Chapter 12. Typical Science Instruments

Objectives: Upon completion of this chapter you will be able to distinguish between remote and direct sensing, and state characteristics of remote sensing instruments, including radar, radiometers, and polarimeters. You will be able to state characteristics of direct-sensing instruments including plasma instruments, dust detectors, cosmic ray, energetic particle detectors, magnetometers, and planetary radio astronomy instruments.

Science Payload

The point has been made that our spacecraft are flown to do science. All the subsystems and components discussed up to this point serve the purpose of enabling science instruments and experiments to carry out their observations. A typical complement of science instruments covers large portions of the electromagnetic spectrum, from near DC to high energy particles, and includes both remote- and direct-sensing components.

Direct and Remote Sensing

Direct-sensing instruments interact with phenomena in their immediate vicinity, and register characteristics of them. The Heavy Ion Counter on Galileo uses direct sensing; it registers the characteristics of ions in the spacecraft's vicinity which enter the instrument. It does not attempt to form any image of the ions' source. Remote sensing instruments record characteristics of objects at a distance, sometimes forming an image by gathering, focusing, and recording reflected light from the sun, or reflected radar waves which were emitted by the spacecraft itself. When an instrument provides the illumination, as does radar, it is referred to as an active remote sensing instrument. If the illumination is not provided by the instrument, as in the case of cameras observing planets in sunlight, it is passive remote sensing.

Direct-Sensing Science Instruments

High-energy Particle Detectors

High-energy Particle Detector instruments measure the energy spectra of trapped energetic electrons, and the energy and composition of atomic nuclei. They may employ several independent solid-state-detector telescopes. The Cosmic Ray instrument on Voyager measures the presence and angular distribution of electrons of 3-110 MeV and nuclei 1-500 MeV from hydrogen to iron. The Energetic Particle Detector on Galileo is sensitive to the same nuclei with energies from 20 keV to 10 MeV.

Low-Energy Charged-Particle Detectors

A low-energy charged-particular detector (LECP) is a mid-range instrument designed to characterize the composition, energies, and angular distributions of charged particles in interplanetary space and within planetary systems. One or more solid-state particle detectors may be mounted on a rotating platform. Voyager's LECP is sensitive from around 10 keV up into the lower ranges of the Cosmic Ray detector. Ulysses' LECP is similar, and is named GLG for its Principal Investigators Gloeckler and Geiss.

Plasma Instruments

Plasma detectors serve the low-end of particle energies. They measure the density, composition, temperature, velocity and three-dimensional distribution of plasmas, which are soups of positive ions and electrons, that exist in interplanetary regions and within planetary magnetospheres. Plasma detectors are sensitive to solar and planetary plasmas, and they observe the solar wind and its interaction with a planetary system.

Dust Detectors

Some spacecraft carry a dust detector which measures the velocity, mass, charge, flight direction and number of dust particles striking the instrument. Galileo's instrument can register up to 100 particles per second and is sensitive to particle masses of between 10^{-16} and 10^{-6} g.

Magnetometers

Magnetometers are direct-sensing instruments which detect and measure the interplanetary and solar magnetic fields in the vicinity of the spacecraft. They typically detect the strength of magnetic fields in three planes. As a magnetometer sweeps an arc through a magnetic field when the spacecraft rotates, an electrical signature is produced proportional to the strength and structure of the field.

Plasma Wave Detectors

Plasma wave detectors typically measure the electrostatic and electromagnetic components of local plasma waves in three dimensions. Plasma wave data provides key information on phenomena related to the interaction of plasma and particles that control the dynamics of a magnetosphere. The instrument functions like a radio receiver sensitive to the wave lengths of plasma in the solar wind, from about 10 Hz to about 60 kHz. When within a planet's magnetosphere, it can be used to detect atmospheric lightning, and events when dust and ring particles strike the spacecraft. Voyager's Plasma Wave data has been used to produce digital sound recordings of the particle bombardment the spacecraft experienced as it passed through the ring planes of the outer planets.

Remote-Sensing Science Instruments

Planetary Radio Astronomy Instruments

A planetary radio astronomy instrument measures radio signals emitted by a target such as a Jovian planet. The instrument on Voyager is sensitive to signals between about 1 kHz and 40 MHz, and uses a dipole antenna 10 m long, which it shares with the plasma wave instrument.

The planetary radio astronomy instrument detected emissions from the heliopause in 1993 (see the illustration in Chapter 1). Ulysses carries a similar instrument.

Imaging Instruments

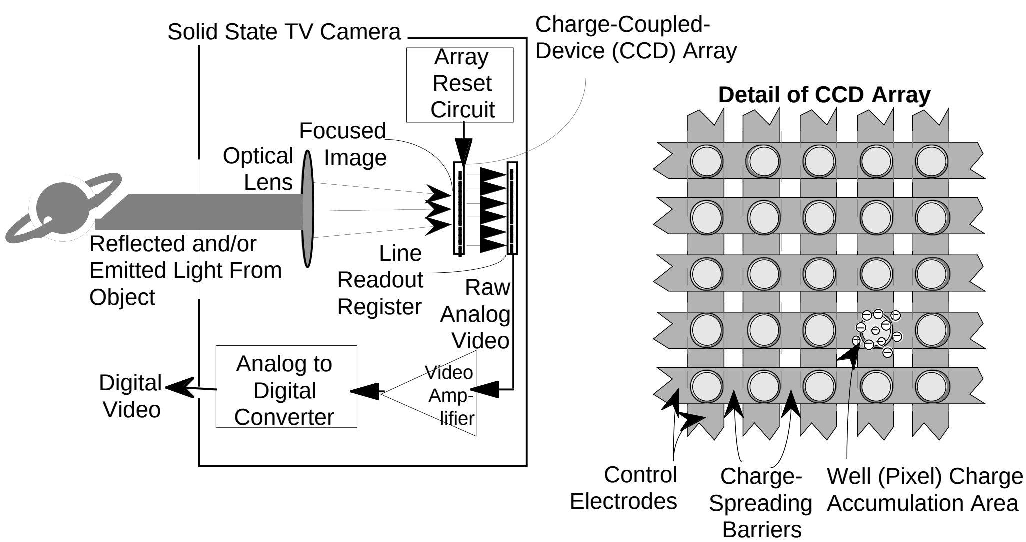
Optical imaging is performed by two families of detectors: vidicons and the newer charge coupled devices (CCDs). Although the detector technology differs, in each case an image is focused by a telescope onto the detector, where it is converted to digital data. Color imaging requires three exposures of the same target, through three different color filters selected from a filter wheel. Ground processing combines data from the three black and white images, reconstructing the original color by utilizing the three values for each picture element (pixel).

A vidicon is a vacuum tube resembling a small CRT. An electron beam is swept across a phosphor coating on the glass where the image is focused, and its electrical potential varies slightly in proportion to the levels of light it encounters. This varying potential becomes the basis of the video signal produced. Viking, Voyager, and many earlier spacecraft used vidicon-based imaging systems.

A CCD is typically a large-scale integrated circuit which has a two dimensional array of hundreds of thousands of charge-isolated wells, each representing a pixel. Light falling on a well is absorbed by a photoconductive substrate, such as silicon, and releases a quantity of electrons proportional to the intensity of the light. The CCD detects and stores an accumulated electrical charge representing the light level on each well. These charges are subsequently read out for conversion to digital data. CCDs are much more sensitive to light of a wider spectrum than vidicon tubes, they are less massive, they require less energy, and they interface more easily with digital circuitry.

Galileo's Solid State Imaging instrument (SSI) contains a CCD with an 800 x 800 pixel array. The cameras on the Mars Observer spacecraft were unique in that they employed a single-dimensional CCD array. The orbital motion of the vehicle over the surface of Mars supplied the second dimension required for image formation.

Solid State Video Imaging With Charge-Coupled Device (CCD) Array System



Polarimeters

Polarimeters are optical instruments which measure the direction and extent of the polarization of light reflected from their targets. Polarimeters consist of a telescope fitted with a selection of polarized filters and optical detectors. Careful analyses of polarimeter data can infer information about the composition and mechanical structure of the objects reflecting the light, such as various chemicals and aerosols in atmospheres, ring arcs, and satellite surfaces reflect light with differing polarizations. The molecules of crystals of most materials are optically asymmetrical; that is, they have no plane or center of symmetry. Asymmetrical materials have the power to rotate the plane of polarization of plane-polarized light.

Photometers

Photometers are optical instruments that measure the intensity of light from a source. They may be directed at targets such as planets or their satellites to quantify the intensity of the light they reflect, thus measuring the object's reflectivity or albedo. Also, photometers can observe a star while a planet's rings or atmosphere intervene during occultation, thus yielding data on the density and structure of the rings or atmosphere.

Spectrometers

Spectrometers are optical instruments which split the light received from objects into their component wavelengths by means of a diffraction grating. (A good example of a diffraction grating is the common compact disc which stores music or data in microscopic tracks. Observing a bright light shining on its surface demonstrates the effect which diffraction gratings produce, separating light into its wavelength, or color, components.) They then measure the amplitudes of the individual wavelengths. This data can be used to infer the composition and other properties of materials that emitted the light or which absorbed specific wavelengths of the light as it passed through the materials. This is useful in analyzing planetary atmospheres. Spectrometers carried on spacecraft are typically sensitive in the infrared and ultraviolet wavelengths. The near-infrared mapping spectrometer (NIMS) on Galileo maps the thermal, compositional, and structural nature of its targets using a two-dimensional array of pixels. (Spectroscopy was discussed in Chapter 6).

Infrared Radiometers

An infrared radiometer is a telescope-based instrument that measures the intensity of infrared (thermal) energy radiated by the targets. By filling the field of view completely with the disc of a planet and measuring its total thermal output, the planet's thermal energy balance can be computed revealing the ratio of solar heating to the planet's internal heating.

Combinations

Sometimes various optical functions are combined into a single instrument, such as photometry and polarimetry combined into a photopolarimeter, or spectroscopy and radiometry combined into a radiometer-spectrometer instrument.

Scan Platforms

Optical instrument are sometimes installed on an articulated, powered appendage to the spacecraft bus called a scan platform, which points in commanded directions, allowing optical observations to be taken independently of the spacecraft's attitude.

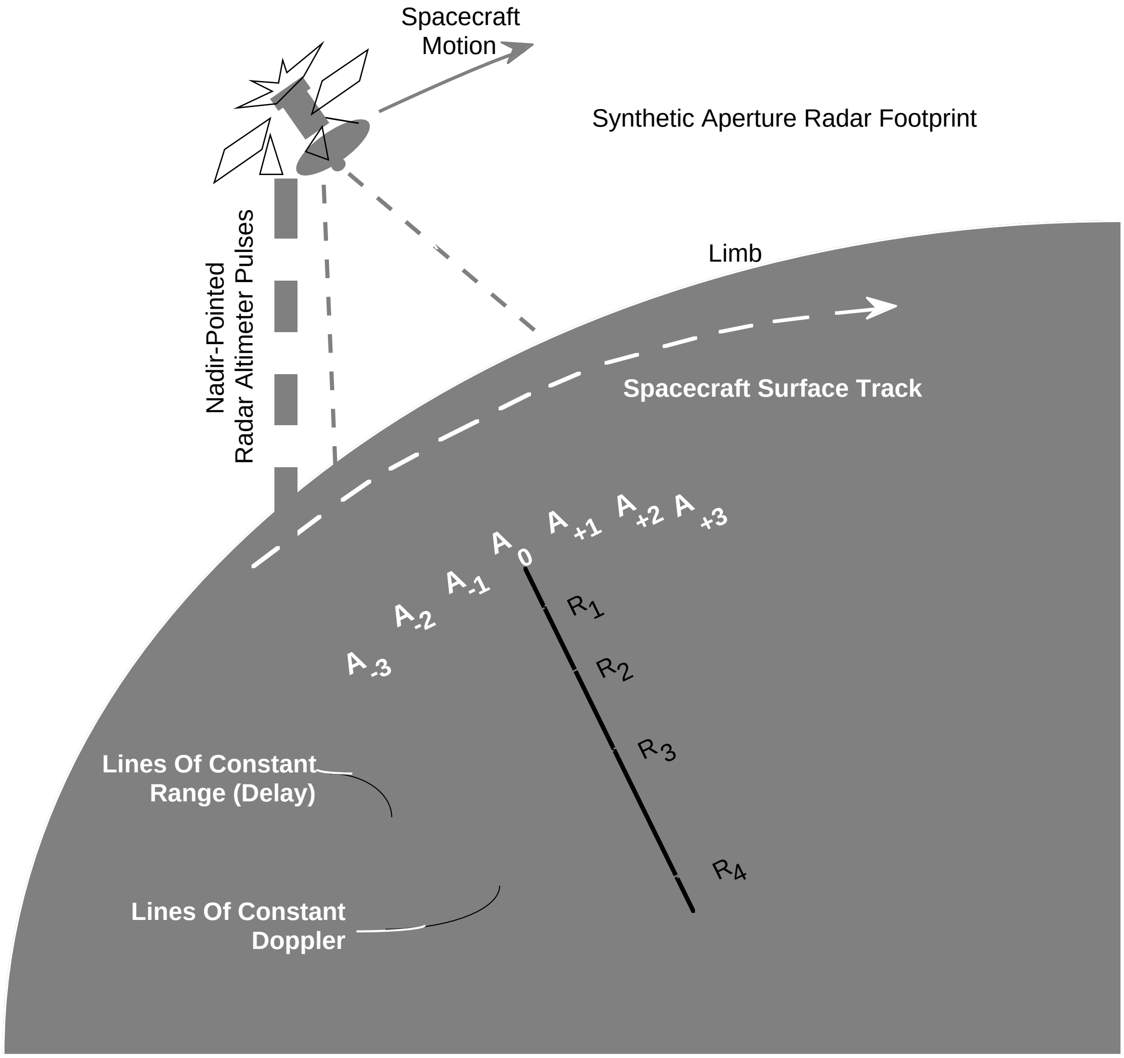
Active Sensing Science Instruments

Synthetic Aperture Radar Imaging

Some solar system objects that are candidates for radar imaging are covered by clouds or haze, making optical imaging difficult or impossible. These atmospheres are transparent to radio frequency waves, and can be imaged using Synthetic Aperture Radar (SAR) instruments, which provide their own penetrating illumination with radio waves. SAR synthesizes the angular resolving power of an antenna many times the size of the antenna aperture actually used. A SAR illuminates its target to the side of its direction of movement, and travels a distance in orbit while the reflected, phase shift-coded pulses are returning and being collected. This provides the basis for synthesizing an antenna (aperture) on the order of kilometers in size, using extensive computer processing.

For a SAR system to develop the resolution equivalent to optical images, the spacecraft's position and velocity must be known with great precision, and its attitude must be controlled tightly. This levies demands on the spacecraft's AACS and requires spacecraft navigation data to be frequently updated. SAR images are constructed of a matrix where lines of constant distance or range intersect with lines of constant Doppler shift.

Magellan's radar instrument alternated its active operations as a SAR imaging system and radar altimeter, with a passive microwave radiometer mode several times per second in orbit at Venus.



Altimeters

Radar pulses may be directed straight down to a planet's surface, the nadir, from a spacecraft in orbit, to measure variations in the height of terrain being overflown. The coded, pulsed signals are timed from the instant they leave the instrument until they are reflected back, and the distance is obtained by dividing by the speed of light. Terrain height is then judged based upon knowledge of the orbital position of the spacecraft. The Pioneer 12 spacecraft and the Magellan spacecraft used radar altimeters at Venus. Laser light may also be used in the same manner for altimetry. Laser altimeters generally have a smaller footprint, and thus higher spatial resolution, than radar altimeters. They require less power. Mars Global Surveyor carries a laser altimeter which uses a small cassegrain telescope.

Recap

1. The Heavy Ion Counter on Galileo uses _______________ sensing: it registers the characteristics of ions which enter the instrument.
2. _____________________ are direct-sensing instruments which detect and measure the interplanetary and solar magnetic fields in the vicinity of the spacecraft.
3. Optical imaging is performed by two families of detectors: vidicons and the newer _______________ _______________ ________________ (CCDs).
4. Spectrometers are optical instruments which split the light received from objects into their component ___________________ by means of a diffraction grating.
5. Sometimes various optical functions are combined into a single instrument, such as photometry and polarimetry combined into a ___________________ .
6. SAR... travels a distance in orbit while the reflected... pulses are returning. This provides the basis for synthesizing an antenna (aperture) on the order of ________________ in size.

1. direct   2. Magnetometers   3. charge coupled devices   4. wavelengths   5. photopolarimeter
6. kilometers

Chapter 13. Spacecraft Navigation

Objectives: Upon completion of this chapter you will be able to describe basic principles of spacecraft navigation, including spacecraft velocity and distance measurement, angular measurement, and orbit determination. You will be able to describe spacecraft trajectory correction maneuvers and orbit trim maneuvers.

Navigating a spacecraft involves measuring its radial distance and velocity, the angular direction to it, and its velocity in the plane-of-sky. From these data, a mathematical model may be constructed and maintained, describing the history of a spacecraft's location in three dimensional space over time. Any necessary corrections to a spacecraft's trajectory or orbit may be identified.based on the model. The navigation history of a spacecraft is incorporated in the reconstruction of its observations of the planet it encounters; it may be applied to the construction of SAR images. Some of the basic factors involved in acquiring navigation data are described below.

Data Types

The art of spacecraft navigation draws upon tracking data, which includes measurements of the Doppler shift of the downlink carrier and the pointing angles of DSN antennas. Navigation also uses data categorized as very long baseline interferometry (VLBI), explained below. These data types differ from the telemetry data, generated by science instruments and spacecraft health sensors, which is transmitted via modulated subcarrier.

Spacecraft Velocity Measurement

In two-way coherent mode, recall from Chapter 10 that a spacecraft determines its downlink frequency based upon a very highly stable uplink frequency. This permits the measurement of the induced Doppler shift to within 1 Hz, since the uplink frequency is known with great precision. The rates of movement of the Earth in its revolution about the sun and its rotation are known to a high degree of accuracy, and are removed. The resulting Doppler shift is directly proportional to the radial component of the spacecraft's velocity, and the velocity is thus computed.

Spacecraft Distance Measurement

A uniquely coded ranging pulse may be added to the uplink to a spacecraft, and its transmission time is recorded. When the spacecraft receives the ranging pulse, it returns the pulse on its downlink. The time it takes the spacecraft to turn the pulse around within its electronics is known from pre-launch testing. When the pulse is received at the DSN, its true elapsed time is determined, and the spacecraft's distance is then computed. Distance may also be determined as well as its angular position, using triangulation. This is described below.

Spacecraft Angular Measurement

The angles at which the DSN antennas point are recorded with an accuracy of thousandths of a degree. These data are useful, but even more precise angular measurements can be provided by VLBI, and by differenced Doppler. A VLBI observation of a spacecraft begins when two DSN stations on separate continents, separated by a very long baseline, track a single spacecraft simultaneously. High-rate recordings are made of the downlink's wave fronts by each station, together with precise timing data. DSN antenna pointing angles are also recorded. After a few minutes, and while still recording, both DSN antennas slew directly to the position of a quasar, which is an extragalactic object whose position is known with high accuracy. Then they slew back to the spacecraft, and end recording a few minutes later. Correlation and analysis of the recorded data yields a very precise triangulation from which both angular position and radial distance may be determined. This process requires knowledge of each station's location with respect to the location of Earth's axis with very high precision. Currently, these locations are known to within 3 cm. Their locations must be determined repeatedly, since the location of the Earth's axis varies several meters over a period of a decade.

Differenced Doppler can provide a measure of a spacecraft's changing three-dimensional position. To visualize this, consider a spacecraft orbiting a planet. If the orbit is in a vertical plane edge on to you, you would observe the downlink to take a higher frequency as it travels towards you. As it recedes away from you, and behind the planet, you notice a lower frequency. Now, imagine a second observer halfway across the Earth. Since the orbit plane is not exactly edge-on as that observer sees it, the other observer will record a slightly different Doppler signature. If you and the other observer were to compare notes and difference your data sets, you would have enough information to determine both the spacecraft's changing velocity and position in three-dimensional space. Two DSSs separated by a large baseline do exactly this. One DSS provides an uplink to the spacecraft so it can generate a stable downlink, and then it receives two-way. The other DSS receives a three-way downlink. The differenced data sets are frequently called "two-way minus three-way." High-precision knowledge of DSN Station positions, as well as a highly precise characterization of atmospheric refraction, makes it possible for DSN to measure spacecraft velocities accurate to within hundredths of a millimeter per second, and angular position to within 10 nano-radians.

Optical Navigation

Spacecraft which are equipped with imaging instruments can use them to observe the spacecraft's destination planet against a known background starfield. These images are called OPNAV images. Interpretation of them provides a very precise data set useful for refining knowledge of a spacecraft's trajectory.

Orbit Determination

The process of spacecraft orbit determination solves for a description of a spacecraft's orbit in terms of its Keplerian elements (described in Chapter 5) based upon the types of observations and measurements described above. If the spacecraft is enroute to a planet, the orbit is heliocentric; if it is in orbit about a planet, the orbit determination is made in reference to that planet. Orbit determination is an iterative process, building upon the results of previous solutions. Many different data inputs are selected as appropriate for input to computer software which uses the laws of Newton and Kepler. The inputs include the various types of navigation data described above, as well as data such as the mass of the sun and planets, their ephemeris and barycentric movement, the effects of the solar wind, a detailed planetary gravity field model, attitude management thruster firings, atmospheric friction, and other factors.

The highly automated process of orbit determination is fairly taken for granted today. During the effort to launch America's first artificial Earth satellite, the JPL craft Explorer 1, a room-sized IBM computer was employed to figure a new satellite's trajectory using Doppler data acquired from Cape Canaveral and a few other tracking sites. The late Caltech physics professor Richard Feynman was asked to come to the Lab and assist with difficulties encountered in processing the data. He accomplished all of the calculations by hand, revealing the fact that Explorer 2 had failed to achieve orbit, and had come down in the Atlantic ocean. The IBM mainframe was coaxed to reach the same result, hours after Professor Feynman had departed for the weekend.

Trajectory Correction Maneuvers

Once a spacecraft's solar or planetary orbital parameters are known, they may be compared to those desired by the project. To correct any discrepancy, a Trajectory Correction Maneuver (TCM) may be planned and executed. This involves computing the direction and magnitude of the vector required to correct to the desired trajectory. An opportune time is determined for making the change. For example, a smaller magnitude of change would be required immediately following a planetary flyby, than would be required after the spacecraft had flown an undesirable trajectory for many weeks or months. The spacecraft is commanded to rotate to the attitude in three-dimensional space computed for implementing the change, and its thrusters are fired for a determined amount of time. TCMs generally involve a velocity change (delta-V) on the order of meters or tens of meters per second. The velocity magnitude is necessarily small due to the limited amount of propellant typically carried.

Orbit Trim Maneuvers

Small changes in a spacecraft's orbit around a planet may be desired for the purpose of adjusting an instrument's field-of-view footprint, improving sensitivity of a gravity field survey, or preventing too much orbital decay. Orbit Trim Maneuvers (OTMs) are carried out generally in the same manner as TCMs. To make a change increasing the altitude of periapsis, an OTM would be designed to increase the spacecraft's velocity when it is at apoapsis. To decrease the apoapsis altitude, an OTM would be executed at periapsis, reducing the spacecraft's velocity. Slight changes in the orbital plane's orientation may also be made with OTMs. Again, the magnitude is necessarily small due to the limited amount of propellant typically carried.

Recap

1. Spacecraft navigation draws upon _________________ data, which includes measurements of the Doppler shift of the spacecraft's downlink carrier.
2. The resulting Doppler shift is directly proportional to the _______________ component of the spacecraft's velocity.
3. A VLBI observation of a spacecraft begins when two DSN stations on separate ____________________ track the spacecraft simultaneously.
4. If the spacecraft is enroute to a planet, the orbit determined is _____________________ .
5. TCMs generally involve a velocity change (delta-V) on the order of ___________ or tens of ___________ per second.

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1. tracking *2. radial* *3. continents* *4. heliocentric* *5. meters - or tens of - meters*

SECTION III. SPACE FLIGHT OPERATIONS

Chapter 14. Launch Phase

Objectives: Upon completion of this chapter you will be able to describe the role launch sites play in total launch energy, state the characteristics of various launch vehicles, and list factors contributing to determination of launch windows. You will be able to describe how the launch day of the year and hour of the day affect interplanetary launch energy, and list the major factors involved in preparations for launch.

Launch Vehicles

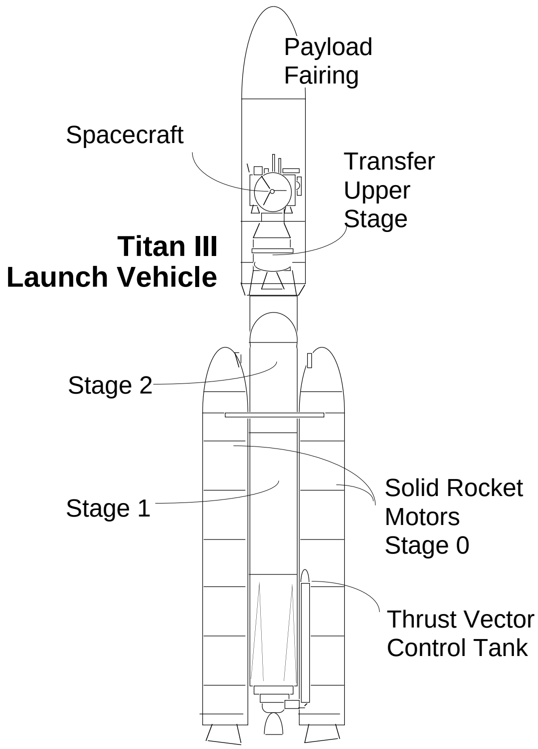
To date, the only way to achieve the propulsive energy to successfully launch spacecraft has been by combustion of chemical propellants, although there are a few other approaches currently being researched. There are two groups of rocket propellants, liquids and solids. Many spacecraft launches involve the use of both types of rockets, for example the solid rocket boosters attached to liquid-propelled expendable rockets, or the space shuttle. Hybrid rockets, which use a combination of solid and liquid, are also being developed. Solid rockets are generally simpler than liquid, but they cannot be shut down once ignited. Liquid and hybrid engines may be shut down after ignition, and conceivably could be re-ignited. A sampling of commonly used launch vehicles follows.

Delta

Delta is a family of two- or three-stage liquid-propelled expendable launch vehicle (ELV), produced by McDonnell Douglas, that use multiple strap-on solid boosters in several configurations. The liquid engines burn kerosene and liquid oxygen (LOX). A Delta II is capable of placing payloads of up to 2200 kg into low equatorial orbit (LEO). A Delta II placed the German X-Ray Observatory ROSAT into orbit in 1990, and launched the Japanese Geotail satellite in 1992.

Titan

Titan, produced by Martin Marietta Aerospace Group in Denver, Colorado, is a liquid-propelled, multiple stage ELV that can accommodate solid propellant strap-on boosters. The liquid engines burn hydrazine and nitric acid. Depending on the upper stage used, the Titan IV can put payloads of up to 18,000 kg into LEO, over 14,000 kg into polar orbit, or 4,500 kg into a geostationary transfer orbit (GTO). A Titan III launched the Viking spacecraft to Mars in 1975. Titan III vehicles launched JPL's Voyager 1 and 2 in 1977, and the Mars Observer spacecraft from the Kennedy Space Center (KSC), Cape Canaveral in 1992. The smaller Titan II can place about 2,000 kg into LEO.



Atlas

Atlas, produced by General Dynamics Corporation, is a liquid-propelled ELV which accommodates a variety of upper stages. Its engines burn kerosene and LOX. With a Centaur upper stage, Atlas is capable of placing 4000 kg into LEO. A Titan IV, equipped with two upgraded solid rocket boosters and a Centaur upper stage, will launch the Cassini Spacecraft on its interplanetary trajectory in 1997. An Atlas/Centaur launched the Infrared Astronomical Satellite (IRAS) into Earth orbit in 1985, and an Atlas is planned to launch the Space Infrared Telescope Facility (SIRTF) into solar orbit in 1998.

Ariane

Ariane is a system of highly reliable liquid-propelled ELVs combined with a selectable number of solid strap-on boosters or liquid boosters. They are launched from the Kourou Space Center in French Guiana by Arianespace, the first space transportation company in the world, composed of a consortium of 36 European aerospace companies, 13 European banks, and the Centre National d'Études Spatiales (CNES). Ariane 4 is capable of placing 4200 kg in GTO. Ariane 4 launched the Topex/Poseidon spacecraft into a high-altitude Earth orbit in 1992. An Ariane 5 launcher is under development, targeted to fly the manned Hermes mini-shuttle and 18,000 kg into LEO.

Proton

The Proton is a liquid-propellant ELV developed by the Soviet CIS Interkosmos. It is launched by Russia from the Baykonur Kosmodrome in Kasakhstan, and is capable of placing 20,000 kg into LEO. It has launched many Earth satellites and interplanetary spacecraft, and is scheduled to send an additional spacecraft to Mars in 1994, with cooperation from the U.S. and France. A western-built satellite for Inmarsat, the 67-country consortium, is planned to be launched by Proton in 1995.

Space Transportation System

America's space shuttle, as the Space Transportation System (STS) is commonly known, is a reusable launching system whose main engines burn liquid hydrogen and LOX. After each flight, its main components, except the external propellant tank, are refurbished to be used on future flights. The STS can put payloads of up to 30,000 kg in LEO. With the appropriate upper stage, spacecraft may be boosted to a geosynchronous orbit or injected into a planetary transfer orbit. Galileo, Magellan, and Ulysses were launched by the STS, using an Inertial Upper Stage (IUS), which is a two-stage solid-propellant vehicle. The STS may be operated to transport spacecraft to orbit, perform satellite rescue, and to carry out a wide variety of scientific missions ranging from the use of orbiting laboratories to small self-contained experiments.

Smaller Launch Vehicles

Many NASA experiments, as well as commercial and military payloads, are becoming smaller and lower in mass, as the art of miniaturization advances. The range of payload mass broadly from 100 to 1300 kg is becoming increasingly significant as smaller spacecraft are designed to have more operational capability. The market for launch vehicles with capacities in this range is growing.

Pegasus is a small, winged solid-propellant ELV built by Orbital Sciences Corporation. It resembles a cruise missile, and is launched from under the wing of an aircraft in flight at high altitude, currently a B-52. It is planned to be able to lift 400 kg into LEO. The Scout was a ground-launched, reliable solid-propellant ELV capable of placing 200 kg into LEO.

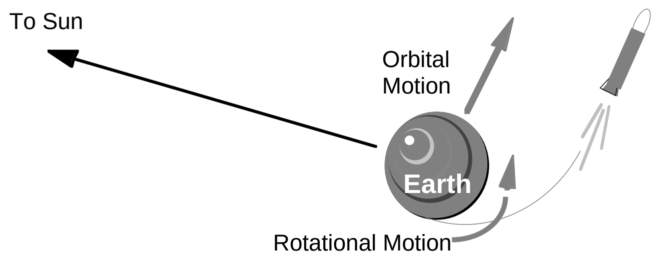
The Conestoga space launch vehicle is a low-cost, solid-propellent launcher made by Space Services, Inc., SSI, in Houston, and is capable of placing payloads of up to 1360 kg into LEO and 450 kg into GTO. Conestoga is a name aptly reminiscent of 19th-century broad-wheeled covered wagons, the expendable "launch" vehicles used by American pioneers to cross the prairie. They were named after the town where they were manufactured in Lancaster County, Pennsylvania.

Launch Sites

If a spacecraft is launched from a site near Earth's equator, it can take optimum advantage of Earth's substantial rotational speed. Sitting on the launch pad near the equator, it is already moving at a speed of over 1650 km per hour relative to Earth's center, a velocity which can be applied to the speed required to orbit Earth (approximately 28,000 km per hour). This means that the launch vehicle needs less propellant for launch, or that a given vehicle can launch a more massive spacecraft into orbit. A spacecraft intended for a high-inclination Earth orbit has no such free ride, though. As mentioned in Chapter 5, the launch vehicle must provide a much larger part, or all, of the energy for the spacecraft's orbital speed.

For interplanetary launches, the vehicle must take advantage of Earth's orbital motion as well, to accommodate the limited energy available from today's launch vehicles. In the diagram below, the launch vehicle is, in addition to using Earth's rotational speed, accelerating generally in the

Launch Using Earth's Rotational and Orbital Velocities



direction of Earth's orbital motion, which has an average velocity of approximately 100,000 km per hour along its orbital path. Of course, the spacecraft must fly a specific direction for its particular trajectory, but it can utilize at least a major component of Earth's pre-existing motion. In the case of a spacecraft embarking on a Hohmann interplanetary transfer orbit, recall that Earth's orbital speed represents the speed at aphelion or perihelion of the transfer orbit, and the spacecraft's velocity merely needs to be increased or decreased in the tangential direction to achieve the desired transfer orbit.

The launch site must also have a clear pathway downrange so the launch vehicle will not fly over populated areas, in case of accidents. The STS has the additional constraint of requiring a landing strip with acceptable wind, weather, and lighting conditions near the launch site as well as at landing sites across the Atlantic Ocean, in case an emergency landing must be attempted.

Launches from the east coast of the United States (the Kennedy Space Center at Cape Canaveral, Florida) are suitable only for low inclination orbits because major population centers underlie the trajectory required for high-inclination launches. The latter are accomplished from Vandenberg Air Force Base on the west coast, in California, because the trajectory for high-inclination Earth orbits is out over the Pacific Ocean. An equatorial site is not required for high-inclination orbital launches.

Complex ground facilities are required for heavy launch vehicles, but smaller vehicles such as the Conestoga require only trailer-mounted facilities, and the Pegasus requires none except its parent airplane.

Launch Windows

A launch window is the span of time during which a launch may take place while satisfying the constraints imposed by safety and mission objectives. For an interplanetary launch, the window is constrained typically within a number of weeks by the location of Earth in its orbit around the sun, in order to permit the vehicle to use Earth's orbital motion for its trajectory, as well as timing it to arrive at its destination when the target planet is in position. The launch window is also constrained typically to a number of hours each day of the previously described window, in order to take advantage of Earth's rotational motion. In the illustration at the top of this page, the vehicle is launching from a site near Earth's terminator, which is going into night time hours as the Earth's rotation takes it around away from the sun. If the example in the illustration were to launch in the early morning hours on the other side of the depicted Earth, it would be launching in a direction opposite Earth's orbital motion. These illustrations are over-simplified, in that they do not differentiate between launch from Earth's surface and injection into interplanetary trajectory. It is actually the latter that must be timed to occur on the proper side of Earth. Actual launch times must also consider how long the spacecraft is to remain in low Earth orbit before its upper stage places it on the desired trajectory (this is not shown in the illustration).

The daily launch window may be further constrained by other factors, for example, the STS's emergency landing site constraints. Of course, a launch which is to rendezvous with another vehicle in Earth orbit must time its launch with the orbital motion of that object. This was the case with the Hubble Space Telescope repair mission executed in December 1993.

Preparations For Launch

The spacecraft must be transported from the site where it was built and tested to the launch site. The spacecraft is sealed inside an environmentally controlled carrier for the trip, and internal conditions are carefully monitored throughout the journey. Once at the launch site, additional testing takes place, and propellants are loaded aboard. Then the spacecraft is mated to its upper stage, and the stack is mated to the launch vehicle.

Pre-launch and launch operations of a JPL spacecraft are typically carried out by personnel at the launch site while in direct communication with persons at the Space Flight Operations Facility at JPL. Additional controllers and engineers at a different location are typically involved with the particular upper stage vehicle, such as the Lockheed personnel at Sunnyvale, California, controlling the inertial upper stage (IUS). The spacecraft's telecommunications link is maintained through ground facilities close to the launch pad prior to launch and during launch, linking the spacecraft's telemetry to controllers and engineers at JPL. Command sequences must be loaded aboard the spacecraft, verified, and initiated at the proper time prior to launch. Spacecraft health must be monitored, and the launch process interrupted if any critical tolerances are exceeded.

Once the spacecraft is launched, the DSN begins tracking, acquiring the task from the launch-site tracking station, and the cruise phase is set to begin.

Recap

1. Ariane 4 is capable of placing ___________ kg in GTO.
2. If a spacecraft is launched from a site near Earth's equator, it can take advantage of Earth's substantial ______________________ speed.
3. Launches from the east coast of the United States are suitable only for ________________ inclination orbits.
4. For an interplanetary launch, the window is constrained... by the location of Earth in its orbit around the sun, in order to permit the vehicle to use Earth's _________________ motion for its trajectory.
5. Launch operations of a JPL spacecraft are typically carried out by personnel at the launch site while in direct communication with persons at the ____________ ______________ _______________ Facility at JPL.

1. 4200   2. rotational   3. low   4. orbital   5. Space Flight Operations

Chapter 15. Cruise Phase

Objectives: Upon completion of this chapter, you will be able to list the major factors involved in spacecraft checkout and characterization, and preparation for encounter. You will be able to characterize typical daily flight operations.

Cruise phase is bounded by launch phase at the beginning, and encounter phase at the end. It is a time during which ground system upgrades and tests may be conducted, and spacecraft flight software modifications are implemented and tested. Cruise operations are typically carried out from the Space Flight Operations Facility at JPL.

Spacecraft Checkout and Characterization

After launch, the spacecraft is commanded to configure for cruise. Appendages which might have been stowed in order to fit within the launch vehicle are deployed either fully or to intermediate cruise positions. Telemetry is analyzed to determine the health of the spacecraft, indicating how well it survived its launch. Any components that appear questionable might be put through tests specially designed and commanded in real time, and their actual state determined as closely as possible by subsequent telemetry analysis.

During the cruise period, additional command sequences are uplinked and loaded aboard for execution, taking the spacecraft through its routine operations, such as tracking Earth with the HGA and monitoring celestial references. The flight team members begin to get the feel of their spacecraft in flight. Inevitably, unforeseen problems arise, and the onboard fault protection algorithms receive their inadvertent tests; the spacecraft will, more likely than not, go into safing or contingency modes (as described in Chapter 11), and it must be painstakingly recovered.

TCMs are executed to fine tune the trajectory. Eventually, as the spacecraft nears its target, the science instruments are powered on and calibrated, if they have not already been powered on earlier during cruise.

Real-time Commanding

Frequently, commands stored on board during cruise or other phases must be augmented by real-time commands, as new activities become desirable, or, rarely, as mistakes are discovered in the on-board command sequence. There is an inherent risk in real-time commanding; it is always possible that the wrong commands may be sent. The longer, planned sequences of commands (generally just called “sequences”) typically benefit from a long process of extensive debate and selection, testing and checking and simulation prior to uplink. These factors may limit the desirability of undertaking many activities by real-time commands that do not have the benefit of the full sequence development process, but the necessity, as well as the convenience, of real-time commanding frequently prevails.

Typical Daily Operations

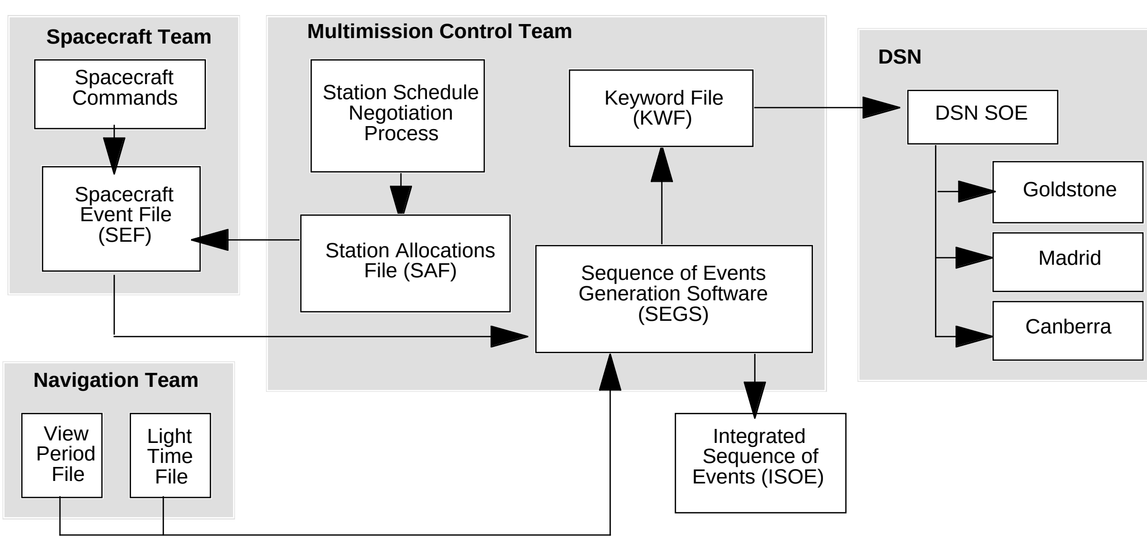
Usually, at least one person is on duty 24 hours a day, seven days a week at JPL to watch the spacecraft while in flight, and respond to any anomalous indications. The person so designated is typically the mission controller or ACE. The ACE is a person on the Mission Control Team who is the single point of contact between the entire flight team, consisting of the Spacecraft Team, the Navigation Team, Science and other teams, and the teams and facilities external to the project such as DSN, SFOF Facilities, Mission Control and Computing Center (MC^3), Operations Planning and Control Team (OPCT), Ground Communications Facility (GCF), AMMOS, and the Information Processing Center (IPC).

"ACE" is not an acronym, despite all attempts to make it one. It simply refers to one single point of contact for a project's real-time flight operations, not too inappropriately a pun for an expert combat pilot. The ACEs are multimission personnel, and one ACE may be serving more than one flight project at a time. For example, in 1993, one ACE was in charge of Magellan, Voyager 1, and Voyager 2 simultaneously. The ACE executes commanding, manages the ground systems, insures the capture of telemetry and tracking data, watches for alarms, evaluates data quality, performs real-time analyses to determine maneuver effectiveness and spacecraft health, and coordinates the activities of the DSN and other teams in support of the projects. Typically, a large portion of the ACE's interactions are with the Spacecraft Team, the DSN, and the OPCT.

Monitoring Spacecraft and Ground Events

An accurate list of expected events is needed to compare with spacecraft events as they occur in real time, in order to make sure the spacecraft is operating as planned. It is also required for the purpose of directing DSN station activity, and to be able to plan command uplinks and other real time operations. That list is called the integrated sequence of events (ISOE). Integrated means that it contains both spacecraft events and DSN ground events. Compiling an ISOE begins with a list of the commands that will be placed in the spacecraft's memory, and which will be executing over a period of typically a week or two into the future. Times of the events are included with the commands. These are supplied in a spacecraft event file (SEF) supplied by the spacecraft team. They are adjusted for light time, and are combined with DSN station information and events. A subset of the list is provided to the DSN as a keyword file (KWF), which the DSN then combines

Sequence of Events Products



with similar listings from other projects to create a sequence of events (SOE) for each particular station. The illustration below shows an excerpt of activities typical on a flight project that contribute to the generation of SOE products.

Tracking the Spacecraft in Flight

DSN tracking schedules have been negotiated months or years in advance. Now the spacecraft is in flight. Near the time when the spacecraft will be rising in the sky due to Earth's rotation, its assigned DSN tracking activity begins. During the period allotted for "precal" activities, the Link Monitor and Control (LMC) operator sits down at his or her console in the Signal Processing Center (SPC) of one the DSN's three Deep Space Communications Complexes (DSCC). The operator will be controlling and monitoring the assigned antenna, called a Deep Space Station (DSS), an assigned set of computers that control its pointing, tracking, commanding, receiving, telemetry processing, ground communications, and other functions.

This string of equipment from the antenna to the project people at JPL is called a link, referring to the two-way communications link between the spacecraft and the project. Prior to the LMC operator's arrival, the Complex Monitor and Control (CMC) operator will have assigned, via directives sent out to the station components over a local area network (LAN), applicable equipment to become part of the link. Now the LMC operator begins sending more directives over the LAN to configure each of the link components specifically for the upcoming support. Predict sets containing uplink and downlink frequencies and Doppler bias ramp rates, pointing angles and bit rates, command modulation levels, and hundreds of other parameters are all sent to the link components. Problems are identified and corrected.

At the end of the precal period, the LMC operator checks the DSS area via closed circuit TV, makes a warning announcement over its outdoor loudspeakers, and the DSS antenna swings to point precisely to the spacecraft's location in the eastern sky. The transmitter comes on, and red beacons on the antenna illuminate as a warning. Upon locking the receivers, telemetry, and tracking equipment to the spacecraft's signal, the link is established. This marks the Beginning of Track (BOT) and Acquisition of Signal (AOS). Depending on the nature of the spacecraft's activities, there may be Loss of Signal (LOS) when the spacecraft turns away to maneuver, or if it goes into occultation behind a planet. This LOS would presumably be followed by another AOS when the maneuver or occultation is complete. During the day, the DSS antenna moves slowly to follow, or track, the spacecraft as Earth rotates.

Near the end of the LMC operator's shift, the DSS is pointing lower on the western horizon. At the same time, another LMC operator inside the SPC of another DSCC a third of the way around the world, is doing his or her precal as the same spacecraft is rising in the east. To accomplish an uplink transfer, the setting DSS's transmitter is turned off precisely two seconds after the rising DSS's transmitter comes on. Scheduled End of Track (EOT) arrives, and the LMC operator at the setting DSS begins postcal activities, idling the link components and returning control of them to the CMC operator.

Preparation for Encounter

Command loads uplinked to the spacecraft are valid for varying lengths of time. So-called quiescent periods such as the lengthy cruises between planets require relatively few activities, and a command load may be valid for several weeks. By comparison, during the closest-approach part of a flyby encounter, a very long and complex load may execute in a matter of hours. Prior to encounter, the spacecraft is generally sent a command sequence that takes it through activities simulating the activities of encounter. Changes in data rate and format, and spacecraft maneuvers, are designed to put the flight team and ground systems through their paces during a realistic simulation, in order to provide some practice for readiness, to shake down the systems and procedures, and to try to uncover flaws or areas for improvement.

Instrument calibrations are undertaken prior to encounter to be sure that experiments are being carried out in a controlled fashion. Optical instruments, for example, may be commanded to take observations of empty space, in order to gain knowledge of flaws or idiosyncrasies in the instrument, which can then be removed from later encounter observations.

Recap

1. ___________________ phase is a time during which time ground system upgrades and tests may be conducted, and spacecraft flight software modifications are implemented and tested.
2. Any components which appear questionable might be put through _________________ which are specially designed and commanded in real time.
3. There is an inherent ___________________ in real-time commanding.
4. The __________ is the single point of contact between the flight team and the teams external to the project.
5. The string of equipment from the antenna to the project people at JPL is called a _____________________.
6. Prior to encounter, the spacecraft is generally sent a command sequence which takes it through activities ___________________ the activities of encounter.

1. Cruise 2. tests 3. risk 4. ACE 5. Link 6. simulating

Chapter 16. Encounter Phase

Objectives: Upon completing this chapter, you will be able to describe major factors involved in flyby operations, planetary orbit insertion, planetary mapping, and gravity field surveying. You will be able to describe the unique opportunities for science data acquisition presented by occultation and problems involved. You will be able to describe the concepts of using aerobraking to alter orbital geometry or decelerate for landing, atmospheric entry, balloon tracking, and sampling.

The term “encounter” is used in this chapter to indicate the high-priority data-gathering period of operations for which the mission was intended. It may last a few months or weeks or less as in the case of a flyby encounter or atmospheric probe entry, or it may last a number of years as in the case of an orbiter. Encounter operations are typically carried out from the Space Flight Operations Facility at JPL, Buildings 230 and 264.

Flyby Operations

All the interplanetary navigation and course corrections accomplished during cruise result in placement of the spacecraft at precisely the correct point and at the correct time to carry out its encounter observations and obtain any planned gravity assist. A flyby spacecraft has a limited opportunity to gather data. Once it has flown by its target, it cannot return to recover lost data. Its operations are planned years in advance of the encounter and refined and practiced in the months prior to the encounter date. Sequences of commands are prepared by the flight team to carry out operations in various phases of the flyby, depending on the spacecraft’s distance from its target. During each of the six Voyager encounters, the phases were titled observatory phase, far encounter phase, near encounter phase, and post encounter phase. They may have different names for different spacecraft, but many of the functions most likely will be similar.

In a flyby operation, observatory phase (OB) is defined as the period when the target can be better resolved in the spacecraft’s optical instruments than it can from Earth-based instruments. This phase generally begins a few months prior to the date of flyby. OB is marked by the spacecraft being completely involved in making observations of its target, and ground resources are completely operational in support of the encounter. This phase marks the end of interplanetary cruise phase, during which time ground system upgrades and tests are conducted, and spacecraft flight software modifications are implemented and tested.

Far encounter phase (FE) includes time when the full disc of a planet can no longer fit within the field of view of the instruments. Observations are designed to accommodate parts of the planet rather than the whole disc, and to take best advantage of the higher resolution available. Near encounter phase (NE) includes the period of closest approach to the target. It is marked by intensely active observations by all of the spacecraft’s science experiments, including onboard instruments, and by radio science investigations. It includes the opportunity to obtain the highest resolution data about the target. Radio science observations include ring plane measurements during which ring structure and particle sizes can be determined, celestial mechanics observations which determine the planet’s or satellites’ mass, and atmospheric occultations which determine atmospheric structures and composition.

Observations must be planned in detail many months or years prior to NE, but precise navigation data may not be available to program accurate pointing of the instruments until only a few days before. Late updates of stored parameters on the spacecraft can be made to supply the pointing data just in time. OPNAVs, discussed in Chapter 13, may be an important navigational input to the process of determining values for late parameter updates. Some observations of the target planet or its environs may be treated as reprogrammable late in the encounter, in order to observe features which had not been seen until FE.

During the end of FE or the beginning of NE, a bow shock crossing may be identified through data from the magnetometer, plasma and plasma wave instruments, as the spacecraft flies into a planet's magnetosphere and leaves the solar wind. When the solar wind is in a state of flux, these crossings may occur again and again as the magnetosphere and the solar wind push back and forth over millions of kilometers. (Traditionally, PIs are not above wagering on the time and distance from a planet where these crossings will take place).

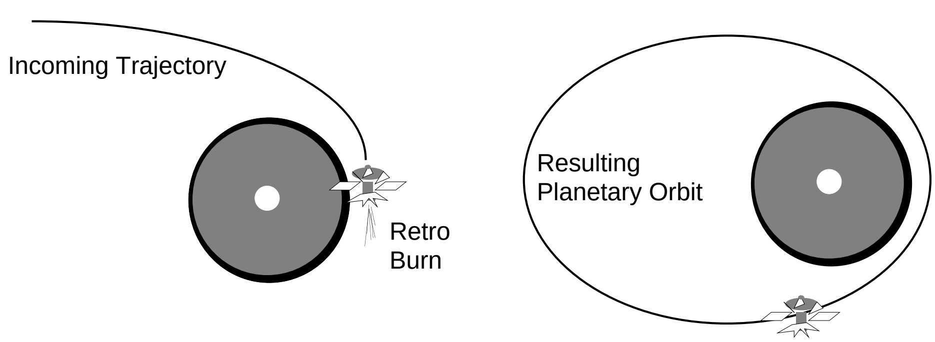
Post encounter phase (PE) begins when NE completes, and the spacecraft is receding from the planet. It is characterized by day after day of observations of a diminishing, thin crescent of the planet just encountered. This is the opportunity to make extensive observations of the night side of the planet. After PE is over, the spacecraft stops observing its target planet, and returns to the activities of cruise phase. DSN resources are relieved of their continuous support of the encounter, and they are generally scheduled to provide less frequent coverage to the mission.

After encounter, instrument calibrations are repeated to be sure that any changes in the instrument's state are accounted for.

Planetary Orbit Insertion

The same type of highly precise interplanetary navigation and course correction for flyby missions are also applied during cruise for an orbiter spacecraft. This process places the spacecraft at precisely the correct location at the correct time to enter into planetary orbit. Orbit insertion requires not only the precise position and timing, but also controlled deceleration. As the spacecraft's trajectory is bent by the planet's gravity, the command sequence aboard the spacecraft fires its engine(s) at the proper moment, and for the proper duration. Once the retro-burn has completed, the spacecraft has been captured into orbit by its target planet. If the retro-burn fails, the spacecraft will continue to fly on past the planet. It is common for the retro-burn to occur on the far side of a planet as viewed from Earth.

Planetary Orbit Insertion



Once inserted into a highly elliptical orbit, Mars Global Surveyor will continue to adjust its orbit via OTMs near periapsis which decelerate the spacecraft further, causing a reduction in the apoapsis altitude, and establishing a close circular orbit at Mars. Galileo used a gravity assist from a close flyby of Jupiter's moon Io to decelerate, augmenting the deceleration provided by the 400 N rocket engine. Thereafter, additional OTMs over a span of two years will vary the orbit slightly to choreograph multiple encounters with the Galilean satellites and the magnetosphere.

System Exploration and Planetary Mapping

At least two broad categories of orbital operations may be identified. Exploring a planetary system includes making observations of the planet and the satellites and rings, etc., in its neighborhood. On the other hand, mapping a planet obtains data mainly from the planet's surface. Galileo will be exploring the entire Jovian system, including its satellites, rings, magnetosphere, the planet, and its environment. At Saturn, Cassini will accomplish a similar exploratory mission, exploring planet's rings and environs, and the large satellite Titan with its atmosphere. Magellan, a planetary mapper, covered 98% the surface of Venus, in great detail, using SAR imaging, altimetry, radiometry, and gravity. Mars Global Surveyor will map the surface of its planet also, using imaging, altimetry, spectroscopy, and gravity survey.

An orbit of low inclination at the target planet is well suited to a system exploration mission, because it provides repeated exposure to satellites orbiting within the equatorial plane, as well as adequate coverage of the planet and its magnetosphere. An orbit of high inclination is better suited for a mapping mission, since the target planet or body will rotate fully below the spacecraft's orbit, providing eventual exposure to every part of the planet's surface.

In either case, during system exploration or planetary mapping, the orbiting spacecraft is involved in an extended encounter period, requiring continuous or nearly continuous support from the flight team members, the DSN, and other institutional teams.

Recap

1. The term ____________________ is used to indicate the high-priority data-gathering period of operations for which the mission was intended.
2. A flyby spacecraft has a limited ________________________ to gather data.
3. Orbit insertion requires not only the precise position and timing, but also controlled _____________________.
4. An orbit of _____________ inclination at the target planet is well suited to a system-exploration mission.
5. An orbit of ___________ inclination is better suited for a mapping operation.

---

1. encounter *2. opportunity* *3. deceleration* *4. low* *5. high*

Occultations

Occultations provide unique opportunities for experiments. Occultations of interest include Earth, the sun, or another star disappearing behind a planet, behind its rings, or behind its atmosphere, as viewed from the spacecraft. During the one-time only occultation opportunity by a planet during a flyby encounter, or repeatedly during an orbital mission, onboard optical instruments may make unique observations. For example, an ultraviolet spectrometer may watch the sun as it disappears behind a planet's atmosphere, and obtain data on the composition and structure of the atmosphere. A photometer watching a bright distant star as it passes behind a ring system yields high-resolution data on the sizes and structures of the ring and its particles.

The spacecraft's radio signal may be observed on Earth as the spacecraft passes behind a planet, and this yields data on the composition and structure of the atmosphere and rings. Observations of the Doppler shift as the spacecraft passes near a planet or satellite can provide direct measurement of the planet's mass to a high degree of accuracy. This is known as a celestial mechanics experiment. Both occultation and celestial mechanics experiments are radio science investigations. Radio science investigations require a stable downlink frequency from the spacecraft. This means it must be in two- or three-way coherent mode, receiving an uplink from the DSN as discussed in Chapter 10. However, this is generally possible on ingress only; the spacecraft is likely to lose the uplink from DSN when it passes behind the planet, and therefore cannot maintain a coherent downlink. For this reason, some spacecraft are equipped with an Ultra Stable Oscillator (USO) in a temperature controlled "oven" which is capable of providing a fairly stable downlink frequency when an uplink is not available.

The first occultation experiment was proposed when JPL was characterizing the precise refraction effects of Earth's atmosphere, with a known structure and composition, for the purpose of tracking spacecraft. It was realized that measurements of the refraction effects induced by another planet's atmosphere could be used to "reverse-engineer" its structure and composition.

Gravity Field Surveying

Planets are not perfectly spherical. Terrestrial planets are rough surfaced, and most planets are at least slightly oblate. Thus they have variations in their mass concentrations, sometimes associated with mountain ranges or other features visible on the surface. A gravity field survey identifies local areas of a planet which exhibit slightly more or slightly less gravitational attraction. These differences are due to the variation of mass distribution.

There are two reasons for surveying the gravity field of a planet. First, highly accurate navigation in orbit at a planet requires a good model of variations in the gravity field, which can be obtained by such a survey. Second, gravity field measurements have the unique advantage of offering scientists a "view" of mass distribution both at and below the surface. They are extremely valuable in determining the nature and origin of features identifiable in imaging data. JPL has pioneered the field of mapping planetary mass concentrations. Application of these techniques to Earth helps geologists locate petroleum and mineral deposits.

To obtain gravity field data, a spacecraft is only required to provide a downlink carrier signal coherent with a highly stable uplink from the DSN. It may be modulated or unmodulated. After the removal of known Doppler shifts induced by planetary motions and the spacecraft's primary orbital motion and other factors, the residual Doppler shifts are indicative of miniscule spacecraft accelerations resulting from variations in mass distribution at and below the surface of the planet.

The gravity feature size that can be resolved is roughly equal to the spacecraft's altitude; with a 250-km altitude, a spacecraft should resolve gravity features roughly 250 km in diameter.

With an X-band (3.6 cm) uplink received at a spacecraft, and a coherent X-band downlink, spacecraft accelerations can be measured to tens of micrometers per second squared. This translates to a sensitivity of milligals in a planetary gravity field. (one gal represents to a gravitational acceleration of 1 cm/sec^2).

The best gravity field coverage is made from low circular orbit. Mars Global Surveyor will be conducting a gravity field survey from circular orbit as one of its first-priority investigations. Magellan's orbit was elliptical during its primary mission, and meaningful gravity data could be taken only for that portion of the orbit plus and minus about 30° true anomaly from periapsis, which occurred at about 10° north latitude.

Atmospheric Entry and Aerobraking

Aerobraking, as the name implies, is the process of decelerating by converting velocity into heat through friction with a planetary atmosphere. Galileo's atmospheric probe was a typical example of an atmospheric entry and aerobraking mission. The probe was designed with an aeroshell that sustained thousands of degrees of heat as it entered the Jovian atmosphere. It decelerated at hundreds of Gs, until it reached a speed where its parachute became effective. At that time, the spent aeroshell was discarded, and the probe carried out its experiments.

The Magellan spacecraft was not designed for atmospheric entry. However, the periapsis altitude of Magellan's orbit was lowered by the use of propulsive maneuvers into the upper reaches of Venus's atmosphere near 140 km above the surface. This is still high above the cloudtops, which are at about 70 km. Flying at this altitude induced deceleration via atmospheric friction during the portion of the spacecraft's orbit near periapsis, thus reducing the height to which it could climb to apoapsis. The solar array, consisting of two large square panels, was kept flat-on to the velocity vector during each pass through the atmosphere, while the HGA trailed in the wind. The solar array reached a maximum of 160°C, and the HGA a maximum of 180°C. After approximately 70 earth days and one thousand orbits of encountering the free molecular flow and decelerating a total of about 1250 m/sec, the apoapsis altitude was lowered to a desirable altitude. The periapsis altitude was then raised to achieve a nearly circular orbit. The objectives of this aerobraking experiment were to demonstrate the use of aerobraking for use on future missions, to characterize the upper atmosphere of Venus, and to be in position to conduct a full-planet gravity field survey from a nearly circular orbit.

Landing

Landing on a planet is generally accomplished first by aerobraking while entering the planet's atmosphere under the protection of an aeroshell. From there, the lander might be designed to parachute to the surface, or to use a propulsion system to soft-land, or both, as did the Viking landers on Mars. The Soviet Venera spacecraft parachuted to the surface of Venus by means of a small rigid disk integral with the spacecrafts' structure which helped slow their descent sufficiently through the very dense atmosphere. A crushable foot pad absorbed the energy from their final impact on the surface.

The lander that is a part of the Mars Pathfinder mission is being designed to absorb landing impact with an array of large air bags. Once the lander is on the surface, petals deploy to expose the instruments and solar panels before operations begin. For a possible future mission, the international science community desires to land a network of seismometer-equipped spacecraft on the surface of Venus to measure seismic activity over a period of months or years.

Balloon Tracking

Once deployed within a planet's atmosphere, having undergone atmospheric entry operations as discussed above, a balloon may ride with the wind and depend on the DSN to track its progress. In 1986, DSN tracked the balloons deployed by the Soviet Vega spacecraft on its way to encounter comet Halley. The process of tracking the balloon across the disc of Venus yielded data on the circulation of the planet's atmosphere.

The Mars Balloon, expected to be deployed in 1996, will descend to just above the surface. Carrying an instrument package, including a camera, within a long, snake- or rope-like structure, it will rise and float when heated by the daytime sunlight, and will sink and allow the "rope" to rest on the surface at night. In this way it is hoped that the balloon package will visit many different locations pseudo-randomly as the winds carry it. In doing so, it will also yield information on atmospheric circulation patterns. The Mars Global Surveyor spacecraft carries radio relay equipment designed to relay information from the balloon-borne instrument package. The Mars Balloon was designed jointly by Russia, CNES, and The Planetary Society, a public non-profit space-interest group in Pasadena.

Sampling

One of the major advantages of having a spacecraft land on the surface of a planet is that it can take direct measurements of the soil. The several Soviet Venera landers accomplished this on the 900°C surface of Venus, and the Viking landers accomplished this on the surface of Mars. Samples are taken from the soil and transported into the spacecraft's instruments where they are analyzed for chemical composition, and the data are relayed back to Earth. The scientific community desires a robotic sample return mission from Mars sometime in the future. Several different scenarios are envisioned for accomplishing this, some of which include a rover to go around and gather up rock and soil samples to deposit inside containers aboard the return vehicle.

Sampling of cosmic dust in the vicinity of the Earth has also become an endeavor of great interest, since interplanetary dust particles can reveal some aspects of the history of solar system formation. Space shuttle experiments have so far been successful at capturing three 10 μm particles from Earth orbit, one intact. Additional attempts to capture interplanetary dust particles are planned.

Recap

1. Occultations of interest include Earth, the sun, or another star ______________________ behind a planet, or behind its rings or its atmosphere, as viewed from the spacecraft.
2. Some spacecraft are equipped with an ______________ _________________ _________________ (USO) in a temperature controlled “oven” which is capable of providing a fairly stable downlink frequency when an uplink is not available.
3. Gravity field measurements have the unique advantage of offering scientists a “view” of _____________ __________________ both at and below the surface.
4. Aerobraking is the process of decelerating by converting velocity into _____________ through friction with a planetary atmosphere.
5. A spacecraft on the surface of a planet can take ________________ measurements of the soil.

1. disappearing *2. Ultra Stable Oscillator* *3. mass distribution* *4. heat* *5. direct*

Chapter 17. Extended Operations Phase

Objectives: Upon completion of this chapter, you will be able to describe completion of primary objectives of a mission, and obtaining additional science data after their completion. You will consider how depletion of resources contributes to the end of a mission, identify resources which affect mission life, and describe logistics of closeout of a mission.

Completion of Primary Objectives

A mission's primary experimental objectives are spelled out well in advance of the spacecraft's launch. The efforts of all of the flight team members are concentrated during the life of the mission toward achieving those objectives. A measure of a mission's success is whether it has gathered enough data to complete or exceed its originally stated objectives. During the course of a mission, there may be inadvertent losses of data. In the case of an orbiter mission, the lost data can be recovered by making repeated observations of the areas of a planet where the loss was sustained when the planet rotates until the spacecraft's orbit coincides once again with areas of the surface that were missed. Such data recovery might add additional time to the portion of a mission when its primary objectives are being achieved. Major outages and their recovery may be planned for during the course of a mission, as in the case of the planet approaching superior conjunction, when the sun obstructs communications with the spacecraft for a number of days.

Additional Science Data

Once a spacecraft has completed its primary objectives, it may still be in a healthy and operable state. Since it has already undergone all the efforts involved in conception, design and construction, launch, cruise and perhaps orbit insertion, it can be very economical to operate an existing spacecraft toward accomplishing new objectives, and retrieve data over and above the initially planned objectives. This has been the case with several JPL spacecraft: it is common for a flight project to have goals in mind for extended missions to take advantage of a still-viable spacecraft in a unique location when the original funding expires.

Voyager was originally approved as a mission to Jupiter and Saturn. Voyager 2's original trajectory had been selected with the hope that the spacecraft might be healthy after a successful Saturn flyby, and that it could take advantage of that good fortune. After Voyager 1 was successful in achieving its objective of reconnaissance of the Saturnian system, including a tricky solar occultation of Titan and associated observations, Voyager 2 was not required to be used solely as a backup spacecraft to duplicate these experiments. Voyager 2's trajectory to Uranus and Neptune was preserved and executed. Approval of additional funding enabled making modifications which were necessary, both in the GDS and in the onboard flight software to continue on to Uranus and Neptune.

By the time Voyager 2 reached Uranus after a five-year cruise from Saturn, it had many new capabilities, such as increased three-axis stability, extended imaging exposure modes, image motion compensation, data compression, and new error-correction coding. In 1993, after 15 years of flight, Voyagers 1 and 2 discovered the first direct evidence of the long-sought-after heliopause. They identified a low frequency signature of solar flare material interacting with the heliopause at an estimated distance of 40 to 70 AU ahead of Voyager 1's location, which was 52 AU from the sun at the time..

The Magellan mission accomplished special stereo imaging tests, and interferometric observation tests after fulfilling its goal of mapping at least 70% of the surface. Once mapping had tallied 98%, and the low latitude gravity survey was completed, all of its original objectives had been met and exceeded. Rather than abandon the spacecraft in orbit, the Project applied funding which had been saved over the course of the primary mission to begin the adventurous Transition Experiment, pioneering the use of aerobraking to attain a nearly circular orbit.

End of Mission

Resources give out. Due to the age of their RTGs, the Pioneers 10 and 11 spacecraft are facing a need in the near future to turn off electrical heaters for the propellant lines in order to conserve electrical power for continued operation of science instruments. Doing so would allow propellant to freeze, possibly making it impossible to re-thaw for use in additional spacecraft maneuvers. This will prevent them from being kept on Earth-point.

Voyagers 1 and 2 are expected to survive until the sunlight they observe is too weak to register on their sun sensors, causing a loss of attitude reference. This is forecast to happen near the year 2015, which may or may not be after they have crossed the heliopause. Electrical energy from their RTGs may fall below a useable level about the same time. Or the spacecraft's supply of hydrazine may become depleted near the same time, making continued three-axis stabilization impossible. Pioneer 12 ran out of hydrazine propellant in 1993, and was unable to further resist the slow decay of its orbit resulting from friction with the tenuous upper atmosphere of Venus. It entered the atmosphere and burned up like a meteor after fourteen years of service.

Components wear out and fail. The Hubble Space Telescope was fitted with many new components, including new attitude-reference gyroscopes, to replace failed and failing units in late 1993. Two of Magellan's attitude-reference gyroscopes had failed prior to the start of the Transition experiment, but of course no replacement was possible. To date, a JPL mission has not been turned off because of lack of funding. But this might not continue to be the case in the future.

Once a mission has ended, the flight team personnel are disbanded, and the ground hardware is returned to the loan pool or sent into long-term storage. DSN resources are freed of contention from the mission, and the additional tracking time allocations may be available to missions currently in their prime.

While layoffs are not uncommon, many personnel from a disbanded flight team are assigned by their section management to new flight projects or other interim work. Many Viking team members joined the Voyager mission after Viking had achieved its success at Mars in the late 1970s. Many of the Voyager flight team members joined the Magellan project after Voyager's last planetary encounter ended in October 1989. Many other ex-Voyager people joined the Galileo and Topex/ Poseidon missions. Some ex-Magellan people are working on Cassini, Mars Global Surveyor, and Mars Pathfinder. Mission's end also provides a convenient time for some employees to begin their retirement.

Recap

1. A measure of a mission's success is whether it has gathered enough ____________________ to complete or exceed its originally stated objectives.
2. It can be very economical to operate an existing spacecraft toward accomplishing ______________ objectives.
3. ___ ___ ___ resources are freed of contention from the mission, and the additional tracking time allocations may be available to missions currently in their prime.

1. data 2. new 3. DSN

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