The Longevity of the Terra Satellite

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Abstract

The Terra Spacecraft is one of the longest running weather satellites in orbit with multiple objectives. Terra has spearheaded Earth research: exploring the connections between the atmosphere, land, ocean, energy system, snow/ice, and how all of this relates to Earth's climate change. Though its designed life expectancy was seven years, Terra has provided data to NASA for over 20 years, allowing scientists to reach further conclusions about what is causing climate change. Being the size of a small bus, the satellite had 5 major instruments onboard built by NASA, Lockheed Martin, and Japan. This paper outlines how Terra's design contributed to its long life of earth observation. NASA and their international partners continuously maneuvered and observed data from Terra in order learn how to better design future Earth observing missions. This paper thoroughly overviews the Terra Spacecraft design and components onboard that benefitted Earth's weather system research for over 20 years.

Keywords: Terra, Mission Design, Instruments, Design parameters, Operations, Mineral mapping, Orbit parameters, Design life, Power requirements

1. Introduction

The Terra satellite is a spacecraft built by NASA and Lockheed Martin and launched in 1999. Terra's purpose was to explore and provide new, useful data about the Earth's land, atmosphere, and ocean. One of Terra's objectives was to give a better understanding about the Earth's energy balance in order to increase accuracy of weather and climate change predictions. Terra is a joint project between 3 countries: the Unites States, Canada, and Japan. Together the countries engineered 5 instruments onboard (ASTER, CERES, MISR, MOPITT, MODIS) to take coinciding measurements and images of the Earth. Terra was originally designed to remain in orbit for seven years; however, after a review of its life in 2014, it is expected that Terra will survive into the early 2020's – over three times its original life expectancy.

2. Instrument Overview

The Terra satellite's five instruments consist of the following:

1. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
2. Clouds and Earth's Radiant Energy System (CERES)
3. Multi-angle Imaging Spectroradiometer (MISR)
4. Measurements of Pollution in the Troposphere (MOPITT)
5. Moderate Resolution Imaging Spectroradiometer (MODIS)

As seen in *Figure 1* all 5 instruments are in close proximity to each other on the 'cold side' of the satellite as the solar array needs to be in direct sunlight to provide power to the instruments. For a size reference, NASA describes the Terra satellite as being the size of “a small bus.”

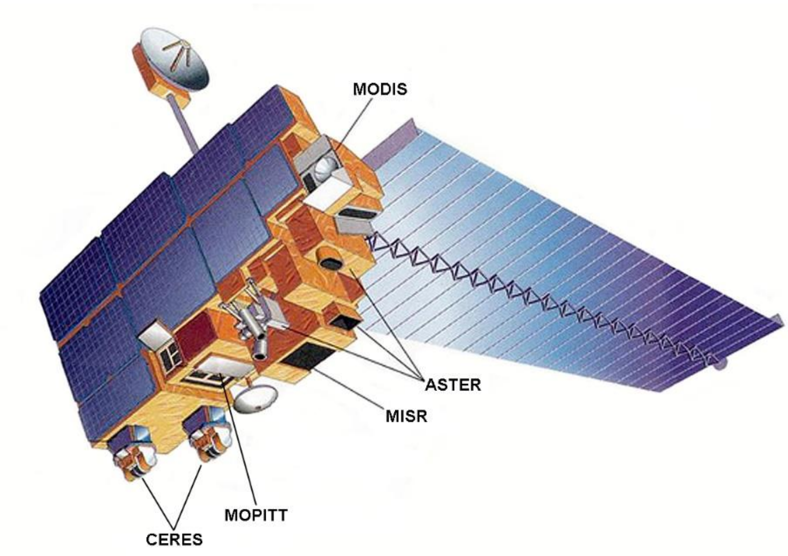

Figure 1 - Illustration of Terra Satellite

2.1 ASTER

The Japanese designed and built ASTER which provides high resolution, 15m – 90m pixel, images of Earth’s surface including mainland, ice, ocean and also clouds. The images are taken in 14 different wavelengths ranging from visible light to near infrared. The data it obtains consists of images which show detailed features of the Earth such as land surface temperature, emissivity, reflectance and elevation. ASTER collects an average of 8 minutes of data per orbit rather than a continuous stream of data. It is the only instrument on board with the ability to take high-spatial-resolution images, allowing it to serve as a zoom platform for the other 4 instruments by which they can change detection and calibration.

ASTER is heavily involved and important for mining exploration and mineral identification on Earth. Many companies have used the data it obtains to explore uninhabited areas for potential mining of various minerals; as seen in *figure 2*.

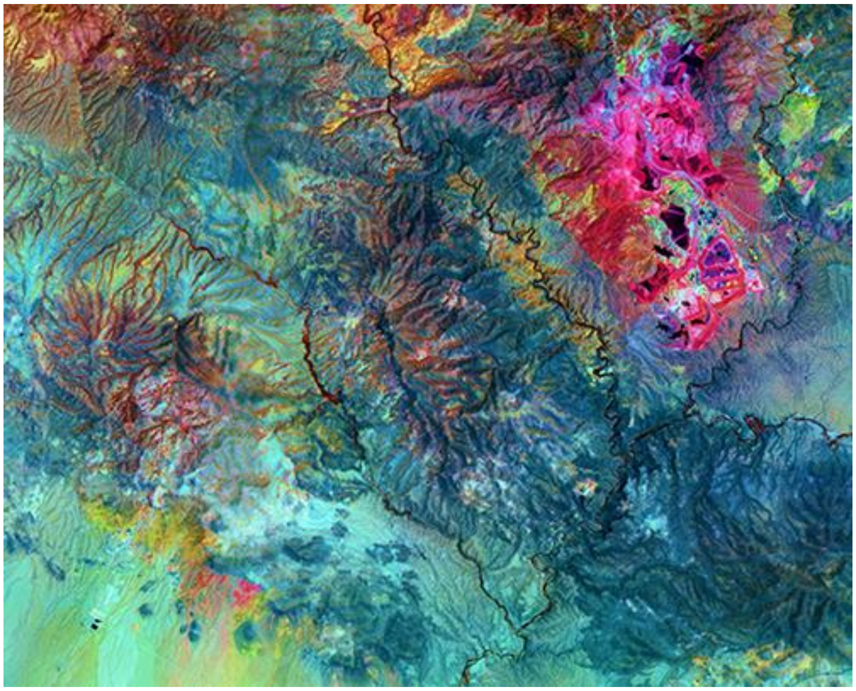

Figure 2 - Copper Identification in Southeast Arizona

The naked eye cannot identify the location of copper; however, as seen in *figure 2,* the ASTER has used near infrared, short wave infrared, and thermal infrared images to identify its location – shown in “vibrant pink”. Multispectral and thermal images can provide mineral mapping of the Earth due to absorption properties on the surface. Photogeologists use the data recorded by the ASTER to distinguish between the surface lithologies, oxides, and clays in the soil.

2.2 CERES

In *figure 1,* it is evident that the Terra satellite has 2 identical CERES instruments on board. Their primary focus is to measure the Earth's total radiation. They also have the ability to measure and gather information about the properties of clouds and how they relate to radiative fluxes from the top of the atmosphere to the Earth's surface. One of the CERES instruments operate in a biaxial mode while the other operates in a "crosstrack" scan mode. The "crosstrack" CERES continuously takes measurements of the Tropical Rainfall Measuring Mission (TRMM) and the Earths Radiation Budget Experiment (ERBE). The biaxial CERES provides information about the angular flux which has since helped scientists improve the accuracy of angular models used to determine Earth's radiation balance. CERES is the only project worldwide whose main objective is to deliver results related to global climate change (as of May 11, 2020).

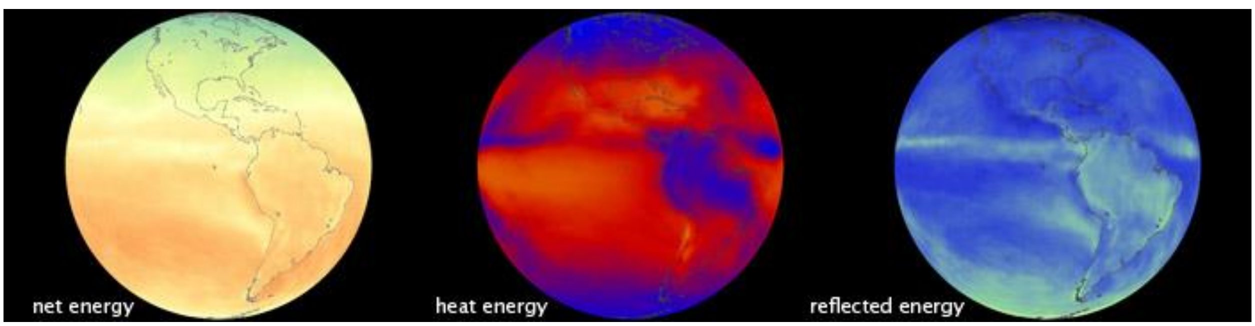

Figure 3 - Earth's Radiant Energy System

As seen in *figure 3*, using three different sets of imaging with the help of some other instruments on board, the radiation emitted from Earth can be tracked and directly related to the climate change over specific landmasses across the Earth,

A meeting between the CERES Science Team in 2018 allowed the results to be analyzed over a 20 year period. In the analysis, they found that "temperatures remain stable" if there are no "outside forces," however the increased human-made greenhouse gases contribute to global warming. CERES has allowed researchers to observe what is happening on a global level versus a local level. The research and data given to NASA by the CERES instruments was published in the *Journal of Climate,* both NASA, and The National Science Foundation continue to fund the research.

2.3 MISR.

NASA built the MISR with the primary objective of recording the amount of sunlight that is scattered due to natural conditions. The instrument is made up of 9 cameras coupled together at fixed angles of 26.1, 45.6, 60.0, 70.5 degrees either side of the one camera pointed at 0 degrees (nadir). The 9 cameras record images in 4 different spectral bands (blue, green, red, and near-infrared) to distinguish the different types of clouds, aerosol particles and surfaces it is taking images of. The total swath is 380 km viewed together by all 9 cameras with a complete global coverage every 9 days.

More specifically, on a monthly, seasonal, and long-term level, the MISR records the types of aerosol particles in the atmosphere made by natural or manmade sources. It also collects certain information about the clouds including their height, type and the distribution of land that they cover.

2.4 MOPITT

The MOPITT instrument's primary function is measuring the pollution in the low atmosphere (troposphere) and how it interacts with the land and ocean biospheres. It does this by specifically tracking carbon monoxide (CO) expelled by manmade sources that are considered to be contributing to climate change. MOPITT uses gas spectrometry sensors to measure emitted and reflected radiance in 3 spectral bands. This allows the instrument to identify the different paths through the troposphere that CO makes and where it gets absorbed. Scientists can then identify the locations where CO is most prominent and, therefore, contributing to climate change.

The MOPITT also records CO emitted by natural sources such as wildfires. For example, *figure 4* shows the CO produced by wildfires in western Africa — in red.

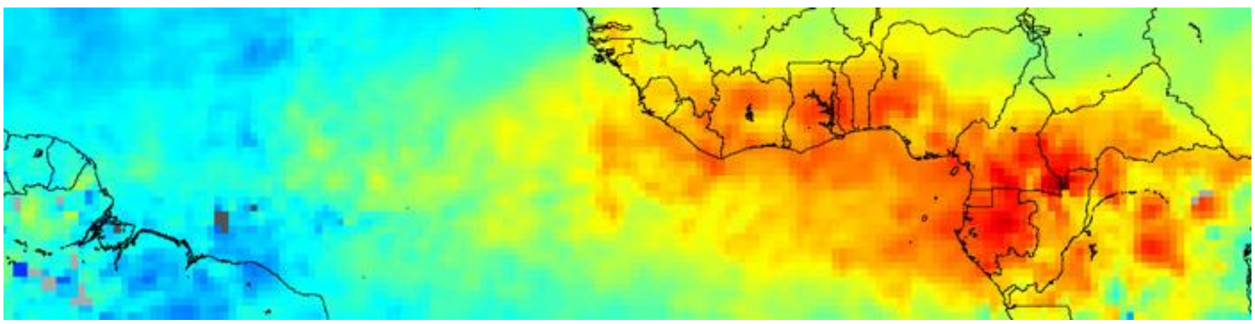

Figure 4 - CO released in Africa due to Wildfires

MOPITT has a special resolution of 22 km by 22 km per pixel and a swath of 640 km (at nadir). It can measure the atmosphere in layers at 5km in length to get an accurate reading of the region CO is absorbed, this measured path through the low atmosphere also allows it to be tracked back to its source.

2.5 MODIS

MODIS is an instrument on board the Terra satellite that accomplishes multiple tasks, one of which is to work with other instruments in order to track a wider array of Earth signs of climate change. MOPITT's duties include measuring the percentage of cloud cover which help CERES and MISR measure data related to Earths Energy Budget (EEB). It helps the MISR measure and record data about the properties of aerosols and clouds in the atmosphere. This data is crucial in helping scientists to better understand Earth's weather and climate system.

MODIS also focuses on large scale changes in the biosphere due to the global carbon cycle, and measures photosynthetic activity of plants (land and marine) to see how green-house gases are being absorbed. Another responsibility of the MODIS is to map the extent of snow and ice due to winter storms and freezing temperatures.

The MODIS has the ability to record data on multiple frequencies due to its large sweeping swath of 2330 km observing every part of the Earth within 1-2 days in 36 different spectral bands total.

3. Orbit

3.1 Orbit Parameters

The Terra satellite has a geocentric orbit in the low earth regime. This means it has a small period of 98.9 minutes having a repeat cycle every 16 days. It was designed to have a near polar, sun synchronous orbit so that it is always within sunlight to provide solar energy to the single array and for the instruments to record data in light. Terra orbits at an altitude of 705 km at an inclination of 98.5 degrees, RAAN (right ascension of the ascending node) of 251.3 degrees, and an AOP (argument of perigee) of 83.8 degrees.

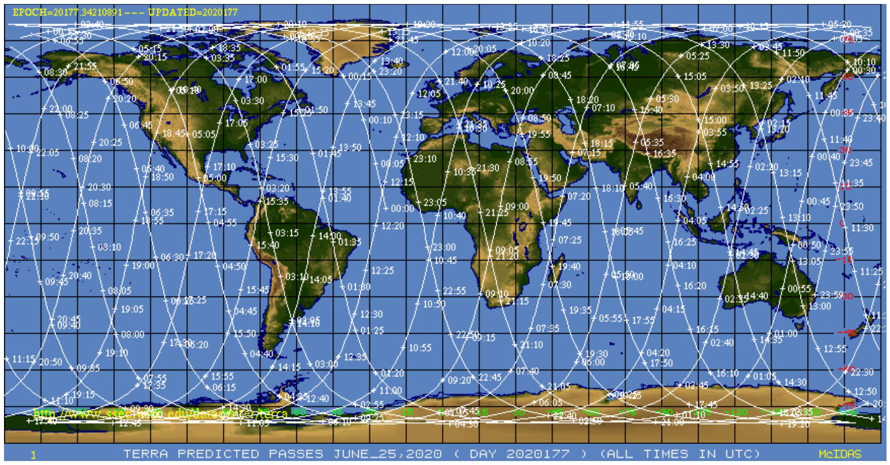

Figure 5 - Terra Groundtrack (June 25th 2020)

Figure 5 displays the Terra's groundtrack over a short period of time. It is evident when looking at *Figure 5* that Terra views a large area of the Earth in a short amount of time. Because of Terra's inclination of 98.5 degrees, it gets close enough to the North and South Pole to take images for research—this can be seen in range of longitude of the figure above.

The Terra crosses the descending node at 10:30am (equatorial crossing) and orbits as part of the "morning constellation." The morning constellation is made up of a series of satellites that provide coincident images to compare each instrument against each other. There is a one-minute separation between the Landsat-7, E0-1; a 15-minute separation between the EO-1 and the SAC-C, and a 1 minute separation between the SAC-C and Terra.

3.2 Designed Life Expectancy

Terra had a designed life expectancy of seven years when it was launched in 1998; however, it has greatly surpassed that—it is still running today and is projected to through the early 2020s. Terra had 338kg of fuel on board and has been gradually using that over its lifespan for maneuvers. There were two large maneuvers at the start of its life—the orbit raise and de-inclination maneuvers. Both used large amounts of fuel compared to the small maneuvers since. All the other fuel has been used by small maneuvers to make up for inclination and drag changes. In the 2014 progress report stated earlier contains the figure below. It displays how the small maneuvers have used fuel and is the means by which they predict the duration of the Terra's life.

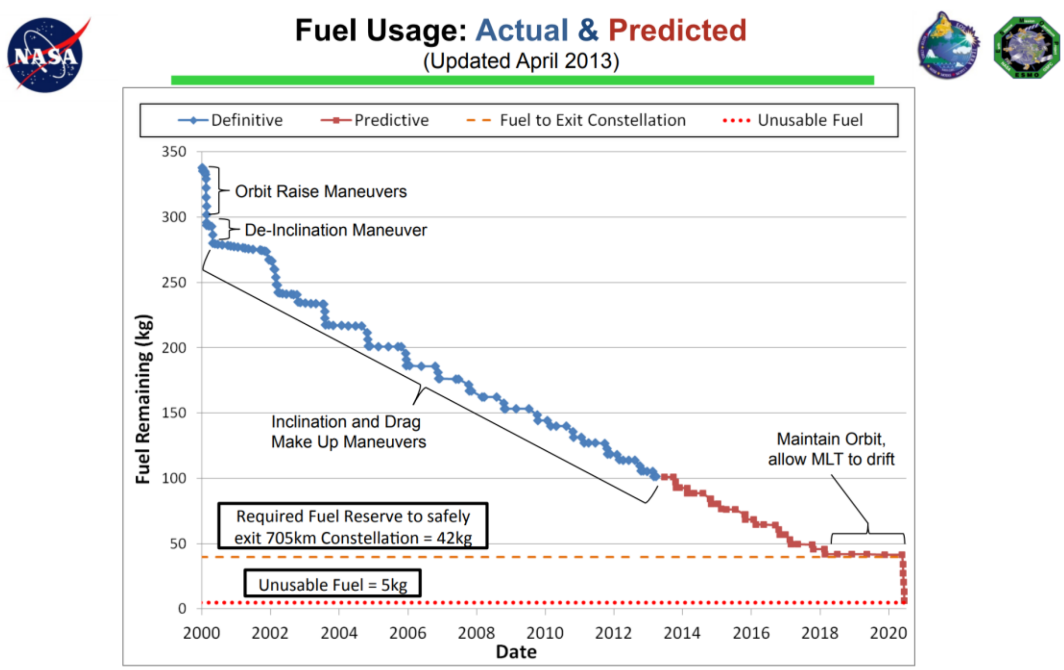

Figure 6 - Past and Predicted Fuel Use

It is well agreed that the Terra can perform propulsive maneuvers to maintain its orbit into the early 2020s. As seen in *figure 6* the equatorial crossing is planned to change from

10:30am to 10:15am to allow drift by conserving onboard fuel so that the orbit is maintained for a longer amount of time.

4. Propulsion

4.1 Launch

The Terra spacecraft was launched at the Western Test Range Vandenberg Air Force Base, California on the Atlas IIAS—a rocket built and designed by Lockheed Martin Astronautics in Denver, Colorado. The Terra launched at 1:33 p.m. EST with a 25-minute launch window. After launch, spacecraft separation was initiated at 14 minutes. The first signal was received by the Tracking and Data Relay Satellite System (TDRSS) seven minutes after launch.

The total US cost of the launch and satellite (not including ground system or foreign instruments on Terra) was 1.3 billion US dollars. The six-year mission cost approximately 120 million US dollars. This money was used to pay employees and fund science operations and computer software/hardware. Because the Terra exceeded its life expectancy by so many years, it is believed to have cost more than the original 120 million dollars allotted for the six-year mission.

4.2 Atlas IIAS

The Atlas IIAS is essentially the same as the Atlas II; however, there are small payload dimension changes: the IIAS can carry heavier and larger payloads. The Atlas IIAS is a 2.5 stage liquid propellant expendable spacecraft launcher—it was the last Rocketdyne-powered Atlas which had the ability to of boosting up to 8.6 metric tons for low earth transfer orbits such as the

Terra orbit. With all 63 Atlas IIASs being successful, the Atlas IIAS was the most reliable launch vehicle of its time.

The Atlas IIAS was powered by the LOXRP – Rocketdyne MA-5A propulsion system which consisted of 2 booster engines located in a booster package that could be jettisoned and a central sustainer engine. All 3 of these chambers thrust at the same time during launch. The booster engines could provide 189 metric tons of thrust combined at sea level and 210 metric tons towards the end of their 164-second boosting phase in a vacuum. The central booster provides an additional 27.1 metric tons of thrust at launch and 38.8 towards the end in a vacuum. It runs for 125 more seconds than the side booster engines.

4.3 Attitude Control

While it is not specified online, it is believed that the Terra Satellite uses the same onboard maneuver propulsion system as the Icesat-2 which uses 1 N Monopropellant Hydrazine Thrusters. They are the primary thrusters onboard for attitude, trajectory, and orbit maneuvers. Though these were considered high-cost thrusters at the Terra's genesis, they are now considered low cost thrusters as a result of multiple refinements. The propellant is supplied to the thruster by a two-stage flow-control valve made up of two identical stable valves connected in series with a single housing. Each thruster is equipped with insulation for optimum thrusting at ignition.

4.4 Thruster Specifications

The specific impulse of a 1 N Monopropellant can be calculated by dividing the nominal thrust in Newtons by its mass flow multiplied by gravity at sea level.

$$I_{sp} = \frac{T}{\dot{m}g_0} = \frac{1N}{(0.00044kg/s)(9.81m/s^2)} = 231.675\ seconds$$

The range of specific impulse for 1N Monopropellant Thrusters is 200 seconds – 223 seconds. Heat dissipation is most likely responsible for most of the energy loss, hence why the calculated impulse is higher than stated on the facts sheet. The nominal specific impulse averages to be 220s which will be used for future calculations.

$$\Delta V = I_{sp} g_0 \ln\left(\frac{M_0}{M_f}\right) = (220s)\left(\frac{9.81m}{s^2}\right)\ln\left(\frac{1155}{817}\right) = \frac{747.2045m}{s}$$

This equation above demonstrates the total accumulated velocity change that could be produced by the 338kg of fuel on board. As seen in *Figure 6* the maneuver velocity changes were significantly smaller than the two larger maneuvers at the beginning of its life. The ratio of empty mass and full mass is calculated below.

$$\frac{M_0}{M_f} = e^{\left(\frac{\Delta V}{I_{sp} g_0}\right)} = e^{\frac{747.2045m/s}{(220s)\left(\frac{9.81m}{s^2}\right)}} = 1.4137$$

The Deputy Project Scientist of the Terra mission, Kenneth Ranson, stated in an email that the fuel mass is 338kg.

5. Power

5.1 Power Requirements

The Terra uses one, single junction, GaAs/Ge solar array on the sunlight side of spacecraft to provide and average power of 2.53 kW. The array can provide a max power of 7.5 kW at 120V at BOL. The solar array's main function is to provide power to all five instruments, the Guidance Navigation and Control (GN&C) subsystem, and for data communication. The regulated voltage of 120 DC (±4%) is distributed by a NASA-designed Power Distribution Unit (PDU), and is achieved through a sequential shunt unit (SSU) under any load conditions. Power is stored and drawn from a nickel hydrogen battery system with 54 cells connected in series to provide power to the spacecraft, especially during its eclipse phases of its orbit.

5.2 Solar Array Design

The Terra satellite is one of a few satellites that have only one solar array to provide power. As can be seen in *Figure 7*, the solar array is 5 m by 9 m having a surface area of 45 m^2 per side. To be in as much direct sunlight as possible, the array can turn 180 degrees to maximize sunlight for power and cold space field of view available to instruments.

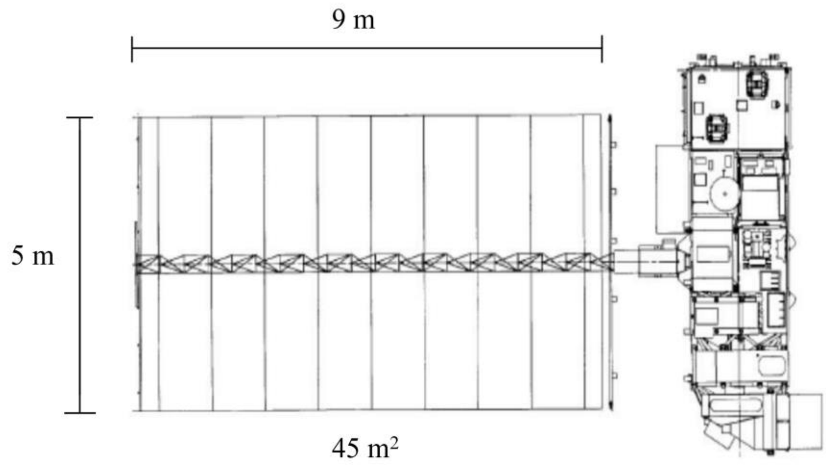

Figure 7 - Terra Satellite Solar Array Design

5.3 Guidance and Navigation Control Subsystem

The Terra Satellite was designed with a three-axis movement stabilizing capability and a single rotating solar array, as stated in section 5.2. The subsystem is comprised of actuators, remote sensing equipment, software, and attitude control electronics (ACE). This equipment includes a three-channel inertial reference unit which calculates the Terra's body movements in each of its control modes and then adjusts its position using thrusters. A magnetometer uses three-axis sensing to determine the Earth's geomagnetic field for the primary purpose of magnetic unloading of reaction wheels. It can also be used to detect when there is a deep-space calibration maneuver failure.

The Earth Sensor Assembly is a backup sensor used for pitch, roll, and yaw sensing of the solar array relative to the sun line. Also on board is a reaction wheel assembly with a primary focus on attitude control. The wheel can work under three modes. In normal mode, the wheel speed controller allows it to range in speed, avoiding zero rpm crossings known as the stagnation point. In 4-wheel mode it regulates the wheel momentum to below 25% capacity by using magnetic torque rods. In 3-wheel mode, the wheel momentum is restricted to below 50% in the same way, this is also known as backup mode. Thrusters are used for all attitude control maneuvers and wheel momentum unloading.

Table 1, from the *Terra – eoPortal Directory,* shows the complete list of sensors and actuators in the GN&C subsystem, along with the number of units and their manufacturers.

Table 1 - GN&C Sensors and Actuators

Sensor component	**Units**	**Manufacturer/model**	**Mission heritage**
Solid State Star Tracker (SSST)	2	BATC / CT-601	MSX, XTE
Earth Sensor Assembly) (ESA)	2	Ithaco / conical scanning	UARS
Coarse Sun Sensor (CSS)	2	Adcole / 42060	UARS
Fine Sun Sensor (FSS)	1	Adcole / 42070	TOPEX
Three Axis Magnetometer (TAM)	2	NASA/GSFC	EUVE, UARS
Inertial Reference Unit (IRU)	2	Kearfott / SKIRU-DII	XTE
Actuator component	**Units**	**Manufacturer/model**	**Heritage**
Reaction Wheel Assembly (RWA)	4	Honeywell / EOS-AM	Similar to EUVE
Magnetic Torquer Rod (MTR)	3	Ithaco / TR500CFR	EUVE
Attitude Control Thruster	6 (x 2)	Olin Aerospace (Primex)	
Delta-v thruster	2 (x 2)	Olin Aerospace (Primex)	

5.4 Communication and Broadcast of Data Software

The Terra spacecraft uses a Tracking and Data Relay (TDRS) system with a steerable high-gain antenna (HGA) and mounted electronics to a boom on the zenith side to maximize communication time without obstruction. Emergency contact communication can be transmitted via the zenith omni or nadir antenna. Command telemetry including engineering data is transmitted in S-band while the science data recorded by the instruments is transmitted via Ku-band at a nominal speed of 150 mb/s. During one orbit the TDRS system transmits an average of two 12 minute groups of data to the ground.

Other than S and Ku band, the Terra can also downlink science data via X-band in three different modes: Direct Downlink (DDL), Direct Broadcast (DB), and Direct Playback (DP). The MODIS and ASTER instruments use DDL and DB to directly send data to users. A Direct Access System (DAS) is on board to provide the Terra with a backup option for X-band transmission to ground stations.

6. Summary

The Terra satellite is coming to the end of its journey very soon. Once all the reserve maneuver fuel has been used, it will burn up in the atmosphere. This mission was an overwhelming success, collecting data for nearly three times as long as originally planned. Terra has provided valuable information about Earth’s weather system and factors contributing to climate change. Terra has been, and still is, a model for future Earth observing missions.

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