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Janus and Lunar Trailblazer: Lockheed Martin Deep Space SmallSats for NASA SIMPLEx Missions

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ABSTRACT

NASA's Small Innovative Missions for Planetary Exploration (SIMPLEx) program is a principal investigator-led planetary science program focusing on small spacecraft. In the SIMPLEx-2 opportunity, the cost cap for SIMPLEx missions is approximately 1/10th the cost of the next larger class of planetary exploration missions, the Discovery Program. Unlike Discovery missions, SIMPLEx missions launch as rideshare payloads with other NASA primary missions. Lockheed Martin has developed a science-capable deep space small spacecraft architecture to support two missions selected for the SIMPLEx-2 opportunity: Janus and Lunar Trailblazer. Janus is a two-spacecraft mission to fly by two different binary Near Earth Asteroids, partnered with Dr. Dan Scheeres at the University of Colorado Boulder. Lunar Trailblazer is a lunar orbiter led by Dr Bethany Ehlmann at Caltech which will map water on the Moon; both have passed PDR and are confirmed for flight. Janus will launch first, in August 2022. A scalable suite of hardware subsystems enables the same low-cost spacecraft architecture to support both missions with a high degree of commonality, despite their disparate mission designs, environments, physical configuration, and science operations. As both missions move through project implementation, the management and engineering teams have learned valuable lessons for developing deep space-capable small spacecraft, adapting from both Earth-orbiting SmallSats and traditional larger planetary exploration missions in the Discovery and New Frontiers program classes. Key lessons learned include the value of early and close coordination between interested science teams and spacecraft providers, the need to tailor the complexity of science investigations to SmallSat spacecraft capabilities, the importance of evaluating component lifetimes against the deep space mission environment, and the challenge of planetary mission design to a rideshare launch. Rideshare missions on planetary launches must meet schedules determined by primary spacecraft with inexorable planetary launch windows and must provide enough propulsion to reach their own destinations which may include planetary orbit insertion or targeting a completely different solar system destination than the primary spacecraft.

INTRODUCTION

Small, low-cost spacecraft are widespread in Low Earth Orbit (LEO) applications and taking on increasingly ambitious missions. The combination of increasing SmallSat capability with the prospect of more frequent, inexpensive launches has led to interest among the planetary science community in executing deep space science missions with small, inexpensive spacecraft. The solar system has thousands of planets, moons, asteroids, comets, and other potential destinations but available budgets support very few flight opportunities. Low-cost missions offer the opportunity to visit scientifically interesting destinations which would otherwise not be explored, or fly instruments to answer questions which would not otherwise be addressed – even if the individual spacecraft and instruments are less capable than a traditional mission.

Compared to small LEO spacecraft, small planetary missions face challenges with small solar arrays often operating farther from the Sun, small antennas transmitting across vastly greater distances, small optical apertures, and small propulsion systems facing much larger ΔV needs. The first mission to apply modern LEO SmallSat components and design practices to planetary missions was JPL's groundbreaking MarCO technology demonstration mission in 2018.[1,2] MarCO proved that two inexpensive 6U CubeSats could successfully operate in deep space, and flight qualified key hardware such as the Iris deep space transponder that has been baselined for subsequent missions. However, MarCO did not carry science instruments or perform significant maneuvers. Several 6U spacecraft on NASA's upcoming Artemis 1 launch will attempt to maneuver into lunar orbit or fly by asteroids, and some will carry science instruments, but many of these CubeSats are still technology demonstrations.[3]

NASA interest in funding competed, principal investigator (PI)-led deep space SmallSat missions in the style of the Discovery and New Frontiers programs appeared in the Planetary Science Deep Space SmallSat (PSDS3) study, which funded 19 studies of missions with widely ranging science goals in 2017.[4] PSDS3 awardees examined SmallSat and CubeSat missions with mass ≤180 kg and notional program budgets of $100 million. The PSDS3 study fed into NASA Science Mission Directorate’s strategy development for SmallSats and rideshare missions. In 2018, NASA SMD released the SIMPLEx-2 announcement of opportunity (AO), soliciting PI-led proposals for rideshare SmallSat missions at a cost cap of $55 million.[5] This is an order of magnitude smaller than the recent cost caps on Discovery missions, which was previously the least expensive class of planetary science missions. (Note that, for the remainder of this paper, we will use “SIMPLEx” to refer to missions meeting the expectations and guidelines established in the SIMPLEx-2 solicitation.) NASA selected three missions under this opportunity for a one-year Phase A/B development to Preliminary Design Review (PDR) and potential selection for flight: EscaPADE, Janus, and Lunar Trailblazer. Janus and Lunar Trailblazer have since passed their NASA confirmation reviews. These are operational science missions and expected to produce science results in line with Planetary Science Decadal Survey science goals; however, SIMPLEx missions are NASA Risk Class D by definition, allowing greater risk acceptance and limited technology development. Note that, because deep space missions may have necessarily long interplanetary cruises, SIMPLEx mission lifetimes may exceed the 2 year lifetime guidelines for Class D stated in NPR 8705.4.[6]

The European Space Agency (ESA) is also developing deep space science SmallSats, and selected the APEX and Juventas CubeSats to accompany the larger Hera mission.[7,8] An important distinction between these CubeSats and NASA SIMPLEx missions is that Hera will deploy both APEX and Juventas *in situ* at the Didymos system, while SIMPLEx missions launch as rideshares but are otherwise independent from their prime missions. SIMPLEx-class spacecraft must maneuver to their destination and communicate with Earth using only their SmallSat subsystems on a non-interference basis with the primary payload.

LOCKHEED MARTIN SIMPLEX MISSIONS

Lockheed Martin is applying our experience developing planetary spacecraft to two of the NASA SIMPLEx missions, Janus and Lunar Trailblazer, totaling three spacecraft. Lockheed Martin has been building planetary spacecraft since the Viking landers of the 1970s. Working with NASA and JPL, Lockheed Martin has helped send planetary missions across the solar system, some of which are shown in Figure 1. By a <500 kg definition, several of these missions were SmallSats, including the 300 kg Lunar Prospector mission which had a budget only about twice the SIMPLEx cost cap once adjusted for inflation.

Figure 1: Lockheed Martin has designed, built, and/or operated dozens of planetary spacecraft in collaboration with NASA and JPL and brings that experience to development of planetary SmallSats.

The same planetary exploration organization within Lockheed Martin that developed spacecraft like the GRAIL lunar orbiters and Phoenix and InSight Mars landers is developing the Janus and Lunar Trailblazer deep space SmallSats. The team also incorporates commercial practices from the LM2100 and LM1000 satellite product lines, and has experience with commodity CubeSats through the Lockheed Martin-funded LunIR spacecraft that will launch on Artemis 1. Lockheed Martin also operates deep space spacecraft after launch from our Mission Support Area. The LM Mission Operations team is currently flying six planetary missions for NASA. Including experienced spacecraft operators in the development teams helps to design for operability from the beginning. Sharing operations staff across multiple missions reduces the cost to operate long missions.

Both Janus and Lunar Trailblazer spacecraft include subsystems from commercial SmallSat industry vendors. Modular and scalable product lines from the SmallSat community enable a high degree of interface and software commonality between the two missions despite their differences, which reduces cost and schedule. This integration approach is similar to a Discovery or New Frontiers mission, except that the SmallSat vendor base is structured more around subsystems than around individual components.

Meeting schedule milestones is paramount for deep space mission development. This has been more challenging than usual for Janus and Lunar Trailblazer because they are being developed during the COVID-19 pandemic, requiring mitigation protocols such as mostly remote work including program reviews. Nevertheless, both programs are on schedule, demonstrating the teams' resiliency and flexibility in support of planetary missions.

An experienced team, established facilities, a design based on flight-proven subsystems, and the ability to share resources across multiple programs help enable capable deep space SmallSat missions.

JANUS

Janus is a reconnaissance mission to near-Earth binary asteroids. Two independent but identical spacecraft will each fly by a different binary asteroid system and image the primary and secondary bodies with a visible and an IR camera. The target systems, 175706 (1996 FG3) and 35107 (1991 VH), represent different stages in the life cycle of binary asteroids.[9] Janus will achieve foundational science on the formation and evolution of microgravity aggregates, one of the most numerous types of objects in the solar system. The principal investigator for Janus is Dr. Daniel Scheeres at the University of Colorado. In addition to building the Janus spacecraft, Lockheed Martin Space also manages the Janus mission. The Janus mission concept drew from the Ross CubeSat mission in the PSDS3 study.[10] Janus is confirmed for launch and completed Critical Design Review (CDR) in March 2021.

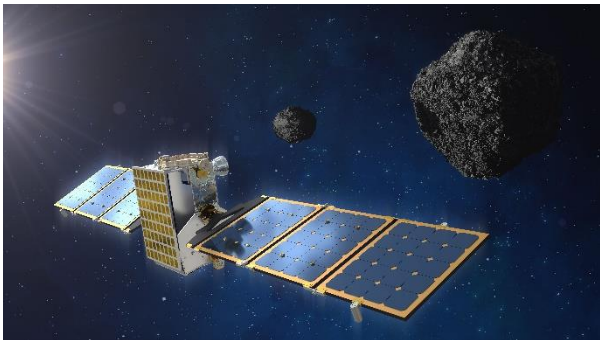


Figure 2: One of the two Janus spacecraft encountering an unexplored binary asteroid

Mission Design

The Janus spacecraft will launch on a Falcon Heavy as secondary payloads with NASA's Psyche mission in August 2022.[11] After initial acquisition, the spacecraft execute deep space maneuvers with electric propulsion thrusters, targeting two asteroid flybys in spring 2026. These thrusters also provide trajectory correction maneuvers and reaction wheel desaturation throughout the mission.

Janus has a nearly four year interplanetary cruise. The spacecraft operate independently from each other. The spacecraft traverse Sun ranges from 1.0 to 1.6 AU, and reach a maximum range from Earth of 2.4 AU. During the cruise there is an approximately 140 day conjunction when the Sun is between the spacecraft and Earth, limiting communication. After cruise, the asteroid encounters take place at a Sun range of 1.24-1.42 AU and Earth range of 0.3-0.6 or 1.1-1.6 AU, with flyby speeds in the 3-5.5 km/s range depending on launch date.

Spacecraft and Instruments

The Janus spacecraft are identical, with a mass of 40 kg, and occupy less than one quarter of the ESPA launch volume allocation each. They deploy from the ESPA ring interface using 8 inch Lightband separation systems. The mass, volume, and launch allocations result from a combination of factors. First, SIMPLEx-2 program requirements limited the total mission mass to 180 kg, even for multiple-spacecraft missions. Second, limiting per-spacecraft mass helps to meet the ΔV needs of the mission. Third, the power and communications needs of this deep space mission were best achieved with an antenna and solar array that did not fit within a 12U CubeSat dispenser. However, for a mission with different power, communications, and propulsion needs, the same core avionics components could fit within a CubeSat-standard envelope.

The avionics are aligned to the Class D designation of SIMPLEx missions, with software fault protections designed to trap and recover from faults in any subsystem. Major subsystems consist of commercially procured components from the SmallSat supplier community. While the target environment for many of these commercial components is Earth orbit, we evaluated and selected them on performance metrics relevant to the Janus mission environment. The spacecraft communicate back to Earth using an Iris Transponder and a high-gain patch antenna mounted to the spacecraft body.[12] The integration and test campaign, flight software, fault protection architecture, autonomy and sequencing, and command and telemetry interface draw extensively from the baseline of Lockheed Martin Discovery and New Frontier missions.

Each spacecraft carries an identical instrument suite from Malin Space Science Systems: an ECAM visible camera based on the engineering cameras on the OSIRIS-REx and Lucy missions and an infrared microbolometer.[13] To compensate for potential navigation and ephemeris errors – in both spacecraft tracking and the uncertainty in asteroid orbit – the spacecraft flight software will process images in real time to track the asteroids during flyby. The combination of closed-loop pointing and the low moment of inertia of small spacecraft allows Janus to fly closer to the asteroids and slew at high rates to view them from different angles during flyby. As a result, Janus will provide higher resolution images than past flybys despite its small size. This approach to spacecraft pointing during the asteroid encounter makes use of significant development for the Discovery-class Lucy mission,[14] an example of enabling synergy between traditional NASA programs and the 10x lower cost SIMPLEx program.

LUNAR TRAILBLAZER

Lunar Trailblazer will orbit the Moon to map the form, abundance, and distribution of water on the lunar surface.[15] This data will have consequences for both lunar science and human exploration. The principal investigator for Lunar Trailblazer is Dr. Bethany Ehlmann at Caltech. JPL manages the Lunar Trailblazer mission. Lunar Trailblazer is also confirmed for flight.

Figure 3: Lunar Trailblazer will map water concentrations on the Moon

Mission Design

Lunar Trailblazer is presently baselined to launch as a secondary payload with the IMAP mission to Sun-Earth L1 in 2025. The propulsion system on Lunar Trailblazer is a monopropellant hydrazine system producing approximately 1 km/s of ΔV. This propulsion system is similar to that on the two GRAIL spacecraft.[16] After deployment from its rideshare launch, the Lunar Trailblazer spacecraft will divert onto a 4-6 month-long cruise taking it to the Moon. It will then insert into lunar polar orbit and perform period reduction maneuvers to achieve science altitude of 100 km. Once in its science orbit, Lunar Trailblazer will conduct a mapping mission of at least one year.

Although electric propulsion technologies offer significantly more propellant mass efficiency at the thruster level, the higher thrust of chemical propulsion allowed a lower total ΔV budget for a mission design to insert into lunar orbit. At the mission level, therefore, including both spacecraft and trajectory design, this is a case where chemical propulsion is overall more mass-efficient than electric propulsion, enabling a spacecraft design that falls within rideshare mass limits. A chemical propulsion system also enables a much faster transfer into lunar orbit, reducing the overall mission duration and therefore the lifetime that components must support. The hydrazine propulsion capability available in the GRAIL and Lunar Trailblazer class can enable SIMPLEx-class spacecraft to reach many other science destinations, as well.

Spacecraft and Instruments

Lunar Trailblazer is approximately 180 kg with launch accommodation on an ESPA Grande. The Lunar Trailblazer spacecraft shares many subsystems and components in common with the Janus spacecraft, sometimes at a larger size in vendors' product lines. The most readily apparent difference in spacecraft design is the propulsion system, which is derived from the hydrazine main engine and warm gas attitude control propulsion system on the 300 kg GRAIL spacecraft. This propulsion system readily scales to both larger and smaller sizes by exchanging the propellant tank size, and the main engine is already well-qualified to the necessary throughput as an attitude control thruster for larger spacecraft. While hydrazine introduces some safety process and procedures on the ground, Lockheed Martin has extensive experience with handling of hydrazine as well as the necessary infrastructure for launch site processing that allows us to safely integrate rideshare spacecraft which have hydrazine propulsion.

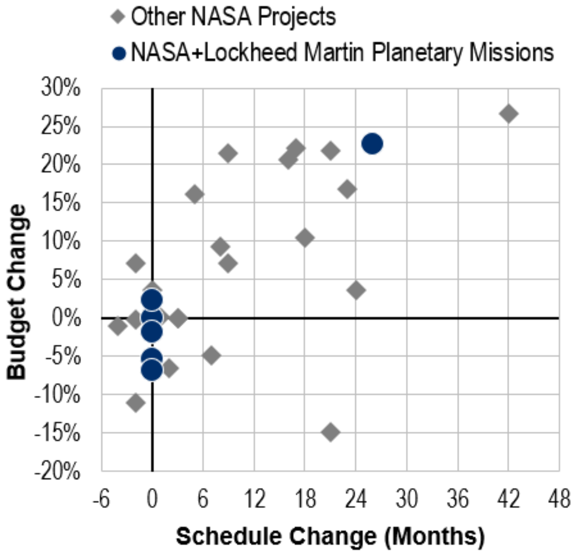
The spacecraft accommodates approximately 20 kg of pushbroom infrared instruments: the High Resolution Volatiles and Minerals Moon Mapper (HVM3) visible/shortwave infrared imaging spectrometer derived from the M3 instrument,[17] and the Lunar Thermal Mapper multispectral thermal infrared imager.[18]

CHALLENGES OF DEEP SPACE SMALLSAT IMPLEMENTATION

Our experience in the PSDS3 study and in implementing SIMPLEx missions has highlighted several of the challenges inherent in implementing deep space SmallSat missions. Although some of these challenges are present on any deep space mission, SmallSat programs may see increased effects due to their reduced spacecraft resources, smaller budgets, and smaller teams.

Program Schedule

Programs targeting interplanetary launches must maintain schedule to meet launch dates determined by the motion of Earth, the destination, and any gravity assist target around the solar system. The schedule pressure is even more intense for secondary payloads, because the primary mission determines the schedule, and if the secondary misses the launch there is unlikely to be any similar launch opportunity to fall back on. For rideshare missions like SIMPLEx, which NASA solicits after selecting the primary mission, the total program schedule is compressed, magnifying the importance of meeting milestone dates during development. This is significantly different from the more relaxed schedule pressures for Earth orbiting missions, whose launch opportunities are physically feasible on almost any day with multiple similar rideshare opportunities per year. Optimistic or unspecific schedules suffering slips of weeks or months are common but have little effect on the mission or spacecraft design in Earth orbit. A dramatic demonstration of the schedule pressures involved in deep space mission design is the OSIRIS-REx mission, which is on track to end with its Sample Return Capsule landing on Earth on 24 September 2023,[19] within hours of the schedule from the original mission proposal in 2009. Throughout its life cycle, the OSIRIS-REx program had to successfully meet key mission dates defined well in advance of NASA's selection of the mission. A beneficial side effect of this punctuality is that planetary missions typically meet their budget as well. Government Accountability Office (GAO) annual reports on NASA project performance during 2009-2021 show five of six planetary missions in which Lockheed Martin had a major role met their original schedule and budget targets (Figure 4). The exception was InSight, which was delivered to the launch site on schedule but delayed by instrument development issues.[20]



Project schedule and budget performance at completion, 2009-2021, from GAO annual *NASA: Assessments of Selected Large-Scale Projects* reports

Figure 4: Planetary missions have a strong track record of launching on schedule

Mission Design

Interplanetary spacecraft launching as rideshares often need high ΔV capability for orbit insertion or if their destination is different from the primary mission on their launch. Unlike the MarCO CubeSats, which shared the same destination (Mars) as the InSight lander and required only minor trajectory correction maneuvers, a spacecraft going to a different planetary body must execute deep space maneuvers, target planetary flybys, and/or insert into orbit at the destination. Another aspect of a rideshare launch that can drive ΔV capability – and therefore spacecraft design – is the need to absorb changes in the interplanetary target launch state vector and launch dates driven by the primary mission as it matures. For SIMPLEx-2, the primary mission, launch provider, and NASA Launch Services Program (which procures and manages the launch) have all been generous and accommodating of the secondary payloads. But, in any launch, secondary payloads are inherently subordinate to the needs of the primary.

High ΔV requirements lead directly to a need for thruster qualification to high propellant throughput levels compared to a LEO mission. Such propulsion systems are readily available for larger or more expensive spacecraft. The SmallSat industry is developing many innovative and low-cost propulsion systems for LEO applications that are attractive for small deep space missions, but either not capable of, or designed to but not tested to the necessary lifetime. This is particularly an issue with electric propulsion systems that need thousands of hours of firing time in a qualification campaign to verify the needed throughput. Products developed for LEO constellations are often not qualified to these throughputs or firing durations. The dearth of mature, affordable, high-throughput propulsion systems for SmallSats has been one of the major development challenges for low-cost planetary missions to date.

Science Instruments

On a mission that balances SmallSat capabilities against a demanding deep space environment, it is important to carefully focus on compelling science investigations that can be achieved within the capabilities of SmallSat missions. It is particularly important for a science team to work with the spacecraft provider during the early proposal formulation stage, as that lays the groundwork for all subsequent architecture development. Some instruments may have more complex accommodations that can drive spacecraft system design, such as power for active cooling or thermal management. Lockheed Martin has a long track record of working with science and instrument teams to help realize achievable science missions, and can advise whether a science mission is a good fit for SIMPLEx or more suited to a larger class like Discovery.

The volume and surface area accommodations of a SmallSat, limited by ESPA standards or CubeSat dispensers, are sometimes more constraining than mass limits. The stowed volume of any deployables, including solar arrays, antennas, and instruments, in addition to propellant tanks, quickly consume available volume. Available spacecraft surface area can also be limiting for thermal reasons, especially when instruments include high-power components.

SmallSat Component Supplier Capabilities

Much early concept development relies on vendor-provided datasheets. For some vendors, capabilities listed on datasheets may be design intent, or even aspirational values rather than verified performance, meaning that a program must maintain robust margins and consider performance acceptance testing, as documented by the Dellingr CubeSat team.[21] Given the year-to-year design iteration that is common in the SmallSat supplier base, selecting components from robust product lines, with an ability to trace a clear design heritage to previously proven components, can be important. Understanding component heritage is a particular challenge in developing a deep space SmallSat mission, as it can be difficult to get information about the on-orbit performance and demonstrated lifetime of a component when suppliers often do not know when their customer spacecraft will launch, how long they operate, or if they fail. The rapid advancement of some SmallSat technologies and products from breadboard demo (TRL ~4-5) to launch (TRL ~7-9) – sometimes skipping extensive ground test campaigns (TRL ~5-8) entirely – can further confound technical review expectations and qualification program planning. This is especially true for SmallSat propulsion systems, which are a relatively new market area compared to other subsystems but must be qualified to high capability for deep space missions. For a component to trade well as an option on a deep space mission, it can important to have a clear qualification or flight operation dataset, regardless of whether the component has been launched on a spacecraft.

Component lifetime is a critical performance measure for a deep space spacecraft, especially because there may be a long interplanetary cruise between launch and the science destination where mission success events take place. Janus spacecraft, for example, have a 42-44 month cruise between launch and the asteroid flybys; components must operate successfully throughout this cruise before the science investigation even begins. It is important to understand what factors drive lifetime in a deep space environment; in LEO, component suppliers often use total radiation dose (TiD) as a surrogate for lifetime, but in deep space far from the Earth, radiation accumulation must be considered in conjunction with other factors like single-event effects or life-limiting cycles. It is therefore helpful to have qualification data for candidate components on a range of life and cycle metrics, for comparison against a mission environment.

Spacecraft Systems

Commercial commodity spacecraft available for the LEO spacecraft market do not offer the required capability for many deep space missions. A commodity bus designed for LEO is optimized for different criteria than are relevant for a deep space mission; for example, batteries are designed for many eclipses per day rather than multiyear storage at deep space flight temperatures, radios are designed for high rather than low data rates, solar arrays and power management systems assume a constant 1 AU Sun distance, and attitude control systems include magnetorquers for momentum management and GPS receivers for position which do not work in interplanetary space. Compounding this problem is the fact that not only do interplanetary missions have to meet very different design drivers from Earth orbiting missions, but they also may have very different design drivers from each other as they visit different destinations across the solar system, experiencing different power and thermal environments with different maneuver designs, and incorporating different instruments with unique interfaces and accommodation needs. In addition, while many constellation operators and spacecraft providers have successfully adopted a launch-and-learn philosophy to design iteration,[22] interplanetary science missions have far fewer opportunities to replenish the mission with an improved iteration of the spacecraft. The infrequency of launches and mission-specific environments necessitate an investment in up-front systems engineering effort for the mission, as well as integrated system testing in mission-specific operating modes, all of which may represent large cost risks to a project attempting to use a commodity spacecraft as-is on a deep space mission. Evaluating all these factors in a mission context, especially early in a program, is critical to deep space mission success.

The variation in Sun ranges an interplanetary spacecraft encounters over its entire mission may drive the architecture of the electrical power system. Commercially available solar array power systems therefore do not produce the same amount of power across a varying Sun range, and so mission design may size a power system more than payload needs do. This is especially true for electric propulsion missions. Thermal system design is also an important Sun-range-dependent factor in sizing the power system.

Communications systems have a different set of design pressures on deep space missions compared to Earth orbiting missions. The clearest example is that the need to transmit a signal across ranges hundreds of millions of km from Earth drives the system to high frequency but low data rates, while communications system technology development is often focused on high data rate for large data volume missions in Earth orbit. In addition, deep space communication systems must have high receive sensitivity, support ranging for navigation, and usually must be compatible with the Deep Space Network and associated ground systems. Few commercial transceiver options are available that meet these criteria. Communications system technologies to help close a link from long distance, such as solid-state power amplifiers or deployable antennas, introduce many system-level effects in power, thermal, and volume that must be included in the early spacecraft design.

Spacecraft flight software must have significant onboard autonomy capabilities for a deep space mission. During interplanetary cruise, spacecraft must be able to operate safely while out of contact with the Earth for long durations. Janus, for example, has a ~140 day solar conjunction during which communication with the spacecraft is not possible. Software must also give the spacecraft the ability to complete some critical maneuvers at a defined point in space relative to planetary bodies, even if there is a failure in a spacecraft component that would otherwise trigger safe mode entry. In addition, flight software must have a robust ability to recover any vulnerable components from upsets while the mission continues to operate. Many of these considerations also have significant implications to ground operation of the spacecraft, which in Earth orbit may be managed pass-to-pass or through continuous ground contact, which contrasts with the less-frequent contacts on deep-space missions.

Despite their smaller sizes and much smaller budgets, credible planetary SmallSat missions are not necessarily easier to execute than large spacecraft. They require program investment in systems engineering, design, and analysis that can stress a small or unpracticed team. Our experience with Janus and Lunar Trailblazer suggests that the solutions to many of the challenges identified above reside at the mission level, in connecting appropriate science objectives and mission design to credible spacecraft capabilities, and often are best addressed at or before the time of mission proposal formulation.

PROSPECTS FOR FUTURE MISSIONS

SIMPLEx is an exciting NASA program for planetary science. We look forward to seeing many more deep space rideshare missions to expand the NASA Science Mission Directorate portfolio. As SIMPLEx-class missions reach for more ambitious destinations – especially when those destinations are very different from the primary mission destination, as discussed above – an increasing fraction of spacecraft resources and program cost will be devoted to basic bus functions and mission execution. Thus, an important consideration for science teams will be balancing a compelling science investigation with a targeted instrument suite. Janus and Lunar Trailblazer are two examples: Janus has a trajectory design and lifetime markedly different from LEO satellites, and with a strategically selected set of science instruments and never-before-seen binary-asteroid targets. Lunar Trailblazer has a shorter mission duration closer to Earth, and returns novel data on the lunar water cycle. Both are finding success within the cost-capped SIMPLEx program. We encourage interested members of the science community to engage with experienced deep space spacecraft providers early in SmallSat concept development, to best understand the critical architecture trades needed for a deep space SmallSat, and formulate their science investigations accordingly.

On cost-capped planetary science missions, it is especially important to draw on a spacecraft provider with knowledge of the deep space environment and deep space mission operations so that projects with limited budget can minimize the uncertainties and risks they must account for. Lockheed Martin has enabled many sophisticated science missions within program cost caps because we can re-use successful designs, processes, and analyses. For example, the OSIRIS-REx Sample Return Capsule is nearly identical to the Stardust Sample Return Capsule, the Janus instrument suite has significant heritage to cameras on OSIRIS-REx and Lucy, and the Lunar Trailblazer propulsion system is based on GRAIL. We look forward to using Janus and Lunar Trailblazer as the foundation for future planetary SmallSats in the same way.

CONCLUSIONS

NASA investment in the SIMPLEx program area is an exciting development for both planetary science and deep space spacecraft design. Janus and Lunar Trailblazer will help prove out SmallSat spacecraft designs for NASA's deep space science missions. These spacecraft are not based on a defined commodity platform, but are configurable for a wide variety of missions. Although SIMPLEx SmallSat missions have much smaller spacecraft masses, execution teams, and program budgets than Discovery and New Frontiers missions, that does not imply a reduction in the systems engineering effort needed for mission success. Early engagement between science teams and spacecraft providers, including during the process of formulating science goals, is a key ingredient for future success of a deep space science mission.

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