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Abstract

NASA has embarked on a program of "better, faster, cheaper" missions for solar system exploration. NASA's new direction includes a large role for private industry in building the spacecraft for these new missions. This new direction for NASA's solar system exploration program poses a challenge to spacecraft builders who have more experience to date with spacecraft for Earth orbiting missions. The objective of this paper is to provide information on the unique design aspects of spacecraft for interplanetary missions in order to benefit those with little or no experience with this type of spacecraft. Hopefully this process will enhance the probability of success and reduce the risk to NASA for these types of missions. The paper will start by illustrating a range of missions with varying scientific objectives for inner planets, outer planets, small bodies, and space physics - and then address the added spacecraft capabilities or modifications compared to Earth-orbiter designs which will make these missions possible.

This paper will describe the unique aspects of these types of missions that drive the spacecraft design process. Some issues such as Earth and Sun range are obvious, but these and other considerations also have a large impact on most other spacecraft subsystems such as propulsion, telecommunications, power, thermal and data processing. Mission issues such as lifetime and interplanetary navigation also affect the spacecraft design. The interplanetary environment (neutral, plasma, radiation and micrometeoroid) is also different than the near-Earth environment in important areas. Finally, the interplanetary launch windows (sometimes as small as 2 weeks every 2 years) drive the spacecraft design and test process in ways different than for many Earth-orbiting spacecraft.

Introduction

Spacecraft for planetary missions often are designed to support mission payloads that are substantially different from the majority of spacecraft designed for Earth orbit. While this paper draws distinctions between spacecraft for planetary missions and spacecraft designed for Earth orbit, it is sometimes a difficult distinction to make because there is a large variety of Earth orbiting spacecraft. Some Earth orbiting spacecraft have many of the mission complexities of planetary spacecraft, such as highly sensitive and complex science instruments or required mission lifetimes of up to 15 years. However the majority of Earth orbiters, especially small, low cost Earth orbiters are not required to meet the design and mission requirements of past planetary spacecraft, In many cases, NASA is counting on these small, low cost Earth orbiters to be the "vehicle" on which to implement "better, faster and cheaper" planetary missions.

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for planetary missions and spacecraft for Earth orbital missions will be different, it may not be apparent what these differences are in the details of the spacecraft design.

This paper dots not attempt to address the unique aspects of planetary spacecraft that land on other planets. Clearly these spacecraft are vastly different from the ordinary Earth orbiter. This paper dots attempt to describe the unique aspects of planetary spacecraft for flyby and orbiter missions in comparison to common Earth orbiting spacecraft.

The unique design aspects of planetary spacecraft are caused by the unique aspects of the missions they perform. The paper has two major sections based upon the mission design: 1) what the spacecraft does and 2) where the spacecraft goes. The second section is further divided into 4 subsections: 1) celestial mechanics , -2) earth to spacecraft range, 3) mission energy and 4) environment. Within each section, the spacecraft design issues are described using the standard definition of spacecraft subsystems i.e. power, propulsion, attitude control, command & data, mechanical systems, telecommunications and thermal control. Along with the unique design aspects of planetary spacecraft, this paper attempts to describe some of the unique. aspects of operating a spacecraft for a planetary mission.

I WHAT THE SPACECRAFT DOES

The operations of planetary spacecraft tend to be sharply divided between cruise and science operations (orbital operations, encounter, etc.). Parts of the spacecraft may be "off" for long periods of time, but must work when the time comes. Short encounter or flyby missions such as Voyager require extensive on board sequencing capability. Mission critical sequences (e.g. orbit insertions, one time only science opportunities) are made more reliable by extensive fault protection. Spacecraft "safe&hold" is usually insufficient to ensure a successful mission in the event of a failure at a critical time. This issue of long dormant periods followed by mission critical events influences the operations of the spacecraft from the training of personnel to the testing of the spacecraft before and after launch.

Spacecraft for planetary missions are often required to carry very sensitive magnetometers that drive the spacecraft to be "magnetically clean"] a rare (but not unheard of) requirement for Earth orbiters. The magnetically clean requirement is addressed by picking special electronic parts and propulsion components and by" shielding other parts or using compensating magnetic fields. Another approach to the "magnetically clean" requirement is to put the magnetometer on a long boom which drives the spacecraft control system design.

When a gamma ray spectrometer (GRS) is part of the payload, the materials in the space.craft must be inventoried to determine their elemental abundancies. Certain elements are excluded] so as to not swamp the signal for those elements from the target planet. Sometimes common spacecraft components used on Earth orbiting spacecraft have to be replaced by special, more expensive components designed not to use the offending elements.

Planetary spacecraft sometimes are called upon to be separable into major functional parts. The separable parts may be. atmospheric probes or landers. These separable. parts drive the mass properties of the design and therefore the control system as well as creating needs for relay antenna s/receivers not commonly required on Earth orbiting spacecraft,

11 WHERE THE SPACECRAFT GOES

Clearly the largest factor that causes spacecraft for planetary missions to be different from Earth orbiting spacecraft is the destination for planetary spacecraft. The design of spacecraft for planetary missions is driven by the following items which are dependent upon "where the spacecraft goes".

The first is celestial mechanics. or the solar system dynamics i.e., the position of the planets relative to each other and their velocity around the sun and relative to each other and how well we can predict their position and velocity.

Second, the earth to spacecraft range is enormous, usually several orders of magnitude larger than that for an Earth orbiter. The range to the Earth is a result of celestial mechanics, but deserves its own discussion because of its very substantial effect On spacecraft design.

Third, the mission energy causes the launch/injection energy and the required post-launch delta V carried by the spacecraft to be significantly larger than the majority of Earth orbiting spacecraft and also causes the trip time to the destination to be very large (measured in years).

Finally, spacecraft for planetary missions are required to operate in an environment that is, in some important measures, different from what Earth orbiters experience. The most important environmental cliff erence is the Sun range which is a nearly constant 1 AU for Earth orbiters and may be as large as 30 AU and as small as 0.02 AU for spacecraft designed for planetary missions.

11.1 Celestial Mechanics

Celestial mechanics manifests itself in several obvious ways: 1) accessibility, once injected onto the interplanetary trajectory the spacecraft cannot be acquired by the Shuttle for upgrade or repair and 2) no Earth orbiter needs to deal with superior conjunctions. A superior conjunction, where the spacecraft is behind the Sun as seen from the Earth, causes a telecommunications "blackout" for several weeks.

Perhaps not so obvious is the manner in which celestial mechanics influences the manner in which the development of a planetary spacecraft is managed with respect to schedules and timing. Celestial mechanics causes planetary missions to have rigid and infrequent launch windows where the time to the next launch window can be measured in years or decades. The pressure to "get to the launch pad" on time is enormous and drive s the entire project from the point of view of schedules and timing. Earth orbiting spacecraft certainly have schedule pressure to "get to the. launch pad" on time and failure to do so can be measured directly in terms of financial penalties. However, if an Earth orbiting spacecraft is delivered late to the launch site and misses the launch window, there is usually another launch window the next week or almost always the next month. It is an entirely different situation to have the next launch window 2 years away or more. The alignment of planets that the Voyager 2 spacecraft used occurs approximately once every 176 years. The best time to launch a spacecraft to observe Pluto's atmosphere occurs during a several year period once. every 249 years.

Because launch opportunities arc less frequent (and in some cases essentially unique), the consequences of planetary spacecraft failure may be more severe than for a typical Earth orbiter. This in turn, create. s the need for high reliability which is usually implemented via greater robustness in design (part quality, fault protection and use of redundancy).

11.2 Earth to Spacecraft Range

To understand the ranges involved, it is instructive to know that he range from the Earth to geosynchronous Earth orbit (GEO) is 0.000239 AU. A planetary spacecraft at a range of 1 AU from the Earth is already a factor of 4,188 times further away from the Earth than the, Earth orbiter at GEO. The effects of the enormous range between the spacecraft and the Earth for planetary spacecraft can be divided into the following three major areas: 1) the effects on the spacecraft to Earth telecommunications, 2) the effects of the substantial Earth to spacecraft light time and 3) spacecraft navigation.

11.2.1 Telecommunications

For telecommunications, the received power is inversely proportional to the square of the range. The power per unit area received from a GEO spacecraft is 4188 squared or 72db larger than that from the planetary spacecraft at 1 AU. This range difference causes many differences between the telecommunications design for planetary spacecraft and for Earth orbiters.

To start with, there are different frequency bands for deep space and near Earth. The receiver acquisition/tracking characteristics are unique for planetary spacecraft. Compared to typical Earth orbiters, the receiver threshold is very low, the loop bandwidth is very narrow and the received signal strength at the ground station is very low for planetary spacecraft, typically as low as -150 dbm. Because the signal strength received on the ground is so low, NASA has built special ground stations which are collectively called the Deep Space Network (DSN). The DSN is a unique, network with its own interface requirements[2], although some standardization between ground stations for Earth orbiters and the DSN is taking place. The DSN is a unique asset on an international scale. The DSN tracks planetary spacecraft from many countries besides the US. While the DSN provides the largest, most sensitive ground stations available in the world, closing the telecommunications link (both up and down) is still so difficult that the margin left in the link for planetary spacecraft is far less than the typical 10 db used on Earth orbiters. in order to minimize the loss due to high gain antenna pointing, pointing accuracies are more. stringent. Finally, the stringent requirements on the telecommunications link for planetary spacecraft has caused the development of sophisticated channel coding techniques such as Reed Solomon. Reed Solomon encoding is now also being applied to Earth orbiting spacecraft.

Even with all the items mentioned in the previous paragraph, the data rates for planetary spacecraft are usually significantly less than for Earth orbiters on both the uplink and the downlink. The low uplink rates for planetary spacecraft can preclude commanding if the spacecraft has high attitude rates caused by a mission need or a spacecraft fault. Earth orbiters have the luxury of being able to receive a command from almost any attitude due to the available power from the "close" ground stations. Conversely, planetary spacecraft usually have specific attitudes in which commands can be received.

The limited downlink data rate puts a premium on data storage, compression, and intelligent use of the downlink, e.g., detailed planning of data taking scenarios. Earth orbiters can use reliable, low-power, solid-state transmitters and omni antennas to support engineering telemetry. For planetary spacecraft, the. high-power transmitters are required for routine communications.

The limited downlink rate. also affects the manner in which the spacecraft is operated in at least the following two ways, Planetary spacecraft may transmit only a small percentage. of the data which can be collected. This generates a need to prioritize data or carefully pick observations which are expected to include the desired data e.g. which frame of a Galileo Ida pass to send down to get a useful picture. Additionally, the lower data rates reduce the engineering visibility that planetary spacecraft provides to the. ground operators relative to what is available from Earth orbiters.

Beside.s the difficulties caused by the range, telecommunications for planetary spacecraft is different from that for Earth orbiters for the following reasons: 1) sometimes the signal must travel through two atmospheres where. one is relatively unknown, 2) planetary missions may have more stringent radio metric requirements (see section 11.2,3) and 3) the spacecraft telecommunications subsystem is used with the DSN as a science instrument, which sometimes causes the addition of an Ultra Stable Oscillator (USO) on board the spacecraft.

11,2.2) Substantial Earth to Spacecraft Light Time

Missions to the planets take the spacecraft great distances from Earth. A consequence of the large spacecraft to Earth range are very long round trip communication times. Round-trip light time is as much as forty minutes for Mars and 8 hours at Pluto (30 AU). The round trip light time for an Earth orbiter is at most a few tenths of a second. The substantial round trip light time combined with certain types of mission requirements drive planetary spacecraft to be more autonomous than an Earth orbiting spacecraft in order to have similar levels of mission risk. The requirement for more autonomous capability for planetary spacecraft is most apparent in the area of fault detection and recovery.

The requirement for greater autonomy for planetary spacecraft is illustrated by considering that the time required for the ground operators of an Earth orbiting spacecraft to receive knowledge of a failure and put corrective action in place on the spacecraft is much less than for planetary spacecraft, The need for autonomous fault diagnosis and recovery on planetary spacecraft requires the designers to develop, design, and validate on board software. The additional fault protection software requires computer memory, processing power and additional telemetry data to implement.

The long round trip light time affects the manner in which planetary spacecraft are commanded. An Earth orbiter can wait for a signal from the ground before. starting to transmit its recorded telemetry; a planetary spacecraft cannot. In addition, a telecommand scheme in which receipt of one command must be acknowledged before the next is sent is clearly unacceptable for planetary spacecraft with long light times.

Besides the area of fault detection and protection and certain extreme mission requirements like landing on another planet which are beyond the scope of this paper and probably beyond the scope of the "better, faster, cheaper" planetary missions also; the autonomy requirements for planetary spacecraft and Earth orbiters may not be much different. As long as the spacecraft is controlled from the ground, the autonomy requirements are similar. Certain spacecraft designs such as stable spinners used on Pioneer Venus and Pioneers 10 and 11 are especially "easy to fly". As mentioned above, the "better, faster, cheaper" planetary missions may not be able to afford the type of mission functionality which would require the spacecraft to be very autonomous.

11,2.3 Navigation

Due to the extreme distances over which planetary spacecraft must be navigated, high accuracy radio metric data are. required. Typical accuracy requirements are a few meters for range measurements and 0.1 mm/sec for Doppler (averaged over one minute). These accuracy requirements imply the need for a wctl-calibrated coherent ranging transponder. When the target body position is highly uncertain, onboard optical measurements, consisting of images of the. target body against a star background, may also be required for navigation. 'I'his places require.mcnts on an on board imaging system for field-of-view, resolution, geometric stability, delectability of dim stars and noise characteristics; as well as telemetry rates sufficient to downlink these images in a timely manner. In some cases onboard processing of the navigation images may be required to reduce the quantity of data transmitted to Earth (as is the case for Galileo) or to reduce response time for critical events.

Navigation for planetary missions causes the spacecraft designer to pay attention to unmodeled accelerations such as those from outgassing, leakage rind uncoupled attitude control maneuvers. The spacecraft acceleration due to these forces should be kept to a few mm/sec^2. Accelerations higher than this can cause increased navigation effort and increased operations cost.

II.3 Mission Energy

Thc destinations fol planetary spacecraft arc energetically a "long way from earth". The required mission energy manifests itself both in terms of the delta **V** required for injection and after launch but also in trip time to the destination. Because the required mission energies are so large, most planetary mission trajectories are "minimum energy" trajectories. A consequence of these "minimum energy" trajectories and the vast distances are long trip times to the destination. Both the spacecraft delta V and trip time for planetary spacecraft arc larger, sometimes much larger, than the values for delta V and trip for the majority of Earth orbiting spacecraft.

The largest delta V for Earth orbiting spacecraft is normally required by a geosynchronous communication spacecraft where the delta V required to go from low Earth orbit (LEO) to GEO is about 4200 m/sec. The total delta V beyond LEO for some planetary missions is 3900 m/sec for a lunar orbiter with a trip time of about 7 days, **5700** m/sec for a Mars orbiter with a trip time of about 0.7 year; 85,000 m/sec for a Mars orbiter with a trip time. of about 40 days and 13,400 m/sec for a Neptune orbiter with a 30 year trip time-[3].Usually, part of this delta V is supplied by the launch vehicle for both the Earth orbiters and planetary spacecraft.

Several of these planetary mission have not be performed precisely because the delta V trip time combination is so large. Because of the large delta V for some planetary missions, there has been research into electric propulsion system and the use of the target body atmospheres to aid in capture at the planet i.e. "aerobraking". Both electric propulsion and aerobraking have significant influences on the design of the spacecraft which are beyond the scope of this paper.

As mentioned above the delta V requirements for both Earth orbiters and planetary spacecraft arc usually partially supplied by the launch vehicle or its upper stages. The delta V remaining for the spacecraft to perform is sometimes much reduced. Earth orbiting spacecraft normally have low delta V requirements except for geosynchronous communication spacecraft where the total delta V budget can be close to 2000 m/sec. The delta V requirements for recent and planned planetary orbiters are 2400 m/sec for' Mars observer, 2885 for Magellan, 1650 for Galileo, and 2290 for Cassini. A Comet

Rendezvous mission being planned by ESA requires about 2100 m/sec. The delta V for these planetary orbiters and the GEO communications spacecraft arc not significantly different, but the manner in which the delta V is applied during the mission causes the design of the spacecraft to be different in Some important ways which are discussed in the paragraphs below.

The long trip times are another result of the fact that planetary spacecraft destinations are energetically a "long way from earth". While some Earth orbiters have design lives as long as 15 years, the duration from their launch to start of operations is measured in weeks, whereas for some planetary missions the true mission does not start until the spacecraft has traveled to the destination, which may take years. The Mars C) server spacecraft had been traveling for nearly a year before its catastrophe. Most Earth orbiting spacecraft would be well into normal operations within a year and some would be finished with operations. The Galileo, Cassini and a Pluto fast flyby spacecraft must travel for 6, 6.6[4] and about 8[5] years respectively, before operations at their destination can begin! The Voyager 2 spacecraft traveled for 12 years before its successful encounter with Neptune.

These delta V and trip requirements cause the design of spacecraft for planetary missions to differ from Earth orbiting spacecraft in the following areas.

The large launch energies cause planetary spacecraft to be launched on the. largest launch vehicles available usually with additional upper stages. This combination of launch vehicle and upper stage(s) is rarely used for Earth orbiting spacecraft and sometimes is unique to the planetary mission, The launch vehicle/upper stage combination place launch load requirements that are at least different from those normally encountered by Earth orbiting spacecraft, although they arc not so different as to be outside the design space used by spacecraft and launch vehicle designers for coupled load analyses. in a programmatic sense, the large, expensive launch vehicle/upper stage combinations acid cost, schedule and performance uncertainty into a planetary project above those normally found in Earth orbiting missions.

The large delta V requirements and the long duration between launch and orbit insertion, where the delta V is applied; cause notable. differences in the chemical propulsion subsystems of planetary spacecraft. The primary engine used to deliver the mission delta V on a planetary spacecraft may have to operate for up to 10 hours and perform 200 cycles compared to a similar engine used on an Earth orbiter that may only need to operate for 2 hours and only 5 Cycles. For a planetary spacecraft, the propellant feed and pressurization system life requirement may be several years. Earth orbiters, such as GEO communication spacecraft, use most of their propellant during the first few weeks of the mission after which the bi-propellant main engine and pressurization system are isolated for the remainder of the mission. The long life requirement for the propellant feed and pressurization system for planetary spacecraft require careful consideration of pressurant leakage and propellant/tankage material interactions which can lead to blocked propellant lines. To reduce the probability of propellant line blockage, the Galileo spacecraft hi-propellant subsystem is used on a routine basis to reduce the accumulation of corrosion products[6]. The requirement for a long storage in space for the propulsion subsystem can drive the requirement for additional isolation between the propellants which cause additional pyro and latch valves to be used.

The lack of proper design and isolation within the hi-propellant pressurization system on the Mars Observer spacecraft is thought to be a leading cause of its failure[7].

The Magellan spacecraft orbiting Venus used a large solid rocket motor (SRM) for orbit insertion. The long duration of "storage" in space caused concern about whether the SRM would ignite and burn properly. SRMs for Earth orbiters are fired usually within days of launch. The trajectories used for some planetary missions often require large maneuvers in route. which cause the primary propulsion system to be used many times with a series of large "burns" required for orbit insertion which can occur years after launch. The expenditure of large amounts of propellant cause the spacecraft inertia properties to change dramatically as a function of mission time, which must be accommodated by the spacecraft attitude control subsystem. Due to the sensitive scientific instruments carried on planetary spacecraft, the contamination from the exhaust products of chemical propulsion engines can be a major concern. This contamination issue can influence the manner in which the engines are operated and the placement of the instruments relative to the engines. This contamination issue can also exist for Earth orbiters that carry similar types of instruments.

The planetary spacecraft thermal design and power consumption arc sometimes driven by the requirement to keep the large amounts of propellant at the appropriate temperature during the long cruise between launch and orbit insertion.

Earth orbiters achieve their final spacecraft mechanical configuration relatively early in their life. Because of the long cruise between launch and destination, many planetary spacecraft do not obtain their final configuration until many months or years into the mission. The Mars Observer spacecraft was to have deployed solar panels, the high gain antenna boom and a science instrument boom after insertion at Mars, nearly one year after launch, The Galileo and Cassini[5] spacecraft will release large probes some 6 to 7 years after launch. The Galileo high gain antenna, which failed to completely open, is an example of a mechanical actuation system used successfully on Earth orbiters which failed to work on a planetary spacecraft. (While the actual cause of the Galileo antenna failure may never be known, the speculated cause is thought to be ground handling rather than space storage.) The issue is whether mechanical actuation devices are less reliable after a long storage/soak in space. Potential design changes include redundant actuators.

The duration of planetary missions also has a large influence on the operations of the spacecraft in the following areas. With cruise such an important and lengthy part of the mission, it is usually necessary to develop an additional set of operational modes, software and procedures. For mission durations measured in decades, personnel turnover and retraining have to be addressed. This increases the importance of both spacecraft operability, so the new personnel have an easier time learning, and robustness, since on-the-job training implies on-the-job mistakes. In order to reduce peak year costs and because the trip time to the destination is so long, quite often the development of encounter command sequences is deferred until after launch. The spacecraft design must not only accommodate the new flight software, but it also must be amenable to test and trouble-shooting "on the fly". The continuing evolution of data systems technology can also have an impact when it is coupled with long mission duration. It may become necessary to change out portions of the ground system during the mission. Expertise in aging flight and ground architectures becomes harder to come by and retain. While the long durations are usually thought of as making the design of planetary spacecraft more difficult than Earth orbiters, the long cruise times do provide plenty of time to diagnose and hopefully correct any errors that occur before the primary mission begins.

The material in the previous paragraph is most applicable to very long missions. Some of the "better, faster, cheaper" planetary missions of the future will have significantly shorter durations which will be more consistent with the experience of Earth orbiting spacecraft,

11.4 Environment

The last of the subareas within "where the. spacecraft is going" that drives the spacecraft design is the environment in which the spacecraft is required to operate. Clearly the environment for planetary spacecraft is, in some important measures, very different from what Earth orbiters experience. To start with, the environment, although usually quite stable, is more uncertain than in other types of missions. Quite often one of the reasons for the mission is to learn more about the environment. Designing for a relatively unknown environment can require more analyses and margins in order to keep the mission risk level close to that for Earth orbiters. This discussion of how the environment affects the design of planetary spacecraft is divided into: 1) the effects from space radiation, 2) the effects from solid particles 3) the effects of the Sun range being different than 1 AU and 4) the lack of the Earth being present.

11.4,1 Space Radiation

In general, space radiation environments can be conveniently divided into: planetary trapped radiation, galactic cosmic radiation, and solar energetic particles.

Except for a relatively swift passage through them, the Earth's trapped radiation belts have little effect on interplanetary spacecraft design. However, other planetary radiation belts can pose a serious threat to planetary spacecraft. The radiation environment around Jupiter is particularly severe, and JPL experience has shown that even relatively brief passages through the Jovian environment (for example, during gravity assists) can dominate the total mission dose. Heavy ion fluxes are also sufficiently intense to disrupt spacecraft critical mission functions during such operations due to single event effects (SEE).

Galactic cosmic radiation (GCR) is composed of high energy nuclei believed to propagate throughout all space unoccupied by dense matter, The Earth's magnetic field provides some shielding against this radiation for spacecraft in low to medium Earth orbits. Even so, the radiation flux associated with GCR in interplanetary space is low and does not contribute significantly to mission total ionizing dose, but sufficient heavy ions are present in the GCR populations to create a SEE threat to some electronic parts throughout the mission.

Solar energetic particles arc also attenuated by the Earth's magnetic field, and in interplanetary space, fluxes due to a given solar event may be 2-3 times more intense than near the Earth and present both a total dose and SEE threat. Solar event fluences fall off as the inverse square of the heliocentric distance outside the Earth's orbit, so this effect is mitigated for direct trajectories to the outer planets, But particle fluences are considered to obey an inverse cubed law inside 1 AU and, for plane.tary spacecraft destined for Venus or Mere ury, the hazards due to solar event radiation may be vastly increased. In the. extreme case. of a spacecraft performing a close solar passage (i. e., within a few radii of the Sun) a single moderate sized solar event can incapacitate the spacecraft.

11.4.2 Solid Particles

The solid particle hazard for interplanetary missions comes from two *sources:* micrometeoroids (particles in orbit around the Sun) and dust (particles in orbit around another solar system body). Artificial debris is encountered only in the immediate post-launch phase of the mission. Particle fluxes are low in interplanetary space, but encounter velocities tend to be very high (-15-50 km/s) and, thus, very damaging. Encounter velocities with dust particles depend upon the nature of the encounter. That is, encounter velocities for Cassini with Saturn ring particles (since Cassini goes into orbit and does not pass Saturn high speed as it would for gravity assist) will be much lower than encounter velocities for Voyager.

11.4.3 Sun Range

The solar range affects the power and thermal control subsystems. Not only is the range to the Sun not 1 AU, but the range to the Sun can have large variations during the mission. This is especially true for missions like Cassini and Galileo which go into Venus and then out to the outer planets. The Cassini spacecraft is being designed[8] to accommodate a Sun range that varies from 0.61 to 10.07 AU. Even a Mars orbiter must accommodate a factor of 3 change in solar intensity. A Mercury orbiter will have to contend with 1 Sun near Earth and at Mercury, 11 Suns (of short wave IR) on one side of the spacecraft and 9 suns (of long wave IR from the planet's surface) on the other side. A few hours later the spacecraft will be in solar eclipse.

Earth orbiters have the "in Sun" and "in eclipse" design points, while the planetary orbiter has the "in eclipse" and an "in Sun" condition that may vary dramatically over the course of the mission. At a minimum, more thermal analyses and testing may be required in order to confidently span the mission design space for a planetary mission. Not only may additional analyses and testing be required, but for those missions going to less than 1 AU the set of thermal control materials and paints available for use may be more limited, and/or entirely new materials may need to be developed.

Besides the thermal control subsystem, the power subsystem is greatly affected by the Sun range encountered by a planetary spacecraft. The effects on the power subsystem arc directly opposite, depending upon whether the mission destination is less than or greater than 1 AU. Spacecraft going to the inner planets have the problem of power increasing with mission time up to some point where typical solar cells developed for Earth orbiters are no longer usable without special coatings, or not usable at all.

Spacecraft going to the outer planets have the problem of power decreasing with mission time up to some point where typical solar cells developed for Earth orbiters are no longer usable. These missions sometimes must invest in solar cells that can operate at very low solar intensities, i.e., the so called "low intensity, low temperature" (1.11."1') solar cells. The spacecraft for these missions usually invest design time or development dollars into consuming as little power as possible via design and operational approache s, or development of power efficient technologies. Solar powered spacecraft going beyond 1AU have the problem of more power than they need close to Earth. The Mars observer spacecraft was deliberately pointed off the Sun during cruise and had 2 of 6 panels undeployed in order to deal with an excess of power near Earth. Of course another approach would have been to produce the power and then shunt it and radiate the excess.

A CO1II1I1O11 design challenge for the planetary spacecraft whose destination is greater than 1 AU is the fact that the spacecraft tends to cool during the mission unless steps are taken to decrease heat loss or provide "make up" heat, both a function of mission time. And, of course, for solar powered spacecraft the. power per unit area of solar array is decreasing at the same rate as is the demand for "make up" heat from heaters is increasing.

Some planetary spacecraft do not use solar arrays at all. Some missions going to the outer planets find it beneficial to switch to Radioisotope Thermoelectric Generators (RTGs) for electric power production The decision to use RTGs or solar arrays or a combination of the two or other power sources for missions to the outer planets depends upon the mission (where it is going and for how long), the state of readiness of the various power source options, the acceptable level of mission risk and the amount of resources (time and dollars) that are available to the mission.

once a mission has chosen to use RTGs, the spacecraft design changes in many ways compared to that of Earth orbiters. Although RTGs have been used on Earth orbiters, it was about 20 years ago in a time period when nuclear safety was much less of an issue than now. The addition of RTGs to a spacecraft cause the following design issues to demand attention. A new radiation environment must be accommodated. Although gammas and neutrons from RTGs pose no single event effects (SEE) threat, they contribute a major part of the total dose to nearby electronic components. These radiation forms are considered "unshieldable" in the sense that no amount of shielding that would be practical on a spacecraft is sufficient to be effective against these particles. Often some of the science instruments can be "blinded" by the warm RTG, and a RTG shade is required. Sometimes a cooling system must be included in order to keep the spacecraft from overheating once enclosed in the launch vehicle. The RTG will probably be required to be conductively isolated from the rest of the spacecraft unless, the designer tries to make use of the RTG waste heat to keep the spacecraft warm, which is a good idea but makes the thermal design of the spacecraft much more complicated than that of an ordinary Earth orbiter.

Besides the very real and sometimes expensive technical design issues that need to be dealt with when using RTGs, there are also real and potentially expensive (measured in millions) environmental and safety design issues. These issues are embodied in two separate, distinct processes: the National Environmental Policy Act (NEPA) compliance process, and the launch approval process dictated by Presidential Directive/NSC-25. NEPA requires an Environmental Assessment or Environmental Impact statement be prepared and released for public comment prior to new start for each NASA flight project. A mission using Radioisotope Heater Units (RHUs) or RTGs must consider the potential radiological risk of these power sources in the EIS (or an EA to determine if any accident scenarios involving radiological releases arc. possible, in which case an EIS could be required). For those planetary missions that use an Earth gravity assist, the EIS must include serious consideration of the probability and consequences of an inadvertent Earth reentry. PD/NSC-25 requires an interagency safety analysis process that concludes with Presidential approval to launch the mission with the nuclear power source.

Because of the difficu ties and expense of the using RTGs, the proposed Discovery program[9] of small planetary missions excludes the use of RTGs on spacecraft proposed for Discovery missions. Even on missions to the far outer planets, such as the proposed Pluto Fast Flyby, there are suggested approaches for performing the mission without an RTG. These design approaches include essentially turning the spacecraft "off" during large. fractions of the cruise phase. and using chemical energy for the relatively high power, short duration encounter phase.

11.4.4 Absence of the Earth

The fact that planetary spacecraft do not orbit around the Earth, affects the attitude. control subsystem greatly. Without a horizon, horizon sensors cannot be used for attitude reference. For orbiters around other planets, horizon sensors designed for Earth need to be modified to accommodate a different atmosphere or the lack of an atmosphere. GPS receivers cannot be used for orbit or attitude information. Without the Earth to use as an attitude reference, planetary spacecraft become highly dependent on celestial sensors and celestial attitude determination. Without a well characterized, adequately strong magnetic field, magnetic torque rods cannot be used for attitude maneuvers or to desatuate momentum wheels, and the magnetic field cannot be used as an attitude reference. While planetary spacecraft may be sent to orbit planets that have a magnetic field, it is usually the case that the magnetic field is not known well enough to usc for attitude determination and control purposes. A final item that can make the design of planetary spacecraft easier than that of Earth orbiters is that planetary spacecraft (as far as we know) do not need to contend with the atomic oxygen found in low Earth orbit.

Summary and Conclusion

The unique aspects of spacecraft for planetary missions are caused by the unique missions which they are called upon to perform. Some of the unique aspects of planetary spacecraft are due to what the spacecraft is doing, But for ordinary flyby and orbiter missions the differences between Earth orbiters and planetary spacecraft are not so large. In the cost constrained environment of the present and foreseeable future, what the spacecraft is called upon to do will not be so much different than what Earth orbiters do. However, where the spacecraft goes will continue to cause spacecraft for planetary missions to have several significant differences compared to Earth orbiters. These differences arc summarized in table 1. The large Earth to spacecraft range for planetary missions drives the telecommunications subsystem and navigation function to have unique aspects. The large Earth range causes the round trip light time to be long which drives the fault detection and recovery design for planetary spacecraft. Large mission energies cause planetary spacecraft to be launched on sometimes unique launch vehicles and to have very long cruise durations and to perform their primary propulsion functions and achieve their final mechanical configurations years after launch. The environment in which the planetary spacecraft operate.s has some unique aspects different from what Earth orbiters experience in the area of space radiation. But the primarily environmental difference is the Sun range which causes some planetary spacecraft to be required to go to the extreme of using nuclear power sources.

After all the analysis, and while there are important differences between Earth orbiting spacecraft and planetary spacecraft, they are still more alike than different for simple flyby and orbiter missions. If NASA is to be successful in implementing its vision of "better, faster, cheaper" planetary missions, then the builders of Earth orbiting spacecraft will have to pay attention to the unique aspects of planetary spacecraft while still producing small, reliable, low cost spacecraft. We hope that this paper will be contribute to the success of those missions,

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TABLE 1 COMPARISON OF EARTH AND 1'I.ANMTAR% SPACECRAFT

EARTH ORBITING SPACECRAFT	PLANETARY SPACECRAFT
Some Launch Window Flexibility	Fixed Planetary Launch Window
Many Missions	Some Unique Mission Aspects
Well Known Celestial Mechanics	Some Unique Celestial Mechanics
Small Earth Range	Enormous Earth Range
Well Known Telecommunications	Unique Telecommunications
No Significant Round Trip Light Time	Round Trip light Time Measured in Hours
Fault Protection Reliant On Ground System	Fault Protection Requires Autonomy Due To Substantial Light Time
Well Known Navigation	Some Unique Navigation Aspects
Standard Launch Vehicles	Some Unique Launch Vehicles
Mission Delta V Above LEO <- 4200 m/sec	Mission Delta V Above LEO Up To -10000 m/sec
Short Cruise Duration To Destination	Long Cruise Duration To Destination
Major Propulsion Events Early	Major Propulsion Events Late
Final Deployments Early	Final Deployments late
Well Known Radiation Environment	Some Unique Radiation Environment

Temperature Control - Solar Input 1 Au Except For Occultations	Solar Flux Varies Significantly - Dependent On Planet
Solar Power Always Available	Nuclear Power Sometimes Required
Attitude References - Horizon Scanners Are Always Available On Earth Orbiters	Horizon Scanners Only Available After Insertion In Planetary Orbit, Must Rely On Sun And Star References During Cruise
Well Known, Usable Magnetic Field	No or Unusable Magnetic Field