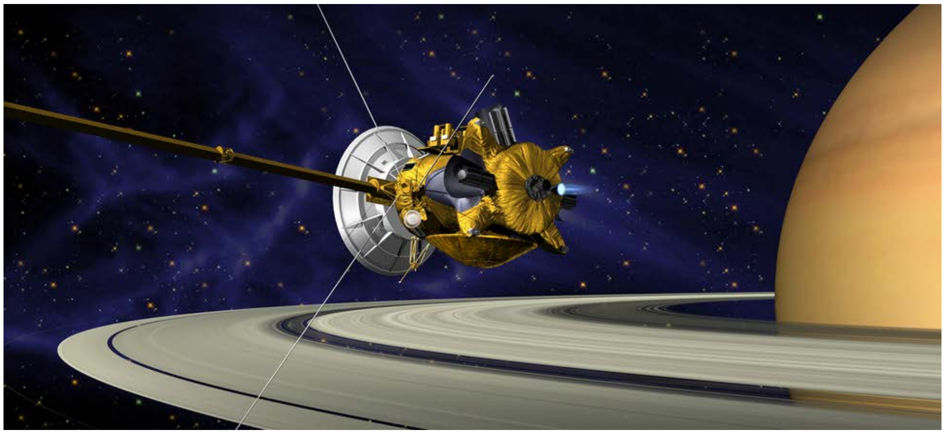
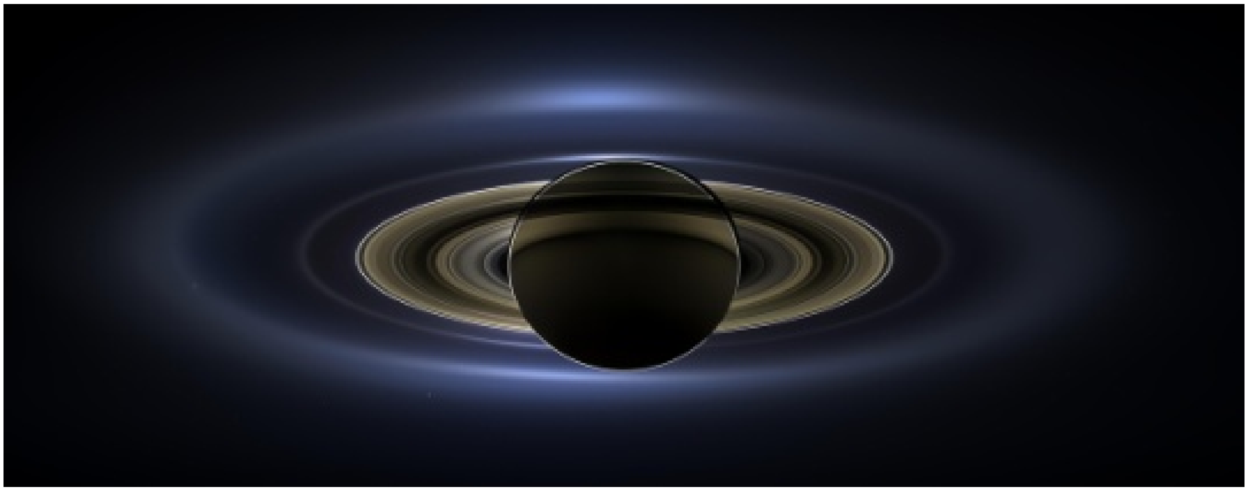
A SunCam online continuing education course

Spacecraft Subsystems Part 6 – Fundamentals of Payload Subsystems





by

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Contents

Figures

1. Introduction

Spacecraft are man-made machines that operate in space. An earth orbiting spacecraft is normally referred to as a satellite, although it is manmade (aka "artificial") as opposed to a natural satellite like our moon. A spacecraft is typically subdivided into two major parts, the payload and the bus. Attitude control, electrical power, thermal control, propulsion, and telemetry & command subsystems are part of the spacecraft bus. With their primary goal of achieving a successful mission, most bus design constraints focus on maximizing the effectiveness of its payload [ref. 1]. Where the mission can be defined as the purpose of the spacecraft and is usually identified as the payload part of the spacecraft (e.g. scientific instruments, communications) – described in this course as ***payload subsystems***.

Spacecraft can operate in deep space (interplanetary or interstellar) or as a satellite orbiting the earth. Interstellar space is about 12 billion miles from the sun. This is the distance where our sun no longer effects the space environment [ref. 4]. A satellite's operating environment largely depends on its orbit type, which is primarily driven by its intended mission. The three common earth orbiting satellite types are geosynchronous orbit (GEO), highly elliptical orbit (HEO), and low earth orbit (LEO) as seen in the following figure [ref. 1].

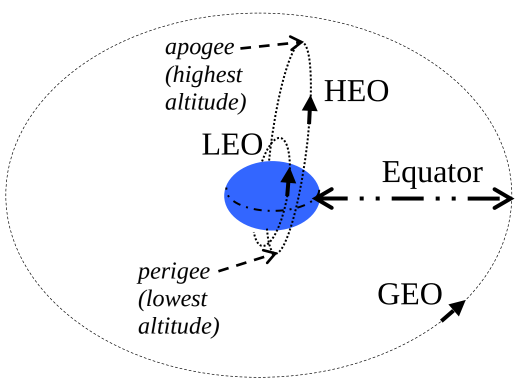

Figure 1.1: Common Earth Orbit Types
[Reprint from source: ref. 1]

<u>*Note: All figures in this course have no scale, unless noted otherwise.*</u>

LEO satellites have an altitude of less than one thousand miles. Satellites in HEO can have a wide ranges of altitudes for perigee (lowest altitude) and apogee (highest altitude) [ref. 3]. GEO satellites, orbiting about the equator at some small angle (inclination angle), have an altitude of ≈ 23,000 miles above earth (more precisely ≈ 22,300 miles).

Other than its highly elliptical orbital characteristic with many altitudes to choose from, another unique feature of this orbital type compared to its near circular LEO and GEO counterparts, is its difference in dwell time. In HEO, the satellite's dwell time at perigee is much shorter than at apogee. This is because the satellite accelerates as it approaches earth (towards perigee) due to the earth's gravitational pull.

At GEO altitude, satellites have the same period of rotation as the earth, appearing fixed relative to earth. Because of this, these satellites are most commonly used for communications purposes (e.g. television) since there is no need for the receive dish on earth to track the satellite [ref. 1].

The mission of a spacecraft's payload will dictate whether the spacecraft needs to be a particular earth orbit or deep space. To help describe payload subsystems, one example of each type: LEO, HEO, GEO, and deep space is featured in this course.

2. LEO | Hubble Space Telescope

Not your typical earth directed LEO payload, Hubble's payload subsystem is focused in the opposite direction – outer space. In order to get a clearer view of space than earth-bound telescopes, higher than natural (e.g. clouds, weather) or manmade (e.g. light) blockages within our atmosphere, the Hubble Space Telescope (HST) was launched in April 1990 on the space shuttle Discovery. Because of its LEO at about 340 miles in altitude, five servicing missions by the space shuttles have enabled the HST to produce unique views of distant stars, galaxies, and our planets for over 25 years. Since 1990, astronomers have used HST's observations to publish over 15,000 scientific papers.

In general, the servicing missions allowed Hubble's original payload instrumentation to be replaced by newer or improved versions of cameras, spectrographs, and fine guidance sensors. Only one payload instrument remains from the original launch, one of the three fine guidance sensors. After its last servicing mission, the Hubble drifts over earth after its release on May 19, 2009 by the crew of the Space Shuttle Atlantis as seen in the following picture.

Figure 2.1: Spacecraft Hubble
Final Release Over Earth (2009)
[Reprint from source: NASA/STScI, http://hubblesite.org/]

Infrared (IR), visible, and ultraviolet (UV) light "seen" by the HST is analyzed by a suite of three types of payload instruments: interferometers, spectrographs, and cameras. The light is captured by Hubble's two mirrors, which includes its 2.4 meter (≈8ft) primary mirror, which is then input into the payload instrumentation for further analysis and processing. Each of the six payload subsystem instruments on the HST are briefly described in the following paragraphs, with their operating wavelength ranges included in the following figure.

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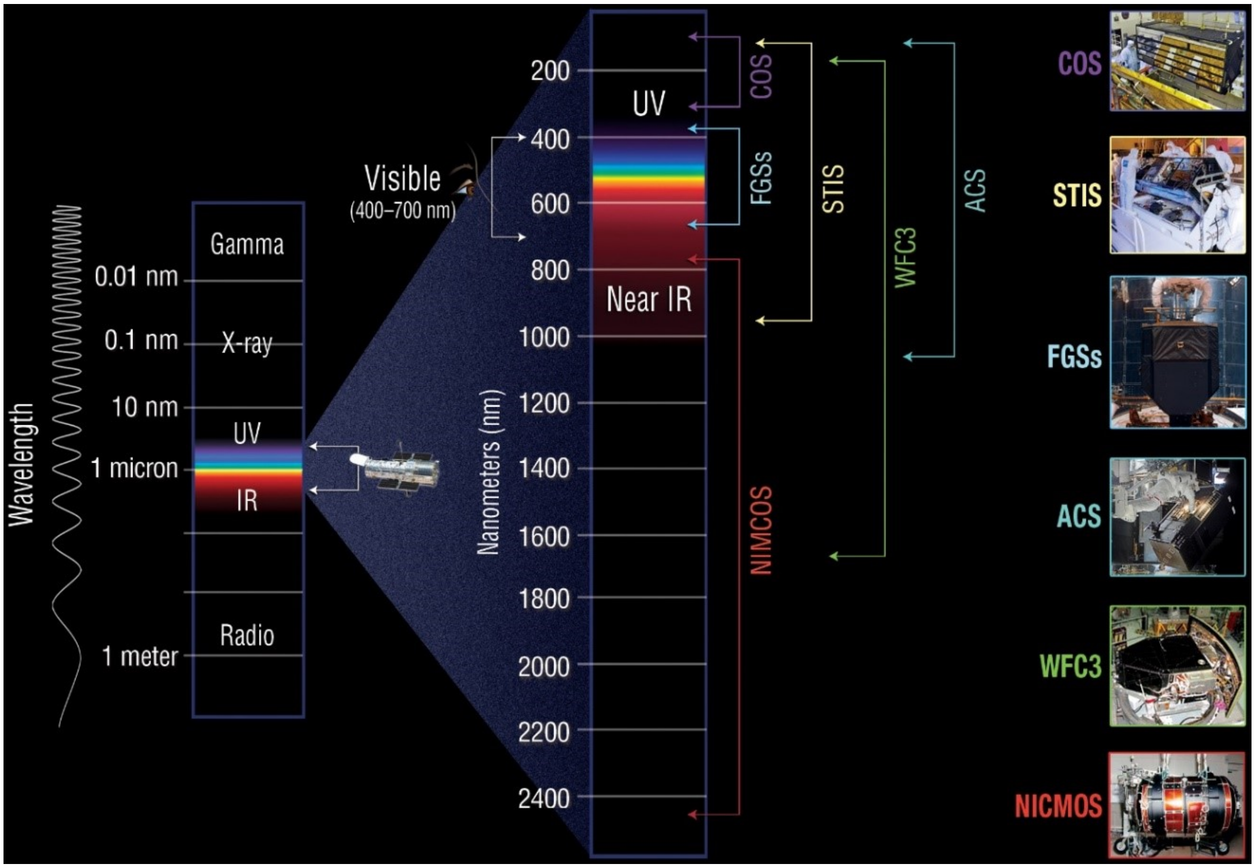

Figure 2.2: Hubble's Payload Instruments – Wavelength Ranges
[Reprint from source: NASA @ nasa.gov]

Fine Guidance Sensor (FGS): Consisting of 3 fixed FGSs (aka interferometers) orthogonal to one another, these instruments are responsible for providing the HST's incredible pointing accuracy and precision. Serving a dual role (attitude control & payload) when Hubble is target pointing, the FGSs operate as follows:

- *attitude determination*: 2 of the 3 FGSs track and lock onto selected stars (known as guide stars) in order to provide precise pointing inputs to the attitude control subsystem
- *payload instrument*: the 3rd FGS measures star relative positions, magnitude deltas (i.e. changes in brightness), angular diameter, and identifies double star systems

Advanced Camera for Surveys (ACS): Consisting of three different types of cameras called channels, this is a third generation instrument that surveys its target objects to provide a broad range of images. Primarily imaging at visible wavelengths, it is also capable of detecting some ultraviolet and near-infrared light.

Wide Field Camera 3 (WFC3): Designed to complement ACS's visible imagery with ultraviolet and infrared imaging. This instrument is the primary workhorse of HST's payload. Consisting of two cameras, one captures visible and ultraviolet wavelengths and the other infrared wavelengths.

The following image, captured using the ACS and WFC3 payload instruments, contains a group of galaxies known as Abell 2163, seen as bright large blurry masses. Because of the extreme distances of these galaxies and stars, some of the light you are seeing in this image originated over 2 billion years ago (yes, it took that long for the light to reach earth, "seen" by the HST!). For perspective, using geological dating techniques, especially radiometric, our earth is estimated to be about 4.5 billion years old.

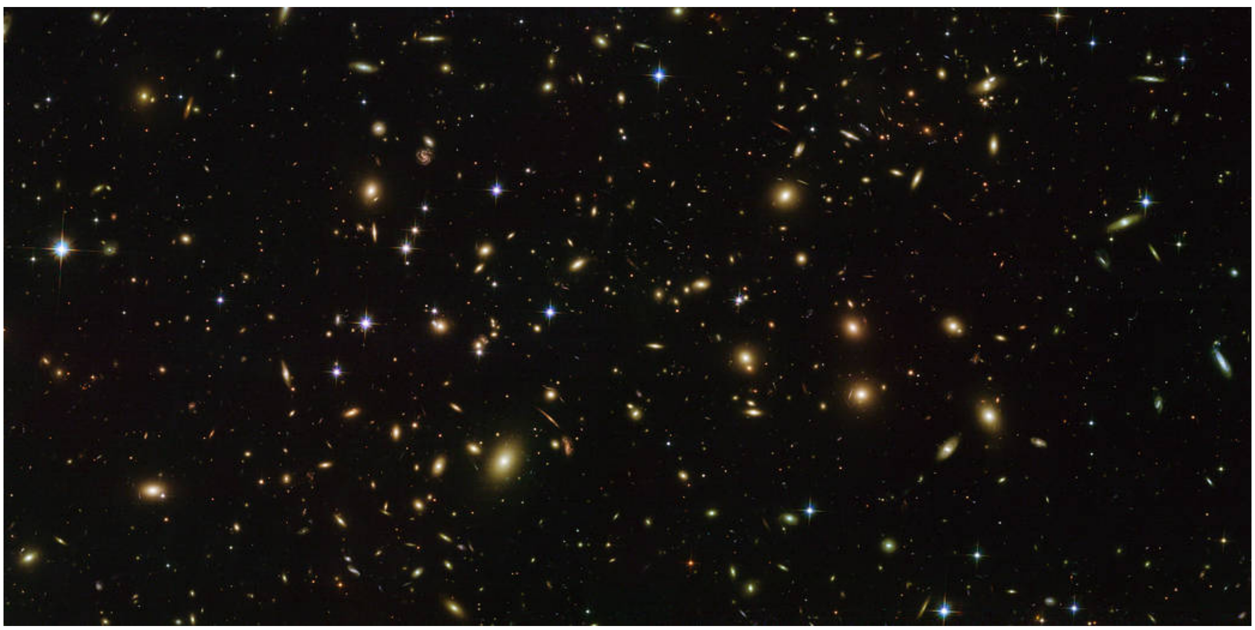

Figure 2.3: Hubble's Picture – Abell 2163 Galaxies
[Reprint from source: ESA/Hubble & NASA @ nasa.gov]

Cosmic Origins Spectrograph (COS): Produces ultraviolet spectral measurements and is the most sensitive UV spectrograph to date. Performs best when observing fixed points of light (e.g. stars) and is good at detecting distant dim objects. This instrument measures temperature, density, chemical composition, and velocity.

Space Telescope Imaging Spectrograph (STIS): Produces high resolution spectra of its target objects, especially bright ones, by having the unique ability to measure many different target points simultaneously. Like the COS, this instrument also measures temperature, density, chemical composition, and velocity.

Near Infrared Camera and Multi-Object Spectrometer (NICMOS): Captured images and spectroscopic measurements of its astronomical target objects at near infrared frequencies. Because of a cryocooler anomaly, many of NICMOS's functions are performed by WFC3.

3. HEO | Van Allen Probes

To further explore the Van Allen radiation belts, two probes (Van Allen A and B), formerly called Radiation Belt Storm Probes, are shown in this artist's rendering in the following figure. In their near equatorial orbit, launched on August 30, 2012, one probe follows the other. The long booms of the EFW payload instrument are visible on the probe in the foreground.

Their mission is to collect radiation measurements while orbiting through the radiation belts. This radiation environment is very hostile to spacecraft. Within the earth's magnetosphere, the two radiation belts have degrading effects on spacecraft thermal control surfaces and solar cells. However, these probes are radiation hardened for this mission, in HEO with an apogee and perigee of about 23,000 and 373 miles respectively. The two radiation belts, with one located between 1,000-8,000 and the other 12,000-25,000 miles in altitude, can be seen as two donuts surrounding the earth in the following image [ref. 2, ref. 3].

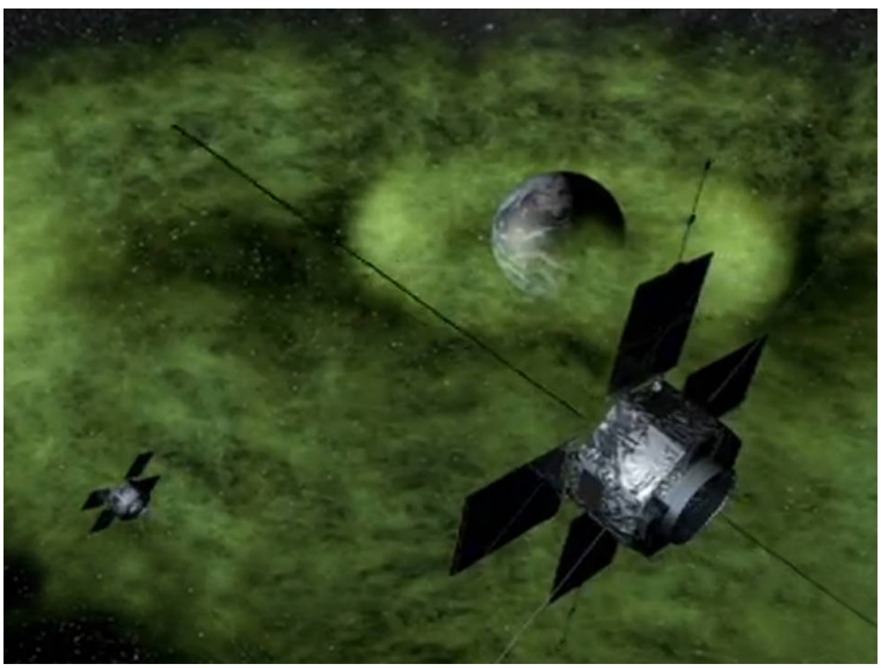

Figure 3.1: Van Allen Probes
[Reprint from source: NASA @ nasa.gov]

There are two key characteristics that make this endeavor more advanced than all previous ones to study the Van Allen radiation belts:

- Each Van Allen probe spacecraft carries the same array of advanced payload instruments to measure the properties of a broad range of particles, waves, and energies.
- By having two spacecraft in close proximity to one another, payload instrument data collected can be compared with each other to help understand how the behavior of the particles contained in the radiation belt change over time.

The seven payload subsystem instruments on each Van Allen Probe are briefly described in the following paragraphs.

Energetic Particle, Composition, and Thermal Plasma Suite (ECT): Observes particles that attribute to the changes in the radiation belts which include:

- electrons
- protons
- charged oxygen ions
- charged helium ions

To help determine if the particle will remain in the radiation belt, this suite of three instruments as described below captures particle data to include their magnetic energy and relative direction.

ECT Helium Oxygen Proton Electron (HOPE): Measures speeds of low energy particles which include: helium, oxygen, protons, electrons. The purpose of this instrument is to determine how electromagnetic waves generated by these low energy particles influence the higher energy particles.

ECT Magnetic Electron Ion Spectrometer (MagEIS): Records electrons and ions of moderate energy ranges, using internal magnets to direct the particles to sensors. Four of these instruments make up this payload, each capturing a different range of the energy spectrum and their relative magnetic direction.

ECT Relativistic Electron Proton Telescope (REPT): Traveling at such extreme speeds, this instrument cannot even capture the electrons and protons. Instead, they do acquire their energy signatures. Using a layer of solid-state detectors, they count and categorize the charged particles: electrons and protons passing through. The following figures are measurement samples from the REPT of the Van Allen A probe. These graphs clearly reveal the high electron flux of the outer belt in the upper two graphs and the high proton flux of the inner belt in the bottom two graphs.

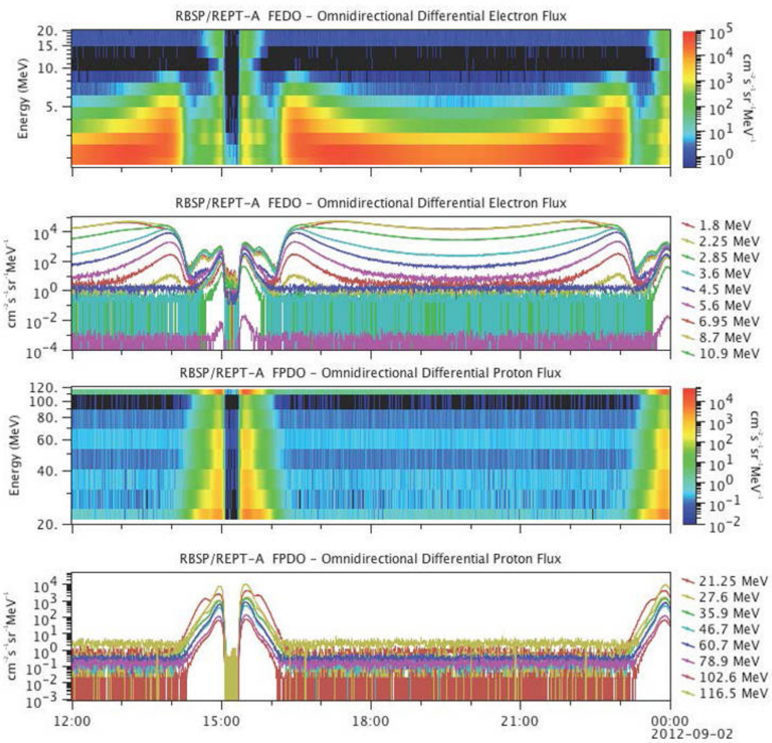

Figure 3.2: REPT Radiation Samples
[Reprint from source: NASA @ nasa.gov]

Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE): Its purpose is to study the electrical current circling the earth at the equator, called ring current. Measurements include the following:

- composition: number of protons, helium, and oxygen
- pressure

Solar and geomagnetic activities change the ring current, and subsequently impacts the radiation belt particles. Scientists will study the data gathered by this instrument to help determine how changes in ring current effect the particles in the radiation belts.

Relativistic Proton Spectrometer (RPS): Concentrating on studying the high energy protons of the inner belt, this instrument measures the protons and their magnitude changes. Due to their extreme speeds, no manmade materials to date can stop these protons, which pass through anything in their path, and are therefore a hazard to both spacecraft hardware and astronauts. The data collected by this instrument will be utilized to help understand how solar activities effect the protons of the inner belt.

Electric Field and Waves Suite (EFW): Measures electric fields to help identify the source(s) of their energy that accelerates the particles, and understand why some electric fields last for milliseconds with an altitude of about 0.5 miles, while others last for hours out to 100,000 miles. Components of the EFW instrument include:

- six long booms consisting of:
  - one pair, 130ft each of flexible cable protrudes from opposite sides of spacecraft body, uses centrifugal force to maintain its position and orientation
  - one pair, 164ft each of flexible cable protrudes from opposite sides of spacecraft body, uses centrifugal force to maintain its position and orientation
  - one pair, 40ft each of rigid cable located along the spin axis of the spacecraft
- six metal spheres located at the end of each boom measures the electric fields

Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS): Identifies which process energizes the particles or results in their removal from the radiation belts. This instrument specializes in studying plasma waves that contain gas particle charging electromagnetic fields, measuring their magnetic and electric properties in all three axes. The magnetic fields are measured using three solenoids, configured orthogonal to each other, with one along each axis. This instrument also uses electric field data collected by the EFW instrument.

4. GEO | Tracking and Data Relay Satellite

With a global constellation of satellites operating at the geosynchronous orbital altitude of 22,300 miles, the TDRS satellites replaced many of the previous ground stations that could only "see" its LEO satellite for a brief time each orbit. A constellation of TDRS satellites provides near continuous satellite communications for its LEO satellite customers. When its ground control station is not in view of its satellite, a TDRS satellite can use its large steerable antennae to track the satellite and then relay its data to earth, and subsequently back to its ground control station. Instead of having multiple ground control stations around the globe, the TDRS system can be used to relay LEO satellite communications to a single controlling ground station.

Since the 1980's, NASA's tracking and data relay satellite (TDRS) systems has been providing near constant communications for its satellite users. Starting with the Space Shuttle program to currently supporting missions like the HST and the international space station (ISS). TDRS's payload subsystem consists of three antennae communications suites: single access, multiple access, and space-to-ground, which are briefly described in the following paragraphs.

Single Access Communications (Space-to-Space): Provided by two large steerable tri-frequency antennae each including:

- S-Band (2.0-2.3 GHz, UHF) low data rates to about 3Mbps
- Ku-Band (13.7-15.0 GHz, SHF) data rates to 300Mbps
- Ka-Band (22.5-27.5 GHz, SHF) date rates to 800Mbps

Multiple Access Communications (Space-to-Space): Using a phased array antenna, S-Band (2.0-3.0 GHz, UHF) consisting of 15 transmit and 32 receive elements

Space-to-Ground Link Communications: Operating in the Ku-band at SHF, one small parabolic dish antenna relays information between single and multiple access communications channels and earth using the following two primary ground sites:

- White Sands Complex in New Mexico – chosen for its dry climate for less rain attenuation
- Guam Remote Ground Terminal (GRGT) – constructed to fill the Indian ocean communications coverage gap, with its antennae protected by radomes to reduce rain attenuation effects as shown in the following figure

Figure 4.1: TDRS's Guam Remote Ground Terminal
[Reprint from source: NASA @ nasa.gov]

In general, first-second-third generation TDRS capabilities have evolved to support higher data rates and provide more customer flexibilities. The following image shows the three payload communications antennae of the third generation version: two 15ft single access steerable antennae, one 2.4m (≈7.87ft) space-to-ground link antenna with the multiple access antenna array just below it in this image.

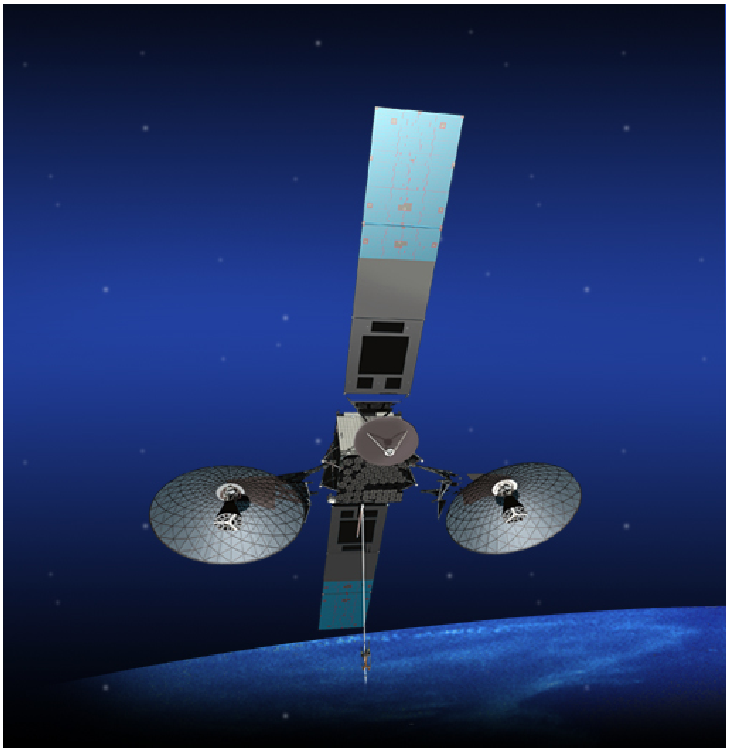

Figure 4.2: TDRS Third Generation Satellite
[Reprint from source: NASA @ nasa.gov]

The first figure on the next page is from my college report in technical writing dated April 28, 1992. This represents the status of the TDRS constellation at that time – now called the first generation. Note, once on orbit, the designation for each satellite changes from a letter to a number. Initially, a primary customer was NASA's space shuttle missions (1981-2011) which included the European Space Agency's Spacelab missions (1983-1998) that performed many experiments from a module fitted inside the shuttle's cargo bay.

As of February 2018, shown in the second figure on the next page, the TDRS constellation consists of eight operational capable satellites:

- two first generation (6-7),
- three second generation (8-10)
- three third generation (11-13)

This figure includes the TDRS constellation and location, grouped by ocean regions – Atlantic, Pacific, Indian. This figure includes an example of how it can work – where one of TDRS #8's large steerable antennae is tracking the LEO ISS satellite, relaying information between it and the GRGT. Note, the ISS's orbital inclination is about 52° (angle between orbital plane and equator), with its altitude at about 254 miles, it takes about 90 minutes to complete each orbit.

	Orbit Designation	Launched by (Mission #)	Date Launched	Initial Position (Status)	Current Position (Status)
TDRS-A	TDRS-1	Challenger (STS-6)	April 5, 1983	41° West Longitude (TDRS East)	171° West Longitude (Spare)
TDRS-B	TDRS-2	******Destroyed in the January 1986 Challenger accident******			
TDRS-C	TDRS-3	Discovery (STS-26)	September 29, 1988	174° West Longitude (TDRS West)	62° West Longitude (Spare)
TDRS-D	TDRS-4	Discovery (STS-29)	March 13, 1990	41° West Longitude (TDRS East)	41° West Longitude (TDRS East)
TDRS-E	TDRS-5	Atlantis (STS-43)	August 2, 1991	174° West Longitude (TDRS West)	174° West Longitude (TDRS West)

Figure 4.3: TDRS Constellation – 1992
[Reprint from source: ref. 5]

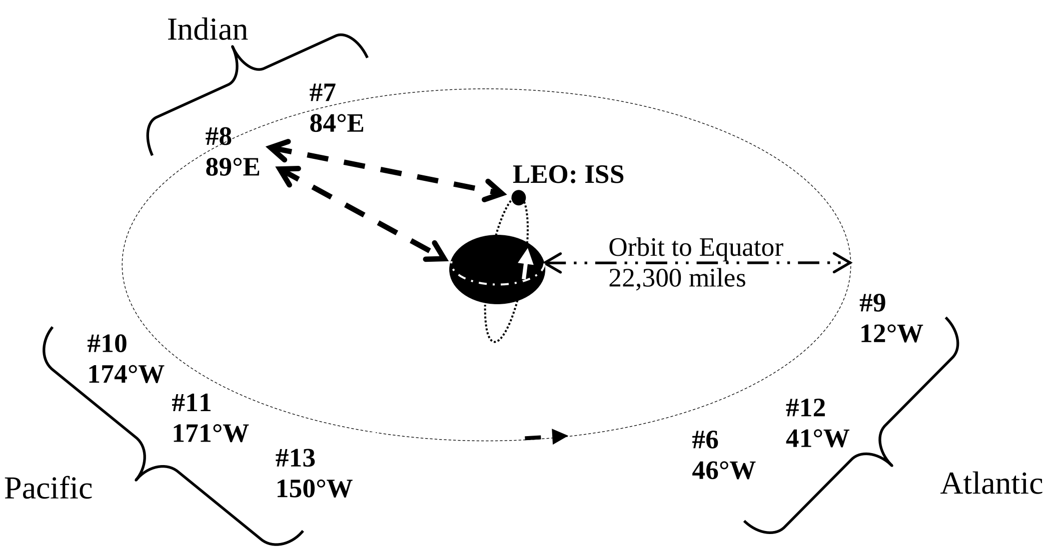

Figure 4.4: TDRS Constellation – 2018

5. Deep Space | Cassini-Huygens

Cassini-Huygens (1997-2017) payload was loaded with 27 science investigations that used 18 different instruments to obtain many unique measurements and images. Its mission was to explore Saturn in much more detail than did the earlier flybys of the two Voyager spacecrafts. Launched with two elements: the Cassini orbiter and the Huygens probe, both equipped with payload instrumentation ready to explore the Saturn system.

Cassini (in the following figure) began orbiting saturn in July 2004, releasing the Huygens probe in December 2004 to further explore the surface of Saturn's largest moon, Titan. Huygens, the disk shaped object on the bottom of Cassini in this image, descended to the moon's surface by parachute on January 14, 2005.

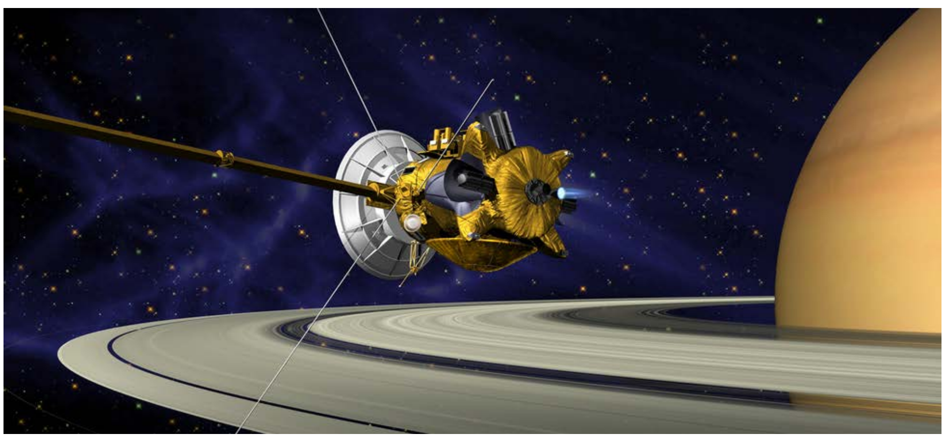

Figure 5.1: Cassini-Huygens Spacecraft, Artist's Rendering
[Reprint from source: NASA @ nasa.gov]

In order for the mission to be accomplished to the fullest, onboard fuel was conserved by using Titan's "free" gravitational forces to achieve major navigation changes. From many different north and south approaches, this moon's gravitational pull created pivot points, therefore changing the spacecraft's trajectory and increasing its velocity as it whipped around Titan. For smaller navigation changes, its propellant was used. The twelve payload subsystem instruments on the Cassini orbiter are briefly described in the following paragraphs.

Cassini's payload consisted of 12 scientific instruments to measure and study various areas of the Saturn system to include: magnetosphere, dust particles, plasma environment, and electromagnetic spectrum. These 12 instruments can be grouped into the following three types:
1) Optical Remote Sensing: Measured saturn, its rings and moons electromagnetic spectrum.

2) Fields, Particles and Waves: Collected, analyzed, and measured dust, plasma, and magnetic fields around saturn.
3) Microwave Remote Sensing: Emitted radio waves to produce atmospheric profiles, determine moon masses and ring particle sizes, and Titan's surface terrain.

Optical Remote Sensing
Imaging Science Subsystem (ISS): Consisted of a wide-angle and a narrow-angle digital camera which used wheel filters to choose the desired visible wavelength to image and some infrared and ultraviolet were also captured. Visible light is between IR and UV on the electromagnetic spectrum as shown in the following figure.

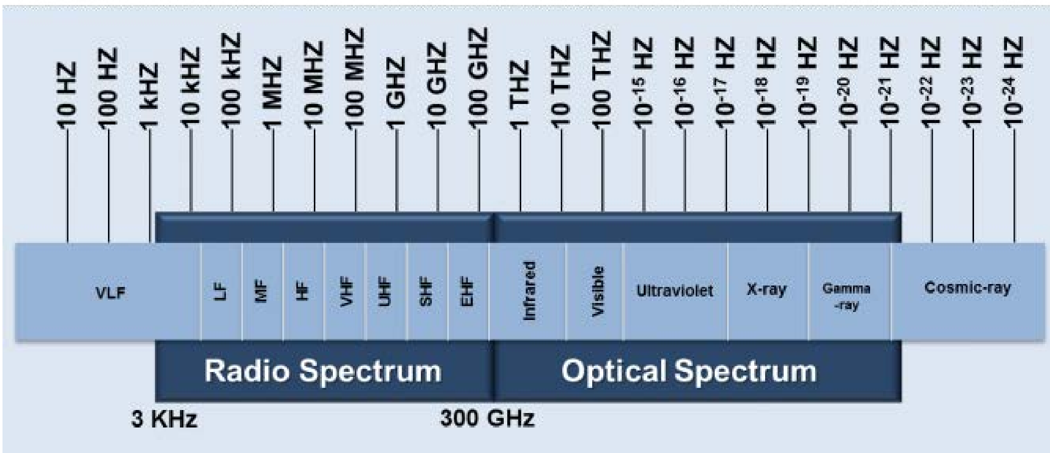

Figure 5.2: Electromagnetic Spectrum
[Reprint from source: NASA @ nasa.gov]

On July 19, 2013, a major event celebrated by many all over the world, the following image was captured of Saturn backlit by the Sun, its rings and moons, with Earth in the background. In the second image you can see Earth (marked with an arrow), which is in the lower right quadrant of the following image.

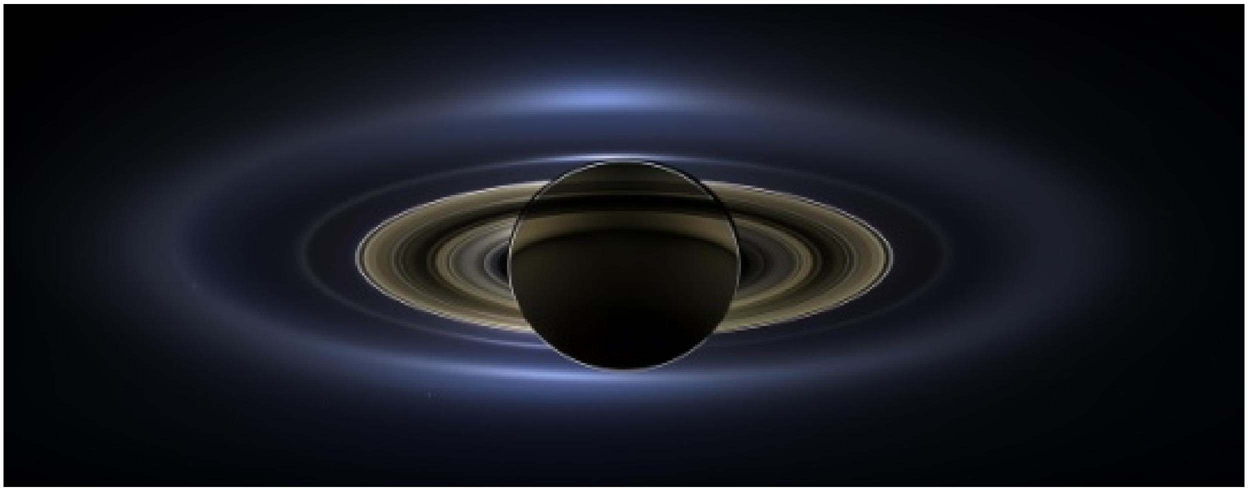

Figure 5.3: Famous Picture by Imaging Science Subsystem
[Reprint from source: NASA @ nasa.gov]

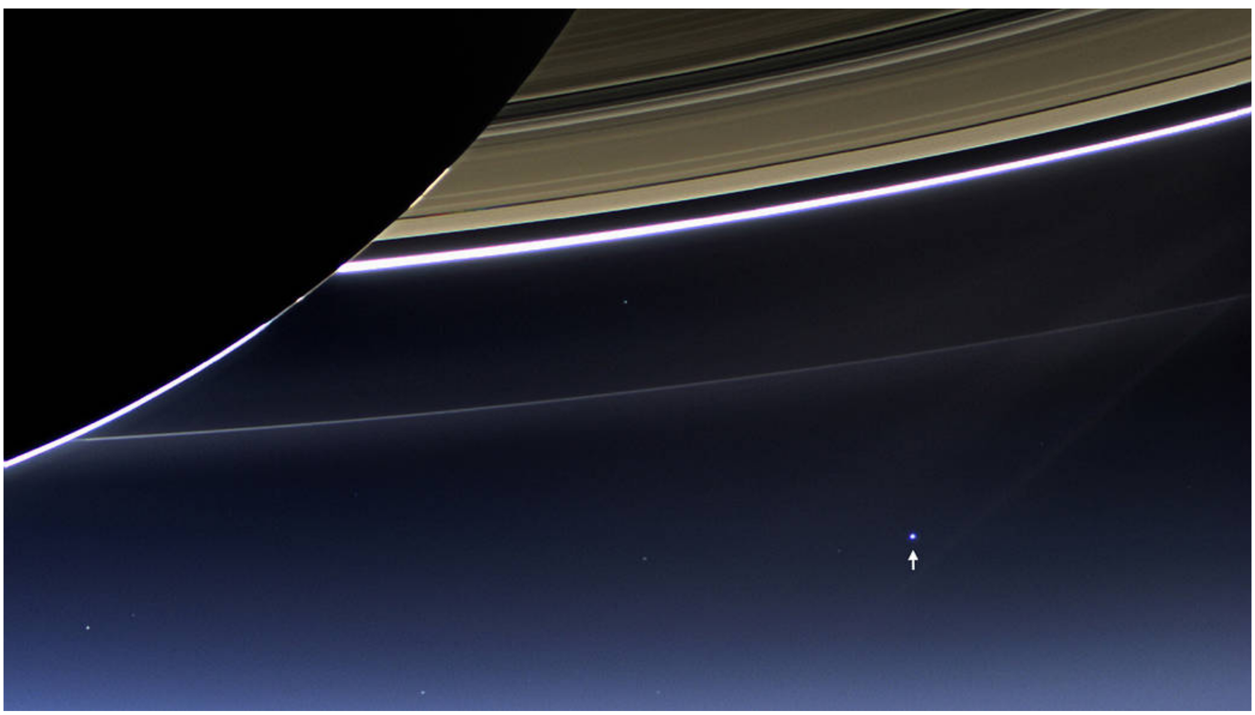

Figure 5.4: Famous Picture by Imaging Science Subsystem w/Earth
[Reprint from source: NASA @ nasa.gov]

Composite Infrared Spectrometer (CIRS): This instrument:

- collected infrared energy
- categorized IR energy by wavelength

- measured IR intensity
- measured object temperature and composition

Ultraviolet Imaging Spectrograph (UVIS): This instrument:
- collected UV energy to be able to detect the presence of gases
- identified gas composition by wavelength (i.e. similar to a rainbow)

Visible and Infrared Mapping Spectrometer (VIMS): This instrument:
- collected visible EM energy by wavelength
- collected IR EM energy by wavelength
- captured reflected and emitted EM energy from detected chemical substances

Fields, Particles and Waves

Cassini Plasma Spectrometer (CAPS): Captured particles and measured their kinetic energy, direction, and mass using the following sensors:
- ion beam sensor
- electron sensor
- ion mass spectrometer

Cosmic Dust Analyzer (CDA): Collected dust particles and determined their:
- speed
- direction
- size
- charge

Lastly, it determined its composition after the particle was fragmented by CDA's detectors.

Ion and Neutral Mass Spectrometer (INMS): Measured Titan's atmosphere and ionosphere, Saturn's magnetosphere and rings, to determine the composition or components of:
- chemical gases
- neutral particles
- low energy ions

Magnetometer (MAG): Recorded magnitudes and directions of the magnetic fields around the Cassini orbiter, similar to sensors used to determine a spacecraft's attitude.

Magnetospheric Imaging Instrument (MIMI): Consisted of three sensors to detect the following around Saturn:
- charged particles (protons, electrons, ions)
- neutral atoms

Radio and Plasma Wave Science (RPWS): Consisted of antennae and sensors to capture the radio and plasma waves the orbiter was experiencing.

Microwave Remote Sensing:
Radar: Emitted radio signals into surfaces and measured the return signal's arrival times and wavelength to create landscape imagery.

Radio Science Subsystem (RSS): Used radio waves to analyze matter by determining changes to the known emitted radio wave signals as they passed through or near an object, or was reflected by one.

NASA's Deep Space Network (DSN) consisting of massive parabolic antennae as shown in the following figure, were considered part of this instrument. These ground antenna sites are located in Australia, Spain, and the United States. The radio signals transmitted to earth by Cassini were considered the experiment.

Figure 5.5: Radio Science Subsystem Ground Element
[Reprint from source: NASA @ nasa.gov]

The 9ft disk shaped European Space Agency's Huygens probe consisted of the entry assembly module and the descent module. The entry assembly module controlled the probe after separation from the Cassini orbiter; also, its heat shield protected the payload equipment and provided braking to help slow the probe during its descent prior to parachute deployment.

The Huygens probe payload consisted of six scientific instruments located in the descent module. Each instrument was active as three parachutes opened in sequence to lower the probe through Titan's atmosphere, touching down on its surface after about a 2.5 hour descent. Each of Huygens's six payload subsystem instruments are briefly described in the following paragraphs.

Huygens Atmospheric Structure Instrument (HASI): Consisted of sensors to measure Titan's atmosphere that included accelerometer, temperature, pressure, permittivity and electromagnetic wave analyzer. These sensors provided the following measurements:

- forces in all three axes
- density and wind gusts
- surface wave motion (if landed in water)
- thermal properties
- electron and ion conductivities
- electromagnetic waves
- surface conductivity and permittivity

Doppler Wind Experiment (DWE): Designed to measure wind speeds using the Doppler effect between the probe's transmitted and the orbiter's received RF signals. Note, police also use the Doppler effect to determine if you are speeding. This measurement was prevented due to an anomaly with one of Cassini's receivers. However, measurements were obtained later using a global network of radio telescopes.

Descent Imager/Spectral Radiometer (DISR): This instrument included radiation and solar sensors, visible and infrared imagers. These sensors took measurements and images over a broad range of fields of view which included:

- radiation flow directions to determine balance
- size and density of aerosols by measuring sunlight magnitudes
- landing site imaging
- horizon and below cloud views
- surface spectral using a lamp to brighten the image

Aerosol Collector and Pyrolyser (ACP): This experiment used the pyrolysis process which captures aerosol particles using filters and ovens. The vaporized volatiles and decomposed organic matter were piped to the GCMS for analysis.

Gas Chromatograph Mass Spectrometer (GCMS): Employed high altitude samplers to measure and identify the chemical composition of Titan's atmosphere. This instrument provided the following:

- molecular gas masses
- molecular and isotopic species separation
- pyrolysis analysis using ACP inputs

- surface composition

To determine the composition of Titan's surface, this instrument was heated just before landing to vaporize the surface.

Surface-Science Package (SSP): Consisting of an acoustic sounder, accelerometer, and a tilt sensor, this instrument was primarily used to take surface impact related measurements which included the following:

- surface chemical state (solid or liquid)
- surface to probe distance
- descent rate
- surface wave magnitudes
- atmospheric composition and temperatures using speed of sound
- deceleration profile before landing
- surface hardness and structure
- descent and landing attitude

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Note: If there was no date on a sourced website article, the year the article was accessed was used.

