mission based on its review of relevant documents and reports and briefings by NASA's Triana science team. In its evaluation, the task group relied heavily on presentations from NASA and members of the Triana science team, and on detailed questioning of the presenters.

2101 Constitution Avenue, NW, Washington, DC 20418 *Telephone* (202) 334 3477 *Fax* (202) 334 3701 ssb@nas.edu
Office Address: Milton Harris Building, Room 584, 2001 Wisconsin Avenue, N.W., Washington, DC 20007

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In the attached more detailed technical assessment, the task group relates Triana's scientific objectives and deliverable data products to the research strategies and priorities proposed in earlier National Research Council and government reports. **The task group found that the scientific goals and objectives of the Triana mission are consonant with published science strategies and priorities for collection of climate data sets and the need for development of new technologies.** However, as an exploratory mission, Triana's focus is the development of new observing techniques, rather than a specific scientific investigation. The apparent spaceflight heritage of some of the Triana technology and the applicable legacy of the data reduction algorithms should contribute to the achievement of the mission's objectives. **The task group concluded that the planned measurements, if successfully implemented, will likely contribute to Triana's stated goals and objectives.** It did not attempt to evaluate the applicability of this heritage for a mission at L1.

The task group also found that the Triana mission will complement and enhance data from other missions because of the unique character of the measurements obtainable at the L1 point in space, which allows continuous imaging of the full sunlit disk of Earth and monitoring of the space environment upstream from Earth. Furthermore, the full-disk Earth observations provide a unique perspective from which to develop new databases and validate and augment existing and planned global databases. As an exploratory mission, Triana may well open up the use of deep-space observation points such as L1 for Earth science. The task group believes that the potential impact is sufficiently valuable to Earth science that such a mission might have been viewed as an earlier NASA priority had adequate technology been available at reasonable cost. **The task group is concerned, however, that because of the compressed schedule there may not be adequate time for instrument testing and calibration prior to launch.**

The task group is also concerned that significant development, testing, and validation of the operational algorithms are needed, and it recommends that this work start immediately. The scientific success of the Triana mission will be judged, in large part, on the quality of the initial data delivered to the scientific community. **The task group therefore recommends that NASA seriously consider increasing the level of effort invested in development and testing of data reduction algorithms for the core Earth data products as soon as possible. In addition, it is concerned that there may be insufficient funding for scientific analysis of the data.** If Triana lasts longer than its nominal 2 years, it will be important for NASA to support the data processing activities for the mission's useful duration.

The task group lacked the proper expertise, resources, and time to conduct a credible cost or cost-benefit analysis (such an effort might take many months and much detailed analysis) or an analysis of the mission goals and objectives within the context of a limited NASA budget or relative to other Earth Science Enterprise missions. However, based on the available information, **the task group found that (1) the cost of Triana is not out of line for a relatively small mission that explores a new Earth observing perspective and provides unique data; (2) since a significant fraction of the Triana funds (according to NASA and the Triana principal investigator, 50 percent of total funding and 90 percent of instrument development money) have already been expended, weighing cost issues would lead to only limited opportunities to save or transfer funds to other projects.** In addition, the task group endorses the statement by

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Congress that the delay in the mission mandated to produce this report may mean additional costs.

The task group emphasizes that the attached discussion of the ability of Triana to achieve the mission's stated goals and objectives is predicated on the assumption that the instruments and satellite have been, and will continue to be, subject to all necessary and appropriate exploratory-mission technical and quality control reviews. *Under no circumstances should this report or the statements contained in it be used as a replacement for these technical evaluations.*

Sincerely,

James J. Duderstadt
Chair, Task Group on the Review of Scientific Aspects of the NASA Triana Mission

Mark Abbott
Acting Chair, Space Studies Board

Eric J. Barron
Chair, Board on Atmospheric Sciences and Climate

Raymond Jeanloz
Chair, Board on Earth Sciences and Resources

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Review of Scientific Aspects of the NASA Triana Mission

INTRODUCTION

In a letter of October 14, 1999,[1] the National Research Council (NRC) was asked to evaluate the scientific goals of Triana, as specified in House Report 106-379.[2] Accordingly, the NRC established the Task Group on the Review of Scientific Aspects of the NASA Triana Mission[3] (referred to here as the task group) under the auspices of the Space Studies Board (SSB), the Board on Earth Sciences and Resources (BESR), and the Board on Atmospheric Sciences and Climate (BASC). The charge to the task group was to review (1) the extent to which the mission's goals and objectives are consonant with published science strategies and priorities, (2) the likelihood that the planned measurements can contribute to achieving the stated goals and objectives, and (3) the extent to which the mission can enhance or complement other missions now in operation or in development.

The task group met on January 12 and 13, 2000, at the National Academies' Georgetown offices in Washington, D.C. Prior to this meeting, it held two teleconferences to discuss the charge to the task group and plans for the meeting, and it also reviewed all relevant NRC reports, relevant government reports, and background materials.[4] On the first day of the meeting, the task group received presentations from NASA's Triana science team, among others.[5] These presentations discussed the technical aspects of the mission, including the science goals and objectives, data products, and instrument specifications and included a variety of opinions regarding the mission. One presenter made a number of recommendations to improve the science return from the mission, including significant redesign of the mission, as well as changes in the science team and data analysis efforts. For example, he proposed postponing the mission "to allow the science analysis efforts to catch up and to possibly reverse some of the downgrades to assure a successful scientific Triana mission that achieves its stated scientific objectives." The task group discussed these recommendations and concluded that several of them were beyond its statement of task; others are adequately covered in this report.[6]

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[1] See Appendix 1.

[2] This conference report accompanied the VA-HUD-Independent Agencies appropriations bill for FY 2000, P.L. 106-379, Title III, p. 158, enacted October 13, 1999.

[3] See Appendix 2 for the task group roster.

[4] Valero, Francisco P.J., Jay Herman, Patrick Minnis, William D. Collins, Robert Sadourny, Warren Wiscombe, Dan Lubin, and Keith Ogilvie, *Triana–a Deep Space Earth and Solar Observatory*, NASA background report, December 1999. Available at <http://triana.gsfc.nasa.gov/home/> posted as pdf file.

[5] See Appendix 3 for the agenda.

[6] This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the NRC's Report Review Committee. See Appendix 4.

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GENERAL MISSION DESCRIPTION

Previous and existing solar and magnetospheric missions demonstrate the suitability of Lagrangian point 1 (L1)[7] as a unique and opportune deep-space location for solar and space observation.[8] Triana was proposed as an exploratory mission to investigate the scientific and technical advantages of L1 for Earth observations. It will have a continuous and simultaneous view of the sunlit face of Earth that is not possible to achieve with low Earth orbit (LEO)[9] or geostationary Earth orbit (GEO)[10] satellites.

Triana is intended to provide a global synoptic view of Earth. It is designed to make measurements in a range of spectral channels to observe spatial and temporal variations in Earth's geophysical parameters, such as ozone, aerosols, clouds, and surface ultraviolet (UV) fluxes. Triana is designed to measure ozone and cloud distributions to enhance studies of their effects on climate and the amount of UV radiation that reaches the ground. The vegetation canopy structure is also intended to be observed in order to contribute to monitoring the status of Earth's vegetation. The global aerosol optical thickness[11] will be measured to increase knowledge of how pollution generated by humans and as a result of natural processes affects Earth.

Simultaneously, instruments on Triana are designed to determine Earth's planetary albedo in three regions of the spectrum—broadband long wave, near-infrared (IR), and UV/visible—to better characterize Earth's radiation budget. These measurements would provide the first direct determination of the radiant power emitted by the full sunlit disk of Earth in the direction of the Sun (i.e., Earth's radiance from which planetary albedo is determined by ratioing to solar irradiance), and therefore increase researchers' understanding of how much of the Sun's energy is absorbed in the atmosphere.

In addition to Earth-viewing instruments, Triana includes an instrument package designed to measure solar wind and the interplanetary magnetic field at L1. Based on these observations Triana, during its limited lifetime, could provide early warning (about 1 hour) to communication satellites and ground-based systems that are susceptible to solar-related disturbances during space weather events. Triana imagery and science data would also be made available for educational purposes, including distribution of Earth full-disk images over the Internet.

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[7] The L1 point is where Earth's gravity reduces the Sun's gravity such that the orbital angular velocity of an object positioned there matches the orbital angular velocity of Earth. A spacecraft at the L1 point thus remains on a line connecting Earth and the Sun.

[8] Stone, E.C., A.M. Frandsen, R.A. Mewaldt, E.R. Christian, D. Margolies, and J.F. Ormes, "The Advanced Composition Explorer," *Space Science Reviews* 86:1-22, 1998. Zwickl, R.D., K.A. Doggett, S. Sahm, W.P. Barrett, R.N. Grubb, T.R. Detman, V.J. Raben, C.W. Smith, P. Riley, R.E. Gold, R.A. Mewaldt, and T. Maruyama, "The NOAA Real-Time Solar Wind (RTSW) System Using ACE Data," *Space Science Reviews* 86:633-648, 1998.

[9] Satellites in low Earth orbit, typically about 400 to 500 miles above Earth's surface, image long strips of Earth's surface as they fly overhead.

[10] Satellites in geostationary Earth orbit, about 22,000 miles above Earth's surface, remain perched above a single point on Earth's equator as Earth rotates on its axis. They can image about one-third of Earth's surface and track the progress of day and night within their view as Earth turns on its axis.

[11] Aerosol optical thickness quantifies the extent to which a radiation beam passing through the atmosphere is weakened by scattering and absorption of atmospheric aerosols. A turbid or hazy atmosphere will thus have a larger aerosol optical thickness than will a clear atmosphere.

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Instrumentation

To accomplish its science goals, Triana has three instruments: the Scripps-Earth Polychromatic Imaging Camera (EPIC), the Scripps-National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR), and the Goddard Space Flight Center (GSFC) Plasma-Magnetometer Solar Weather Package (Plasma-Mag).

EPIC

The EPIC instrument is designed to provide ozone, aerosol, and cloud reflectivity data for the full sunlit disk of Earth. EPIC is a framing camera with a charge-coupled detector (CCD) focal plane array that will image the whole Earth disk from the L1 vantage point. The size of the array, 2048 by 2048 pixels, coupled with the Cassegrain telescope of 30.5-cm aperture and 282-cm focal length (f 9.38), provides a nominal spatial resolution of about 8 by 8 km for pixels viewed at nadir,[12] yielding a ground-projected pixel area of 64 km^2. When observations approach the edge of the Earth disk, the effective pixel size grows and the pixel changes shape as Earth's surface tilts away from the instrument. At 70° view zenith angle, the nominal pixel area is 187 km^2; at 80°, the nominal pixel size is 369 km^2. The changing size and shape of the pixels at the edge of the disk will degrad the effective spatial resolution of the measurements. The effective spatial resolution is somewhat coarser due to the point-spread function of the optics, which is expected to be about 10 by 10 km (nadir). Earth's illuminated disk is expected to occupy about 60 percent of the array.

The Epic camera's CCD array, operated at –40° C, has a high quantum efficiency beginning at about 250 nanometers (nm), thus permitting imaging in wavelengths from the UV to the near-IR. Through the use of a filter wheel fitted with filters whose surfaces are hardened by ion-assisted deposition, the camera records images of Earth in 10 spectral bands (Table 1). Shutter speeds are programmable to adjust for the wavelength-dependent sensitivity of the camera's detectors and for in-band scene brightness. The digital intensity conversion provides 12 bits of precision (0 to 4095) in the output signal. The signal-to-noise ratio of the array's detectors is designed to equal 200:1 at median signal intensities. Measured, calibrated radiances will be observed hourly for bands 1 to 5 and 9 to 10, and every 15 minutes for bands 6 to 8. These radiances will be Earth-located by attaching a latitude and longitude tag to each pixel. They will be archived in Earth Observing System – Hierarchical Data Format (EOS-HDF).

The Triana science team intends to calibrate this instrument before it is launched and to track its calibration in flight when the camera views the far side of the Moon as it comes between L1 and Earth. This event occurs about once per month and permits the monitoring of detector and filter degradation for the life of the mission. The technique assumes that the Moon's surface has a highly stable brightness and can thus be used as a reflectance standard.

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[12] At the nadir view, the instrument looks directly "down" at the surface from directly above the surface—that is, at an angle perpendicular to the surface.

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TABLE 1 EPIC's Filters Specifications

Band	Center Wavelength (nm)	Bandwidth (nm)	Previous Space Flight Heritage	Frequency	Purpose
1	317.5	1	TOMS	1 hour	Ozone
2	325	1	TOMS	1 hour	Ozone, SO_2
3	340	3	TOMS	1 hour	Aerosols
4	388	3	TOMS	1 hour	Aerosols, clouds
5	393.5	1	(New)	1 hour	Cloud height
6	443 (blue)	10	MODIS	15 minutes	Aerosols
7	551 (green)	10	MODIS	15 minutes	Aerosols, ozone
8	645 (red)	10	MODIS*	15 minutes	Aerosols, vegetation
9	870	15	MODIS	1 hour	Clouds, vegetation
10	905	30	MODIS	1 hour	Precipitable water

*The MODIS band has a 50-nm bandwidth.

NISTAR

The balance between incoming radiation from the Sun (in the near-UV, visible, and near-IR regions of the spectrum) that Earth reflects and absorbs, and radiation outgoing from Earth to space (in the thermal infrared spectrum) determines the budget of energy available for climate processes. By providing the first determination of the radiation reflected and emitted by the full sunlit disk of Earth in the direction of the Sun, the NISTAR instrument at L1 can contribute to researchers' knowledge of this radiation balance.

NISTAR is a suite of four radiation detectors mounted together with a filter wheel, shutter wheel, front-end baffles, and rear-end control and detection electronics, and boresight aligned with EPIC. Three of the four detectors are absolute devices, called electrical substitution active cavity radiometers,[13] which measure the integrated power from a single source of radiation (i.e., irradiance), in this case Earth as a planet. The NISTAR instrument is designed so that during a typical observation of Earth's radiation flux, two filters in the filter wheel placed over two of the three active cavities permit the measurement of two bands of radiation (from 0.2 to 4 μm and from 0.7 to 4 μm) while an open position in the filter wheel admits the entire radiation spectrum at all wavelengths. Because the time response of active cavity radiometers is on the order of 3 minutes, a fourth channel of NISTAR contains a photodiode that has a much faster time response but inferior accuracy and stability. In addition to providing higher time resolution, the photodiode channel permits in-flight measurements of the transmittances of the filters (which can be positioned over the cavities or the photodiode). NISTAR is designed to use the in-flight filter transmittance measurements and periodic use of redundant filters to track the stability of the radiation flux measurements throughout the mission.

Preliminary laboratory operations indicate that the goal of 0.1 percent accuracy and noise levels of 10 nW are attainable. Stabilities are unknown, but NIST reported that it has made efforts in the design of NISTAR to minimize drift and to monitor in-flight the

[13] An active cavity radiometer makes accurate measurements of optical power by comparing it with equivalent electrical power at constant temperature when a shutter successively exposes and blocks the source of radiation. The active cavities respond to the electromagnetic spectrum from 0.2 to 100 μm, and thus to solar radiation that Earth reflects and to longer wavelength radiation that Earth emits.

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radiometric sensitivity. Extensive preflight testing, calibration, and characterization are also planned using the laboratory standards at NIST.

The combination of NISTAR's full-disk measurements of Earth's radiance with EPIC's spatially resolved radiance measurements potentially offers a capability for future radiation budget monitoring with improved in-flight calibration and stability. The technology in NISTAR is based on well-established laboratory practices,[14] but its use in space will be new.

Plasma-Mag

The Plasma-Mag instruments are designed to measure the velocity distributions of solar wind electrons and ions (protons and alpha particles), and the interplanetary magnetic field at the L1 location. These are standard measurements that have been made previously and are currently being made on the Advanced Composition Explorer (ACE)[15] and the Solar Wind Observatory (WIND), except that a ≈30-fold improvement in the time resolution of the solar wind ion measurements can be accomplished on a 3-axis stabilized spacecraft such as Triana using existing designs. The magnetic field vector is determined with a sensitivity level of less than 0.1 nanoTesla (nT) and a dynamic range of 10^8 using standard technology optimized for small size and low power. Both the solar wind and magnetic field are sampled once every second.

The Plasma-Mag instrument package consists of four parts: (1) a Faraday cup to measure the velocity distribution of solar wind protons and helium nuclei (typically about 1 kiloelectron volt per atomic mass unit [keV/amu]), (2) a "top-hat" type electrostatic deflection analyzer that is operated in the range of 3 electron volts (eV) to 2 keV and has a sufficiently broad field of view to allow inference of the 3-dimensional solar wind electron velocity spectra, (3) a triaxal flux-gate magnetometer, and (4) a data handling unit for processing the signals from the three instruments. The magnetometer and electron analyzers are mounted on a 3-meter boom to minimize the effects of spacecraft potential and the magnetic field.

All three instrument designs have been used extensively in space applications,[16] and algorithms for deriving the physical parameters (e.g., solar wind density, bulk speed and temperature, magnetic field strength and direction) from the raw data are well established and tested, but have only been used with instruments on spinning spacecraft.[17]

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[14] Rice J.P., S.R. Lorentz, and T.M. Jung, "The Next Generation of Active Cavity Radiometers for Space-based Remote Sensing," American Meteorological Society conference proceedings: 10th Conference on Atmospheric Radiation: A Symposium with Tributes to the Works of Verner E. Suomi, pp. 85-88, 1999.

[15] For more information about the NASA missions and instruments referred to in this report, see <http://www.earth.nasa.gov/missions/index.htmll and http://www.spacescience.nasa.gov/missions/index.htm>.

[16] Ogilvie, K.W., D.J. Chornay, R.J. Fritzenreiter, F. Hunsaker, J. Keller, J. Lobell, G. Miller, J.D. Scudder, E.C. Sittler, Jr., R.B. Torbert, D. Bodet, G. Needell, A.J. Lazarus, J.T., Tappan, A. Mavretic, and E. Gergin, "SWE, A Comprehensive Plasma Instrument for the Wind Spacecraft," *Space Science Reviews* 71(1/4):55-77, February 1995.

[17] Scudder J., F. Hunsacker, G. Miller, J. Lobell, T. Zawistowski, K. Ogilvie, J. Keller, D. Chornay, F. Herrero, R. Fitzenreiter, D. Fairfield, J. Needell, D. Bodet, J. Googins, C. Kletzing, R. Torbert, J. Vandiver, R. Bentley, W. Fillius, C. McIlwain, E. Whipple, and A. Korth, "Hydra - A 3-Dimensional Electron and Ion Hot Plasma Instrument for the Polar Spacecraft of the GGS Mission," *Space Science Reviews* 71(1/4):459-495, February 1995.

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The plasma and magnetometer instruments are nearly identical to corresponding sensors flown successfully on the WIND and Polar spacecraft.[18]

Triana's Orbit and Earth-Viewing Geometry

The L1 point provides a unique view of Earth for the EPIC camera and NISTAR radiometers and also allows observations of the solar wind upstream from Earth with the Plasma-Mag instrument. The L1 point is located on the direct line between Earth and the Sun, about one-hundredth of the distance from Earth to the Sun. The mission is designed so that the spacecraft will not actually be located directly at the L1 point. If it were, radio communication would be too noisy, since earthbound antennas focused on the spacecraft would also see the Sun, a strong source of radio noise directly behind the spacecraft. Instead, Triana is designed to orbit around the Earth-Sun axis in a near-circular ellipse centered on the L1 point. This small orbit (Lissajous orbit) requires about 6 months for a complete revolution and provides a view of Earth that diverges from the Earth-Sun axis by 4°. The orbit also changes shape on a 4-year cycle such that the initial 4° divergence of view point expands to 15° through the cycle. Thus, Triana's EPIC and NISTAR instruments will view Earth from a direction that diverges from the direction of the Sun's illumination by an angle of 4 to 15°.[19]

The near-coincidence of view and illumination direction has important implications for the algorithms that transform EPIC radiances and NISTAR irradiances into geophysical data products. For example, the scattering angle of aerosol and cloud phase functions will be 165 to 177°, indicating scattering in nearly the backward scattering direction.[20] Since some scattering functions show rapid change with angle in this angular region, Triana data reduction algorithms are designed to accommodate the effects of the change in viewing geometry that will be experienced over the life of the mission. Over water, Sun glint can brighten surface reflectance when the Sun is near the overhead position. As a result, some ocean retrievals will be limited to morning and afternoon observations when glint is not a problem.

For land observations, the view is very near to the "hot-spot" (perfect backscatter) direction, at which surface bidirectional reflectance in reflective wavelengths is known to reach a peak. The hot-spot effect is produced by shadow hiding, in which structures or projections that cast shadows (e.g., plant canopies, individual plant leaves) also hide their own shadows when viewed from the same position as their illumination. While these directional effects may need to be "corrected" in some algorithms (e.g., to deduce albedos from NISTAR and EPIC observations), they can be a source of information for other algorithms (e.g., yielding potential Triana geophysical data products describing surface

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[18] Lepping R.P., M.H. Acuña, L.F. Burlaga, W.M. Farrell, J.A. Slavin, K.H. Schatten, F. Mariani, N.F. Ness, F.M. Neubauer, Y.C. Whang, J.B. Byrnes, R.S. Kennon, P.V. Panetta, J. Scheifele, and E.M. Worley, "The Wind Magnetic Field Investigation," *Space Science Reviews* 71(1/4): 207-229, February 1995. Acuña, M.H., K.W. Ogilvie, D.N. Baker, S.A. Curtis, D.H. Fairfield, and W.H. Mish, "The Global Geospace Science Program and Its Investigations," *Space Science Reviews* 71(1/4):5-21, February 1995. Harten, Ronald, and Kenn Clark, "The Design Features of the GGS Wind and Polar Spacecraft," *Space Science Reviews* 71(1/4): 23-40, February 1995.

[19] For clarity, this simple description assumes a static Earth-Sun axis, whereas the axis is actually in constant motion as Earth revolves around the Sun.

[20] Radiation that is scattered in the backward scattering direction is exactly reversed in direction and so proceeds directly on a line toward its source.

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vegetation structure). Because of the unique viewing point, observations from L1 may also help to fill in the angular observation domains of LEO and GEO imagers, which acquire hot-spot data only under very limited conditions.

A continuous view of Earth from the L1 point shows the changes in Earth's disk with the seasons. During the northern hemisphere summer, the arctic regions will be tilted toward the Sun and thus continuously visible, while antarctic regions will be continuously visible during the southern hemisphere summer. Polar visibility also depends on the position of Triana on its Lissajous orbit, which in turn depends on its launch date. If Triana is "above" the plane of the ecliptic during the northern hemisphere summer, its view of the arctic region will be better. The Triana science team prefers this scenario, as it will improve the quality and area of continuous measurement of ozone in the arctic.

Data Processing and Distribution

Triana's primary data products, as reported by the Triana science team, are shown in Table 2. Some of the data products will require both Triana data and ancillary data from other sources, such as ground-based instruments or other satellites.

As envisioned, the Triana data system will provide multiple streams to accommodate different user needs. The Triana data would be received on Earth at five to seven ground stations and from there would be transmitted to the Mission Operations Center (MOC) at the Goddard Space Flight Center. At a ground station, the data would be parsed into three streams—spacecraft status, time-critical science and image data, and data that are not time-critical. Time-critical data, which would be forwarded immediately to the MOC, include EPIC visible channels (443-, 551-, and 645-nm bands) observed every 15 minutes, aerosol and ozone channels observed every hour, and the entire Plasma-Mag data stream. The remaining data would be forwarded within 8 hours. Because of their potential urgency, the Plasma-Mag data are proposed to be transmitted directly to the National Oceanic and Atmospheric Administration (NOAA) for use in space weather forecasts and advisories. Geophysical and image processing of data would occur at the Triana Science and Operations Center (TSOC) at Scripps Institution of Oceanography, University of California, San Diego. EPIC visible channels will be calibrated, geolocated, georegistered, and posted on the Triana Web site within 30 to 45 minutes after acquisition. The NISTAR data will be received as a continuous stream, processed, and stored at the TSOC. NIST will then confirm that the data were collected properly and did not arrive during filter movement, spacecraft slew, or during an instrument calibration period.

The TSOC will store all raw and processed science and image data for the life of the mission (2 to 5 years) plus 3 years. The EPIC and NISTAR data will be managed at the Langley Distributed Active Archive Center. The task group did not review the data archiving or management plans.

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TABLE 2 NASA's Objectives for Triana Primary Data Products

Data Product	Coverage	Resolution			Accuracy	Relevant NRC and Government Reports*
		Spatial	Real Time	Full		
EPIC						
Total column ozone		8-16 km			± 3%	2, 3, 4, 5, 9, 12
Aerosol index		8-16 km			± 3%	3, 10
Aerosol optical depth		8-16 km			± 10%	2, 3, 4, 5, 9, 10, 12
Cloud height		16 km			± 30 mb	4, 5, 9, 10, 11
UV radiance		8-16 km			± 10%	3, 4, 5
Precipitable water		8-16 km			± 10%	3, 4, 5, 9, 10, 11, 12
Volcanic SO_2		8-16 km			± 10%	4, 5**
Cloud reflectivity		8-16 km			± 5%	2, 4, 5, 10, 11, 12
NISTAR						
Broad band radiances						2, 12
0.2 to >100 microns	Sunlit full disk of Earth				± 0.1%	10, 11
0.2 to 4 microns					± 0.1%	4, 10, 12
0.7 to 4 microns					± 0.1%	10
Planetary albedo Measurements	Sunlit full disk of Earth				± 0.003% absolute	10, 11
Plasma-Mag						
Solar wind proton density			minute	1.5 second	± 2%	1, 4, 6, 7, 8, 9
Solar wind velocity			minute	1.5 second	± 10%	4, 6, 7, 8, 9
Solar wind proton thermal speed			minute	1.5 second	± 10%	1, 4, 6, 7, 8, 9
Solar wind electron thermal speed			NA	1.5 second	± 10%	1, 4, 6, 7, 8, 9
Magnetometer						
Vector measurements of the interplanetary magnetic field			1 minute	20 milli-seconds	± 1% each component	1, 4, 6, 7, 8, 9

Note: Except for that in the right-hand column, the information in Table 2 was provided by the Triana science team and represents NASA's program plans and objectives.

*Compiled by the task group, this column lists previously published NRC and government reports that describe the value of these kinds of data for advancing understanding. See the key below for corresponding full references. One of the ways the task group addressed the issue of whether the Triana mission and goals are consonant with published science strategies was to compare Triana's primary data products as defined by the science team with priorities in relevant NRC and government reports.
**This report indicates the need to understand the contribution of volcanoes to the sulfur budget, radiation balance, and impact on stratospheric chemistry and physics.

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Key

1. Space Studies Board, National Research Council, *An Assessment of the Solar and Space Physics Aspects of NASA's Space Science Enterprise Strategic Plan,* National Academy Press, Washington, D.C., 1997.
2. Space Studies Board, National Research Council, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design*, National Academy Press, Washington, D.C., in preparation, February 2000.
3. National Research Council, *A Review of the U.S. Global Change Research Program and NASA's Mission to Planet Earth/Earth Observing System,* National Academy Press, Washington, D.C., 1995.
4. National Research Council, *Global Environmental Change: Research Pathways for the Next Decade*, National Academy Press, Washington, D.C., 1998.
5. National Research Council, *The Atmospheric Sciences Entering the Twenty-First Century,* National Academy Press, Washington, D.C., 1998.
6. Space Studies Board, National Research Council, *A Science Strategy for Space Physics,* Committee on Solar and Space Physics, National Academy Press, Washington, D.C., 1995.
7. Space Studies Board, National Research Council, *Space Weather: A Research Briefing*, Committee on Solar and Space Research and Board on Atmospheric Sciences and Climate Committee on Solar-Terrestrial Research, National Academy Press, Washington, D.C., 1997. Available only as an electronic document at <http://www.nas.edu/ssb/cover.html>.
8. National Research Council, *Toward a New National Weather Service—Continuity of NOAA Satellites,* National Academy Press, Washington, D.C., 1997.
9. National Research Council, *A Vision for the National Weather Service: Road Map for the Future,* National Academy Press, Washington, D.C., 1999.
10. Office of Science and Technology Policy, *Our Changing Planet: A U.S. Strategy for Global Change Research.* Committee on Earth Sciences, Washington, D.C., 1989.
11. National Research Council, *Research Strategies of the U.S. Global Change Research Program*, Committee on Global Change, National Academy Press, Washington, D.C., 1990.
12. Space Studies Board, National Research Council, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation*, National Academy Press, Washington, D.C., in preparation, 2000.

TECHNICAL ASSESSMENT

1. Are Triana's goals and objectives consonant with published science strategies and priorities?

The goals and objectives of the Triana mission fall within two general categories: (1) to launch a modest exploratory mission to demonstrate the value of remote sensing observations from L1 for Earth science and (2) to gather global climate data and fill operational needs related to global change and solar weather. **In general, the task group found that the scientific goals and objectives are consistent with the strategies and priorities for collection of climate data sets, and the need for development of new technologies, as articulated in relevant reports published by the National Research Council and other similar organizations.**

The task group could not find within any of the recently published reports of the NRC a specific recommendation to use L1 as the point from which to gather Earth science information. Nevertheless, the task group found that observation from L1 has the potential to provide data that can address several high-priority and conceptual issues that the reports highlight. For example, the proposed Triana mission is consistent with some recommendations made in the recent NRC report *Research Pathways for the Next*

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Decade,[21] such as the need to elucidate "the connections among radiation, dynamics, chemistry and climate" and the need for "a scientific understanding of the entire Earth System on a global scale" (p. 5), with the caveat that although Triana views the full sunlit disk of Earth it cannot determine the thermal budget of the planet as a whole. The *Pathways* report stresses three objectives: (1) the need for well-calibrated observations, which Triana is designed to accomplish by using both the Moon and absolute radiometry; (2) the need to adopt multiple observational approaches, which Triana is designed to provide in conjunction with LEO and GEO missions; and (3) the need for technical innovation, which the use of both L1 for Earth observations and the NISTAR instrument exemplifies. The *Pathways* report also recommends the use of "smaller and more focused missions along the lines of the new Earth System Science Pathfinders" (p. xi). Triana is a relatively small mission comparable to an Earth System Science Pathfinder, but its focus is on exploring the technique of using L1 for Earth observations, rather than addressing a specific scientific problem.

Perhaps Triana's most important contribution to Earth science observations is the potential for using L1 observations of Earth to integrate data from multiple spaceborne as well as surface and airborne observation platforms into a self-consistent global database for studying the planet and documenting the extent of regional and global change. The L1 view allows the continuous acquisition of data from the entire full sunlit disk of Earth. These data overlap in both space and time the data gathered by essentially all other networks. The caveat here, however, is that Triana observations have a particular scattering geometry (close to backscatter), and the integration will therefore require additional processing of the data sets. Data from L1 may be useful for cross-calibrating independent observations and hence for assembling improved, self-consistent global databases from the diverse set of existing observations. Moreover, because of its large spatial coverage and temporal continuity, the data from Triana at L1 can be used to fill in data gaps left by other networks and spaceborne platforms.

Triana at the L1 view also has the potential to provide atmospheric observations (particularly of ozone) at a finer temporal and spatial resolution for a larger portion of the globe than can currently be obtained from either LEO or GEO. For example, it is well known that both the planetary-scale circulation and small-scale mixing are equally important to the transport of chemical substances in the stratosphere. Few LEO and GEO measurements of trace species encompass these widely separated scales simultaneously. The hemispheric, high-resolution (8 km) ozone and aerosol data to be sampled by EPIC on Triana will be a unique set of observations for elucidating transport processes at both large and small scales. Such data should be valuable in furthering understanding of the chemistry of the stratosphere (e.g., ozone layer) and its response to anthropogenic and natural perturbations.

The observations proposed by the Triana science team also have the potential to address a number of more specific scientific issues related to climate and space weather. As Table 2 indicates, most of the principal data products anticipated from Triana are identified as priorities in relevant NRC reports. These reports were produced over a number of years and using a variety of methodologies. The task group concluded that it would be difficult, if not impossible, to establish more refined estimates of priorities among these reports. Therefore, for the primary data products listed in Table 2, the task group has noted which earlier reports have indicated that the data were desirable, but it has not attempted to establish relative priorities.

The observations from EPIC and NISTAR are designed to address the connections between radiation dynamics, chemistry, and climate, a theme that is highlighted in many recent NRC

[21]National Research Council, *Global Environmental Change: Research Pathways for the Next Decade*, National Academy Press, Washington, D.C., 1998.

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reports.[22] The Plasma-Mag instrument is designed to provide data on the small-scale structure of the solar wind with a high time resolution, objectives consistent with the recommendations of NRC reports.[23] The Triana mission is also consistent with more general recommendations to adopt multiple observational approaches.[24] It is also possible that the Triana Earth observations will secure useful near-real-time information on the occurrence and evolution of potentially harmful environmental events (e.g., forest fires, volcanoes, UV irradiance peaks), thereby demonstrating the utility of L1 imaging for future operational products of societal relevance.

Without doubt, the Triana mission will have valuable space weather operational applications, the importance of which both NRC reports and the National Space Weather Program[25] confirm. In conjunction with the present ACE mission (also at L1 but in a different orbit), Triana's Plasma-Mag enhances the ability of NOAA's Space Environment Center to carry out its mission to provide warning of imminent solar storm events, especially those whose terrestrial impact is less certain. Because the environment at L1 is very benign, it is expected that the ACE spacecraft and its instruments will remain healthy and thus will be able to provide space weather data to NOAA's Space Environment Center for at least 4 years beyond the end of ACE's prime mission in 2002 (providing NASA funds the mission's extension). However, if the ACE spacecraft is lost or its plasma or magnetometer instrument fails, then Triana as the only upstream monitor of solar wind and interplanetary magnetic fields could be critical to the Space Environment Center's mission.

As an exploratory mission Triana has experimental and innovative aspects that carry higher than usual risks but have the potential to make unique scientific contributions. The use of L1 for making Earth observations is itself experimental, since it will test the algorithms used to reduce remotely sensed data from a new combination of solar zenith angle and

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[22] Space Studies Board, National Research Council, *Readiness for the Upcoming Solar Maximum*, National Academy Press, Washington, D.C., 1998. Space Studies Board, National Research Council, *Earth Observations from Space: History, Promise, and Reality,* National Academy Press, Washington, D.C., 1995. Space Studies Board, National Research Council, *An Assessment of the Solar and Space Physics Aspects of NASA's Space Science Enterprise Strategic Plan,* National Academy Press, Washington, D.C., 1997. Space Studies Board, National Research Council, Letter Report: "Assessment of NASA's Plans for Post-2002 Earth Observing Mission," National Academy Press, Washington, D.C., 1999. Space Studies Board, National Research Council, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design*, National Academy Press, Washington, D.C., in preparation, February 2000. Space Studies Board, National Research Council, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs,* National Academy Press, Washington, D.C., in press, February 2000. National Research Council, *A Review of the U.S. Global Change Research Program and NASA's Mission to Planet Earth/Earth Observing System,* National Academy Press, Washington, D.C., 1995. National Research Council, *Global Environmental Change: Research Pathways for the Next Decade*, National Academy Press, Washington, D.C., 1998. National Research Council, *The Atmospheric Sciences Entering the Twenty-First Century,* National Academy Press, Washington, D.C., 1998. National Research Council, *Adequacy of Climate Observing Systems,* National Academy Press, Washington, D.C., 1999. Space Studies Board, National Research Council, *A Science Strategy for Space Physics,* National Academy Press, Washington, D.C., 1995. Space Studies Board, National Research Council, *Space Weather: A Research Briefing*, National Academy Press, Washington, D.C., 1997. Available only as an electronic document online at <http//www.nas.edu/ssb/cover/html>. Office of Science and Technology Policy, *Our Changing Planet: A U.S. Strategy for Global Change Research,* Committee on Earth Sciences, Washington, D.C., 1989. National Research Council, *Research Strategies for the U.S. Global Change Research Program*, National Academy Press, Washington, D.C., 1990.

[23] National Research Council, *Adequacy of Climate Observing Systems,* National Academy Press, Washington, D.C., 1999. Space Studies Board, National Research Council, *Earth Observations from Space: History, Promise, and Reality,* National Academy Press, Washington, D.C., 1995. Space Studies Board, National Research Council, *An Assessment of the Solar and Space Physics Aspects of NASA's Space Science Enterprise Strategic Plan,* National Academy Press, Washington, D.C., 1997.

[24] National Research Council, *Global Environmental Change: Research Pathways for the Next Decade*, National Academy Press, Washington, D.C., 1998.

[25] The National Space Weather Program, The Implementation Plan, FCM-P31-1997, Washington, D.C.

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viewing/backscattering angles. The NISTAR instrument is based on an established laboratory technology, but one that has never before been used on a space-based platform; it is a completely new technological application of both hardware and algorithms. If the instrument performs properly and suitable algorithms are developed to provide sufficiently accurate data, NISTAR may provide unique observations of Earth's radiation parameters. Similarly, the proposal to use hot-spot data from EPIC to infer forest canopy structure is experimental but has the potential to make a significant contribution to the area of terrestrial ecology.

2. Can Triana's goals and objectives be achieved with the planned measurements?

The task group conducted neither a technical review of the Triana instrumentation or satellite nor a risk analysis. Such activities were beyond its scope and were precluded by the time and budgetary constraints placed on the preparation of this report. Nevertheless, the task group agreed on a number of general issues related to the likely scientific success of the mission based on a review of relevant documents, reports, and briefings by the Triana science team. The task group emphasizes that the following discussion of the ability of Triana to achieve its goals and objectives is predicated on the assumption that the instruments and satellite have been and will continue to be subject to all necessary and appropriate exploratory-mission technical and quality control reviews. *Under no circumstances should this report or the statements contained in it be used as a replacement for these technical evaluations.*

Space missions, by their very nature, are risky, and exploratory missions such as Triana typically carry additional risk. It appears that Triana has been subjected to an unusually tight schedule and constrained budget. It is not unreasonable, in the task group's view, to expect that missions implemented on a short time line and with a constrained budget might carry more risk, although no specific evidence suggests that this is the case for Triana. Suffice it to say that the short time line and tight budget for Triana should not be allowed to preclude the rigorous technical evaluations and quality controls normally carried out by NASA for exploratory missions. This applies especially to the NIST portion of the mission and NISTAR, since NIST has no experience in the construction, quality control, and implementation of space instrumentation and NISTAR has no prior flight heritage.

Some aspects of the mission led the task group to be optimistic. Because the radiation environment at L1 is more benign than for LEO and GEO, once the platform reaches L1, the chances of instrument damage or degradation from radiation will be significantly less than for more typical space-based missions focusing on Earth. Because it is never eclipsed, the Triana spacecraft will experience less thermal stress than most LEO and GEO missions. Another encouraging sign is the fact that all three of Triana's instruments have been built and are now in the testing phase. However, a critical part of this phase—the thermal and vibration testing—has yet to be conducted. Successful completion of these milestones will enhance the prognosis for Triana's success.

EPIC

The EPIC camera relies on largely proven technology, and its fabrication is not apparently a significant technological challenge. According to the Triana science team, EPIC's basic CCD array technology has been applied in other spaceborne imagers (namely the Michelson Doppler Imager on the Solar and Heliospheric Observatory [SOHO] and the

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Transition Region and Coronal Explorer [TRACE]). However, the array utilizes two new features—back side thinning and back side illumination.[26] Back side thinned and illuminated arrays are currently used in many earthbound astronomical instruments. Although there is a flight heritage for back side-illuminated arrays, Triana would be the first spaceborne application of a back side thinned and illuminated array. NASA has assured the task group that the filters, which are fabricated with ion-assisted surface deposition, have been built and tested, and closely meet the nominal specifications.

NISTAR

The NISTAR radiometers are absolute detectors that measure power directly, thereby precluding the need for complex transfer algorithms and inversions to obtain geophysical data products from detector signals, other than the transmission functions of the filters that isolate the solar and thermal signals. The approach relected in NISTAR's inclusion on Triana for monitoring Earth's irradiance has not been utilized in the past because of the lack of absolute radiometric devices with sufficient sensitivity when operating near room temperature. Similar types of devices have for two decades measured the power from the Sun,[27] and independent NASA instruments of this type will provide the measurements of incident solar energy needed to derive planetary albedo during the Triana mission. NISTAR will implement analogous, simultaneous measurements of integrated power from the full sunlit disk of Earth itself, permitting measurements of Earth's planetary albedo as a function of time, including visible and near-IR bands separately.

The NISTAR measurements should be possible because of significant radiometric advances that NIST has pioneered in the construction of radiometers. These new radiometers are designed to achieve adequate signals relative to noise at room temperature and are based on laboratory cryogenic radiometers used extensively as national power standards.[28] The filters that separate radiant fluxes into visible and near-IR spectral regions have ion-assisted deposition on their surfaces and are multiply redundant, features that help, respectively, to minimize and permit tracking of their in-flight stability drifts. Dual carriage filter and shutter wheels are designed for adequate thermal isolation of the receiver cavities from the surrounding environment.

The NISTAR hardware has been constructed and is currently undergoing laboratory testing at NIST. The task group notes that algorithms remain to be developed to derive the planetary parameters from the NISTAR radiation measurements. Since the sunlit disk albedo measurements planned by NISTAR are new observables, and the derived geophysical parameters from NISTAR and EPIC are new data products, all of which lack algorithm heritage, it is not possible yet to assess the effort required to deduce reliable geophysical data from these observations. However, experience with similar data sets (e.g., ERBE) suggests that a significant time investment will be required.

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[26] The back side thinning process removes excess silicon to enhance sensitivity in the ultraviolet region. Back side illumination, in which the array is illuminated from the side from which the signal is read out, improves sensitivity and makes the array less susceptible to on-orbit radiation degradation.

[27] The Sun's signal of ~100 milliwatt per square centimeter at LEO is five orders of magnitude higher than the 1 microwatt per square centimeter signal from Earth at L1.

[28] Examples of technological advances used in the design of these new radiometers include (1) positive temperature coefficient thermistors that achieve order-of-magnitude sensitivity determination of cavity temperature compared with the normally used platinum resistance wire; (2) AC bridge circuitry that minimizes noise by isolating the frequency of the measured signals; (3) stable phosphorous nickel surface coatings that maximize optical electrical equivalence; and (4) diamond turned apertures and precision optical aperture area determinations.

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Plasma-Mag

The goals and scientific aims of the Plasma-Mag investigation are to (1) study plasma turbulence and structures in the solar wind using the fast (≈1 sec) time resolution capabilities of Plasma-Mag, (2) study the large-scale solar wind structures using multipoint and correlative observations from complementary space environment missions (ACE, WIND, Solar Terrestrial Relations Observatory [STEREO], and SOHO), and (3) provide real-time solar wind parameters required for space weather forecasting. The task group concluded that the likelihood that these objectives and goals will be achieved is high, because measurements of the type planned by Plasma-Mag are widely used in space environment missions.

The interplanetary environment is a highly turbulent medium that supports a great variety of wave motions. Shocks, discontinuities, and small-scale structures such as "magnetic holes" (in which the magnetic field nearly vanishes) are often present. A fast sampling (≈1-sec time resolution) such as would be provided by the Plasma-Mag solar wind instruments on Triana could be useful for further progress on these problems.[29] For example, high-time-resolution measurements may help researchers better understand the wave damping and heating of particles expected to take place near the proton cyclotron frequency. Such measurements are likely to be useful to properly characterize discontinuities and shocks in the solar wind. High-time-resolution plasma data will enable studies of the smaller magnetic hole structures that have frequently been observed at lower time resolutions.[30]

Solar wind and magnetic field observations from Plasma-Mag will be valuable in studies examining a variety of large-scale structures such as the shocks, current sheets, and magnetic clouds often associated with coronal mass ejections. With a constellation of four spacecraft (Triana, ACE, WIND, and STEREO) separated by large distances (on the order of 200 Earth radii), the geometry of relatively stable structures in the near-Earth space environment can be determined. This configuration of four spacecraft will also enable determination of, for example, the size and configuration of larger magnetic holes and would allow multi-spacecraft studies of the geometric configurations and structures of coronal transient related disturbances.

The Plasma-Mag on Triana at L1 is designed to provide in near real time and on a continuous basis the primary set of measurements required by the Space Environment Center of NOAA to monitor and forecast Earth's solar environment and provide accurate, reliable, and useful warnings of solar-terrestrial interactions. The required primary measurements are the solar wind plasma ion density, velocity, and temperature, and the magnetic field vector in standard coordinates. The required time resolution is 1 minute or faster. The Plasma-Mag instrument package is intended to take the measurements and compute on-board averages of solar wind and magnetic field parameters in real time once per minute. The launch of Triana in 2001 or later will provide overlap with ACE for many years, allowing for cross-calibration. The availability of real-time solar wind data from L1 spacecraft at two separate points in space would enhance the reliability of detecting the geoeffectiveness of disturbances not directly on the Sun-Earth line by providing additional information about the irregularities in the solar wind.

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[29] Valero, Francisco P.J., Jay Herman, Patrick Minnis, William D. Collins, Robert Sadourny, Warren Wiscombe, Dan Lubin, and Keith Ogilvie, *Triana – a Deep Space Earth and Solar Observatory*, NASA background report, December 1999. Available at <http://triana.gsfc.nasa.gov/home/> posted as pdf file.

[30] Burlaga, L.F., "Micro-Scale Structures in the Interplanetary Medium," *Solar Physics* 4:67, 1968. Burgla, L.F., and N.F. Ness, "Macro- and Microstructure of the Interplanetary Magnetic Field," *Can. J. Physics* 46:S962, 1968. Fitzenreiter, R.J., and L.F. Burlaga, "Structure of Current Sheets in Magnetic Holes at 1AU," *J. Geophysics Res.* 83:5579, 1978. Turner, J.M., L.F. Burlaga, N.F. Ness, and J.F. Lamarie, "Magnetic Holes in the Solar Wind," *J. Geophysics Res.* 82:1921-1924, 1977.

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Data Products

The main advantage of Triana is that it will view the full sunlit disk of Earth, continuously and synoptically. The technique employed by EPIC (of combining a telescope with a CCD camera) allows particularly high spatial resolution considering the L1 vantage point. For stratospheric and upper-atmosphere studies based on total ozone column data, EPIC's 8-km spatial resolution at nadir (and up to 14 km at the highest usable viewing angle) is far superior to that available for UV channels on the Total Ozone Mapping Spectrometer (TOMS) (≈ 80 km)(which uses a scanning spectrometer and photomultiplier in LEO). Coupled with the monitoring of diurnal variations obtained from L1, EPIC's 8-km spatial resolution will permit preliminary studies of stratospheric processes at time and space scales not resolved thus far with LEO satellites. The 8-km spatial resolution is also sufficient for lower-atmosphere studies of aerosol optical depth, precipitable water, and clouds (with some caveats as discussed below) but is much less optimal for surface process investigations. For surface processes the main advantage is the observation geometry, the so-called hot-spot view, which is rarely realized from other spacecraft and thus offers new opportunities, in particular for studying canopy properties.

Table 2 lists the data products that the Triana mission is intended to deliver in quasi-real time. Most algorithms needed to produce the EPIC and Plasma-Mag data have notable heritage, with some algorithms more mature than others. For instance, in the case of total column ozone measurements, the TOMS heritage is significant,[31] and if the EPIC instrument functions according to specification, total column ozone should be a relatively straightforward data product for the Triana team to deliver from the start of the mission. On the other hand, in the case of aerosol optical depth estimation based on a ratio of UV radiances, the algorithm is less mature and has limited documentation. Some adjustments are likely to be necessary after launch, particularly over bright surfaces or at high viewing angles (e.g., arctic). So, while it can be expected that the generation of most data products will be achieved to a scientifically useful accuracy, the accuracy of some data products is expected to be higher than that of others. NISTAR in contrast is a new instrument, so that significant algorithm development, testing, and validation are needed to enable processing of its raw data into useful information. The relationship between the accuracy of the derived data products and the accuracy of the raw data is unclear.

To take full advantage of the new opportunities offered by Triana requires special attention to the accuracy and stability of the NISTAR and EPIC instruments. The accuracy will be obtained through on-board calibration of the instruments. For instance, NISTAR is a self-calibrating instrument by virtue of multiple redundant filters, an unfiltered absolute radiometric channel, and inter-calibration of EPIC with other spaceborne instruments, while EPIC stability will be assessed through monthly monitoring of the back side of the Moon. The level of accuracy to be achieved from inter-calibration is difficult to assess since most of the other instruments with which EPIC will be inter-calibrated are themselves poorly calibrated (e.g., the Advanced Very High Resolution Radiometer [AVHRR], the Visible Infrared Spin-Scan Radiometer (VISSR) on the U.S. Geostationary Meteorological Satellite [GOES]). The innovative and particularly attractive approach of using the Moon for performing instrument in-flight stability assessment appears to have been very well thought out, but operational experience may lead to refinements in the techniques with time.

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[31] Valero, Francisco P.J., Jay Herman, Patrick Minnis, William D. Collins, Robert Sadourny, Warren Wiscombe, Dan Lubin, and Keith Ogilvie, *Triana – a Deep Space Earth and Solar Observatory*, NASA background report, December 1999. Available at <http://triana.gsfc.nasa.gov/home/> posted as pdf file.

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With regard to the generation of atmospheric data products besides ozone (aerosol optical depth, total precipitable water), one issue of concern is the determination of cloud data in pixels that are only partially cloudy across their areas. The accuracy of the retrieved parameters will depend on the quality of the scene determination in cloud-free pixels. Cloudy pixel determination will be achieved using the commonly applied radiance threshold method. With relatively small pixels (≈ 1 km), such as those from AVHRR or the Moderate Resolution Imaging Spectroradiometer (MODIS) for instance, the cloud/clear distinction is relatively straightforward. However, it becomes more difficult as the spatial resolution decreases (i.e., the size of the pixels increases). Due to the typical cloud size, an 8-km pixel is more likely than a 1-km pixel to be partially cloudy. A lower threshold value will ensure that no clouds (or at least few clouds) are present and is likely to produce more accurate data, but it will limit the number of pixels usable in retrievals of geophysical data. A higher threshold will allow more partly cloudy pixels to be included, but will induce a reduction in the accuracy of the parameter retrieved. Also, since the Triana observations are made at high scattering angles (between 140 and 160°), the computed threshold value will have to account for this scattering angle. This means that thresholding algorithms developed for other instruments such as AVHRR and MODIS will need to be adjusted to the EPIC spatial resolution and observation geometry, and their performance evaluated. Some guidance could be obtained from the work done with the Polarization and Directionality of Earth's Reflectances (POLDER) instrument,[32] which has a similar resolution. This, however, suggests that the heritage from other sensors for cloud detection will not be directly applicable and that a significant amount of work will have to be done both before and after launch to adjust for the EPIC instrument and Triana viewing characteristics.

Another issue of concern is estimation from NISTAR and EPIC of Earth's albedo. Because albedo concerns solar radiation reflected in all directions from the whole Earth disk, it cannot be measured directly from a look in a single direction. Extrapolating the data from one direction to others requires coming up with an angular distribution model that essentially transforms measurements from one direction into another. Such a model varies with surface type. EPIC data will be used to assign each pixel of the Earth disk to a particular surface type (cloud, water, vegetation, and so on). Given the surface type and the imaging geometry, a weight representing the angular distribution model will be assigned that accounts for the directional effects, and the weights will be aggregated to provide whole-Earth albedo. Angular distribution models can be built from the observations of other instruments (e.g., Clouds and Earth's Radiant Energy System [CERES]). The procedure employed is rather complex—since it uses a combination of measurements from NISTAR, EPIC, and CERES, for instance, to build the albedo of the sunlit side of the planet—and will likely need some testing and adjustment.

For the concerns raised here, it is not the possibility of producing excellent data sets that is in question, but rather the level of effort that will be required to do so. Indeed, for the Triana mission to produce useful geophysical parameters will require that great care be taken in the development, testing, and validation of the operational algorithms. The expected resources needed for these functions are inconsistent with the current, very limited, level of effort to support development of these algorithms. In view of the extremely short time frame of the mission and the necessary algorithm adjustments alluded to above, substantial work on the data reduction algorithms should start immediately. Operational algorithms can take a long time to implement and fully test. The scientific success of the Triana mission will be judged, in large part, on the quality of the initial data delivered to the scientific community. The task group

[32] The instrument will observe from space the polarization, and the directional and spectral characteristics, of solar light reflected by the Earth-atmosphere system.

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therefore recommends that NASA seriously consider increasing as soon as possible the level of effort invested in development and testing of data reduction algorithms for the core Earth data products. The more research-oriented data products can and will take more time to produce and test, and that is entirely acceptable. The Plasma-Mag algorithms have a long heritage and have been well proven; it is just a matter of transferring them to operational algorithms. Although this effort should not be neglected, it should require much less investment than that needed for the EPIC or NISTAR algorithms, data reduction, and analysis effort.

3. Does Triana Enhance or Complement Other Missions Now in Operation or in Development?

The Triana science team asserts that, in addition to providing unique capabilities for remote sensing observation of Earth, Triana will enhance and complement other missions because of its L1 vantage point for continuous imaging of the full sunlit disk of Earth. The task group generally supports this view, although the nature and extent of enhancement will likely vary among the instruments. Many of the details of the complementary nature of Triana are discussed in the preceding sections.

Interactions with Earth-viewing missions at LEO and GEO will extend in time and coverage, and in accuracy through cross-calibrations, the data quality and value of all of the missions. For example: (1) EPIC will significantly extend TOMS, which samples data once a day at local noon at a nadir resolution of 80 km, to a near-continuous sampling at a nadir resolution of 8 km; (2) EPIC will also enhance the temporal coverage of MODIS, which, unlike Triana, covers the entire Earth's surface but does so every 1 to 2 days; (3) EPIC and the Multi-angle Imaging Spectroradiometer (MISR), POLDER, and the Along Track Scanning Radiometer (ATSR-2) fill in angular space for each other; (4) NISTAR augments CERES with continuous planetary albedo near 180° backscatter in similar spectral bands; and (5) Triana complements GEO satellites with high-latitude observations, although the utility of the data near the fringe of the disk is somewhat questionable.

Triana's synoptic view of Earth will help to put localized, ground-based, and airborne field observations into a global context. For example, measurements of tropical cirrus cloud microphysics and radiation during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers (CRYSTAL) campaigns, planned for 2002 and 2004, can be correlated with concurrent observations by Triana at L1. Work at Department of Energy – Atmospheric Radiation Measurement (DOE-ARM) sites also, for example, will benefit from such correlative observation.[33]

Triana will also augment existing Sun-viewing satellites at L1. Plasma-Mag will enhance the time resolution and spatial coverage of solar wind data from WIND and ACE. It will complement, and may succeed, ACE in operational utility.

In turn, Triana will benefit from the presence of other satellites. Data from instruments with higher spatial resolution such as MODIS and the Sea-Viewing Wide Field Sensor[34] (SeaWiFS) will improve EPIC data, especially aerosols, and add new information about cloud

[33] Valero, Francisco P.J., Jay Herman, Patrick Minnis, William D. Collins, Robert Sadourny, Warren Wiscombe, Dan Lubin, and Keith Ogilvie, *Triana – a Deep Space Earth and Solar Observatory*, NASA background report, December 1999. Available at <http://triana.gsfc.nasa.gov/home/> posted as a pdf file.

[34] It provides global estimates of oceanic chlorophyll-a and other bio-optical quantities to the international research community.

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properties. Triana's in-flight validation should benefit from the calibration heritage of TOMS and MODIS. Radiation fields observed by CERES can be directly compared with NISTAR data.

SUMMARY

The task group's assessment of Triana's scientific objectives and goals is based on its review of the relevant literature and presentations regarding the proposed scientific mission. The task group found that (1) **the scientific goals and objectives of the Triana mission are consonant with published science strategies and priorities for collection of climate data sets and the need for development of new technologies; (2) if successfully implemented, the planned measurements will likely contribute to Triana's stated goals and objectives; and (3) the Triana mission will complement and enhance data from other missions now in operation or in development because of the unique character of the measurements obtainable at the L1 point in space, which allows continuous imaging of the full sunlit disk of Earth and monitoring of the space environment upstream from Earth.** Nevertheless, **the task group recommends that NASA seriously consider increasing the level of effort invested in development and testing of data reduction algorithms for the core Earth data products as soon as possible and ensure that all the appropriate technical and management reviews are performed.** In addition, if Triana lasts longer than its nominal 2 years, it will be important for NASA to support the data processing activities for the mission's useful duration.

More specifically, **the task group found that the scientific objectives and deliverable data products of the Triana mission as described by NASA's Triana science team are consonant with science strategies and priorities proposed by various NRC and government reports**, as summarized in Table 2 of this report. The task group notes that Triana's primary focus is technique and technology development at L1, as the *Pathways* report recommended for future Earth Science System Pathfinder missions, rather than any one specific scientific problem. **The task group concluded that the mission, if successfully implemented, is likely to achieve the stated goals and objectives, although as in most exploratory missions there can be no assurance of success.** A detailed analysis of instrumentation, data collection and reduction, systems operations, management, cost, and risk was beyond the scope of the charge to this task group. However, it was impressed by the detailed efforts of the Triana science team and their extensive use of heritage technology and data reduction algorithms where they were available.

The task group found that the Triana mission will complement and enhance other missions because of the unique character of measurements made from the L1 point, which allow continuous imaging of the full sunlight disk of Earth and monitoring of solar wind properties relevant to space weather. Furthermore, such observations from L1 should provide a unique perspective to develop new databases and validate and augment existing and planned global and local interplanetary databases.

Triana is an exploratory mission that may open up the use of deep-space observation points such as L1 for Earth science. The task group believes that the potential impact is sufficiently valuable to Earth science that such a mission might well have been viewed as an earlier NASA priority had adequate technology been available at reasonable cost.

The task group lacked the proper expertise, resources, and time to conduct a credible cost or cost-benefit analysis (such an effort might take many months and much detailed analysis) or an analysis of the mission goals and objectives within the context of a limited NASA budget or relative to other Earth Science Enterprise missions. However, based on the available information, **the task group found that (1) the cost of Triana is not out of line for a relatively small**

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mission that explores a new Earth observing perspective and provides unique data; (2) since a significant fraction of the Triana funds (according to NASA and the Triana principal investigator, 50 percent of total funding and 90 percent of instrument development money) have already been expended, weighing cost issues would lead to only limited opportunities to save or transfer funds to other projects.

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National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Appendix 1

Reply to Attn of: Y

OCT 14 1999

Dr. Bruce Alberts
President
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. Alberts:

The Conference Report (House Report 106-379) accompanying H.R. 2684, the FY 2000 VA-HUD-Independent Agencies appropriations bill, states:

> "The conferees have not terminated the Triana program as the House had proposed. Instead, the conferees direct NASA to suspend all work on the development of the Triana using funds made available by this appropriation until the National Academy of Sciences (NAS) has completed an evaluation of the scientific goals of the Triana mission. The conferees expect the NAS to move expeditiously to complete its evaluation. In the event of a favorable report from the NAS, NASA may not launch Triana prior to January 1, 2001. The conferees have no objection to NASA's reserving funds made available by this appropriation for potential termination costs. The conferees recognize that, if a favorable report is rendered by the NAS, there will be some additional cost resulting from the delay."

This is to request that the National Research Council (NRC) undertake the evaluation of the scientific goals of Triana, as specified in the Conference Report.

In July 1998, NASA released an open, competitive Announcement of Opportunity for a Triana mission to conduct Earth remote sensing investigations from L1. In October 1998, Dr. Francisco Valero of the Scripps Institution of Oceanography was selected as Principal Investigator to implement the Triana mission based upon the scientific merits of his proposal; the supporting team includes scientists from 8 universities, industry, international and government research laboratories. The mission selection also included enhancements to proposed instrumentation and the addition of a Space Science-funded space weather

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monitoring instrument suite. The scientific themes addressed by Triana are:

- solar radiation and climate, including cloud radiative properties;
- ozone, aerosols and ultraviolet radiation;
- stratospheric dynamics;
- vegetation canopy structure; and,
- solar wind and space weather.

The Triana science team will assure the technical specifications for the mission will meet these objectives.

NASA is prepared to support the NRC review with assistance from the Triana science team. Triana is a very important mission for the future direction of NASA's Earth Science Enterprise, and an objective and thorough review of the scientific goals of the mission by the NRC will be valuable. Because the suspension of work on Triana while the evaluation is underway will undoubtedly impact the total cost of the mission, NASA is seeking the completion of the evaluation at the earliest possible date. Thank you in advance for undertaking this challenge. I look forward to hearing from you soon.

Sincerely,

Ghassem R. Asrar
Associate Administrator for
Earth Science

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Appendix 2

Task Group on the Review of Scientific Aspects of the NASA Triana Mission
Membership List
December 10, 1999

James J. Duderstadt, Chair
University of Michigan

William L. Chameides
Georgia Institute of Technology

Catherine Gautier
University of California, Santa Barbara

George Gloeckler
University of Maryland

William E. Gordon (retired)
Rice University

Judith Lean
Naval Research Laboratory

Noboru Nakamura
University of Chicago

Alan Strahler
Boston University

NRC Staff

Tamara L. Dickinson
Senior Program Officer

Rebecca Shapack
Research Assistant

Sharon Seaward
Senior Project Assistant

Note: This project was a joint project of the Space Studies Board, the Board on Earth Sciences and Resources, and the Board on Atmospheric Sciences and Climate of the National Research Council.

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Appendix 3

Agenda for the Meeting of the Task Group on the Review of Scientific Aspects of the NASA Triana Mission

Wednesday, January 12, 2000

Open Session

9:00 a.m.	Triana Overview and Science Objectives Including a discussion of data distribution and outreach	Francisco P.J. Valero Triana PI
	Scripps-Earth Polychromatic Imaging Camera (EPIC)	Dave Chenette Lockheed Martin Advanced Technology Center
	EPIC Science Retrievals	Jay Herman GSFC Project Office Scientist
	Cloud Particles and Albedo Estimates	Patrick Minnis Langley Research Center
11:30	Atmospheric Dynamics	Robert Sadourny Laboratoire de Meteorologie Dynamique, Ecole Normale Superieure, France
12:00 p.m.	Lunch	
1:00 p.m.	Scripps-National Institute of Standards and Technology Advanced Radiometer (NISTAR)	Steven Lorentz NIST
	Far Infra-Red and Climate Change	Warren Wiscombe Goddard Space Flight Center
	Land Surface Remote Sensing and Hot Spot Analysis	Sig Gerstl Los Alamos National Laboratory
	Shortwave and Near Infra-Red Albedo	Patrick Minnis Langley Research Center

Note: The task group met on January 12 and 13, 2000 at the National Academies' Cecil and Ida Green Building, 2001 Wisconsin Avenue, N.W., Room 130, Washington, D.C., 20007.

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Appendix 3

Wednesday, January 12 (Cont.)

	Near Infra-Red/Visible Infrared Ratio: Implications for Climate	William Collins National Center for Atmospheric Research
	Solar Wind and Space Weather	Alan Lazarus Massachusetts Institute of Technology
	Societal Relevance of Triana's Solar Wind Data	Ernie Hildner Director, Space Environment Center, NOAA
	Complementary Space Science Missions	George Withbroe Science Program Director, Sun-Earth Connection
	Triana in the Earth Science Enterprise Context Including a discussion of complementary Earth science missions	Jack Kaye Earth Science Research Division Director
6:00 p.m.	Summary Remarks	Francisco P.J. Valero, PI

Thursday, January, 13, 2000

Closed Session

Note: The task group met on January 12 and 13, 2000 at the National Academies' Cecil and Ida Green Building, 2001 Wisconsin Avenue, N.W., Room 130, Washington, D.C., 20007.

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Appendix 4

Acknowledge of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with the procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making their published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Alexander H. Flax, Consultant,
Harold K. Forsen, Bechtel Corporation (retired),
Michael F. Goodchild, University of California, Santa Barbara,
Richard Goody, Harvard University (retired),
Anthony C. Janetos, World Resources Institute,
M. Patrick McCormick, Hampton University,
John McElroy, University of Texas, Arlington, and
James A. Van Allen, University of Iowa.

Although the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring task group and the NRC.

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