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The ISIS Mission Concept: An Impactor for Surface and Interior Science

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Abstract. The Impactor for Surface and Interior Science (ISIS) mission concept is a kinetic asteroid impactor mission to the target of NASA's OSIRIS-REx asteroid sample return mission. The ISIS mission concept calls for the ISIS spacecraft, an independent and autonomous smart impactor, to guide itself to a hyper-velocity impact with 1999 RQ36 while the OSIRIS-REx spacecraft observes the collision. Later the OSIRIS-REx spacecraft descends to reconnoiter the impact site and measure the momentum imparted to the asteroid through the impact before departing on its journey back to Earth. In this paper we discuss the planetary science, human exploration and impact mitigation drivers for mission, and we describe the current mission concept and flight system design.

1. Introduction

The kinetic impactor mission concept has taken different forms in the last decade or more. In July 2005, NASA's Deep Impact mission employed an impactor to excavate material from the interior of Comet 9P/Tempel 1 to, among other things, study the chemistry of the comet's interior from spectral data and to infer the mechanical properties of the surface material through studies of the cratering event. ESA's Don Quijote asteroid mission concept was envisioned as a precursor deflection experiment as well as a characterization mission. That mission planned to send two separate spacecraft to a sub-kilometer near-Earth asteroid (NEA). The Observer spacecraft would arrive first and rendezvous in order to study the asteroid and thoroughly characterize it before the Impactor spacecraft arrived at several km/s to collide and create a crater and ejecta.

The ISIS mission concept is modeled after the Don Quijote mission in several major respects. However, there are two key differences with respect to Don Quijote. First, the ISIS mission does not require a dedicated launch vehicle, and second, it does not require a dedicated observer spacecraft. These differences are not minor, but rather are critical enabling aspects because they allow the ISIS mission costs to be dramatically less than a stand-alone mission such as Don Quijote.

ISIS plans to launch as a secondary payload with InSight, NASA's recently selected Discovery mission. Without ISIS, the InSight launch is expected to have well over 1000 kg of excess launch capacity. The ISIS mission would take full advantage of this unused launch capability, and thereby avoid the unsatisfying prospect of sending a rocket up only "half full."

The observer spacecraft for the ISIS mission would be the OSIRIS-REx asteroid sample return mission, the latest in NASA's New Frontiers line of planetary missions. The two missions would be strong partners in this investigation, and thus the ISIS name is apt, given that Egyptian mythology tells us that Isis was the wife of Osiris. The OSIRIS-REx mission calls for a rendezvous with its target asteroid, 101955 (1999 RQ36), followed by about nine months of careful characterization of the asteroid, leading up to the crucial sample collection effort. After OSIRIS-REx has safely stowed its sample, it must wait a number of months for the departure window to Earth. During this otherwise idle period, the ISIS spacecraft would arrive for a spectacular hypervelocity impact on 1999 RQ36, forming a crater tens of meters in diameter and ejecting thousands of tons of escaping material.

OSIRIS-REx would observe the impact from a safe vantage point, and after the debris has cleared it would execute a series of slow flybys near the asteroid to study the crater and surrounding areas. During this time OSIRIS-REx would also refine the orbit of the asteroid to allow a precise estimate of the orbital deflection caused by the ISIS impact. Sometime after conducting the ISIS science investigation, OSIRIS-REx would fire its thrusters for its injection home.

Table 1. ISIS Mission Timeline.

Event	Date	Remarks
ISIS Launch	09-Mar-2016	Co-manifest with InSight
Deep Space Maneuver 1	08-Apr-2016	1220 m/s
Mars Flyby 1	31-Jul-2016	V_∞ = 7.0 km/s, Altitude = 300 km
OSIRIS-REx Launch Window Open	04-Sep-2016	
OSIRIS-REx Rendezvous with 1999 RQ36	15-Oct-2018	
Mars Flyby 2	24-Jan-2019	V_∞ = 7.0 km/s, Altitude = 2890 km
Deep Space Maneuver 2	18-Jun-2019	72 m/s
End of OSIRIS-REx Proximity Ops	20-Jan-2020	Includes three sampling attempts
ISIS Arrival & Impact	10-Feb-2021	V_∞ = 13.4 km/s
End of ISIS Science Operations	11-May-2021	90 days
End of OSIRIS-REx Departure Window	28-Jun-2021	

2. Mission Design

The ISIS mission faces a number of technical and schedule constraints that limit flexibility, and yet the baseline mission meets each of the mission requirements. ISIS plans to launch in March 2016 as a secondary payload co-manifested with InSight, NASA's most recently selected Discovery mission. As a secondary payload, the ISIS launch energy and direction are dependent on InSight's launch conditions, and thus a post-launch Deep Space Maneuver (DSM) of 1.22 km/s is required. After the DSM, ISIS would perform two flybys of Mars, in July 2016 and January 2019, before finally impacting 1999 RQ36 in February 2021 (See Figure **1**).

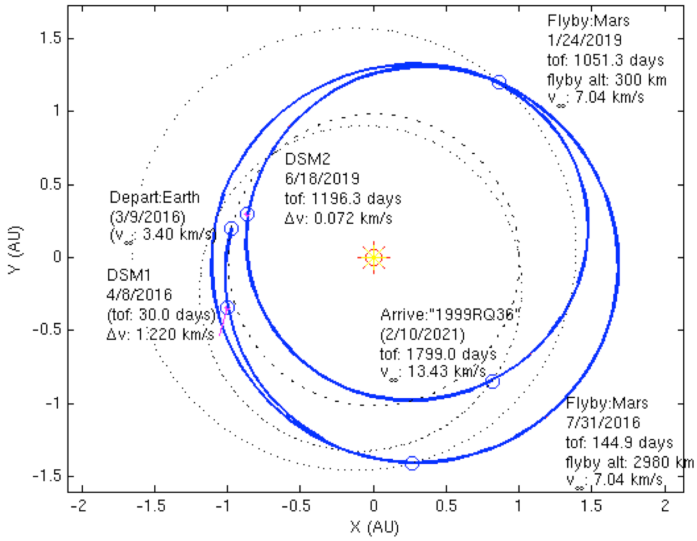

Figure 1. Overview of ISIS mission trajectory.

OSIRIS-REx is scheduled to launch in September 2016, about six months after InSight, and the rendezvous with 1999 RQ36 is planned for October 2018. The OSIRIS-REx team expects to collect its sample by July 2019, but there is schedule margin for a total of three sampling attempts until early January 2020. The window for the OSIRIS-REx injection back to Earth does not open until March 4, 2021, and so the OSIRIS-REx spacecraft expects to wait at least 14 months for its departure window to open. The baseline ISIS impact is planned for late in this period, about 4.5 months before the close of the OSIRIS-REx departure window in late June 2021 (See Figure **2**). Table **1** provides a detailed schedule of critical milestones for both the ISIS and OSIRIS-REx missions.

In addition to the launch constraint from being co-manifested with InSight and the schedule constraint with OSIRIS-REx, other key mission constraints are imposed to provide suitable conditions for terminal guidance. Impact velocities should fall between 8 and 20 km/sec, as velocities on the low end of this range leave too little asteroid deflection to be robustly detected, while higher velocities would require more costly hardware to support terminal guidance accuracy requirements. These velocities are within the range expected for hazardous asteroid mitigation, and thus are where the velocity-dependent deflection parameter β needs to be measured [1].

Additionally, a low phase angle on approach provides a brighter target, which allows for earlier detection and simpler targeting. Phase angles greater than 120° would raise significant challenges and likely levy additional costs, while phase angles less than 45° allow the most straightforward targeting approach. The baseline ISIS impact velocity is 13.4 km/s, and a phase angle of 9°. The energy delivered to the surface would be equivalent to 9 tons of TNT, sufficient (depending on the target strength or cohesion) to make a substantial or even regional crater, but several orders of magnitude below the catastrophic disruption threshold for an asteroid of this diameter [2].

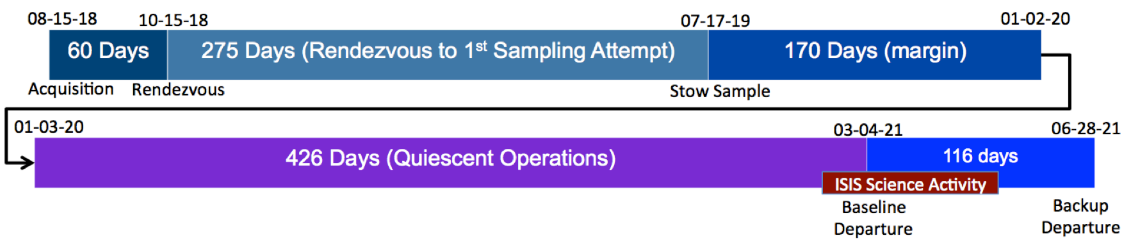

Figure 2. Timeline of OSIRIS-REx proximity operations with the 90-day ISIS operations period superimposed.

3. Concept of Operations

The ISIS concept of operations begins with the OSIRIS-REx spacecraft entering a radio science orbit around 1999 RQ36 in order to establish the pre-impact asteroid ephemeris to very high precision. Well before the ISIS impact, OSIRIS-REx would move to a safe vantage point from which to observe the ISIS impact and view the ejecta cone as it expands over a period of several minutes. The spacecraft would also monitor for lofted debris at locations far from the impact to understand the shock and seismic wave propagation through the small body.

After the impact the ISIS science investigation includes three phases, each expected to last 15-20 days. In the first phase, OSIRIS-REx would monitor the debris generated by the impact until it has cleared enough to allow a safe start to the second phase, which consists of a low pass, or perhaps a few passes, over the impact area to obtain spectra and high-resolution imagery (1-2 cm/pixel) of the crater, as well as areas far from the impact site. The final stage in the ISIS science investigation calls for the OSIRIS-REx spacecraft to again enter a radio science orbit, perhaps a terminator orbit with radius 1-2 km, in order to facilitate the estimation of the asteroid deflection provided by the ISIS impact. The ISIS science investigation would be complete in 90 days with comfortable schedule margin, at which point OSIRIS-REx would be free to implement its Earth-return injection maneuver.

4. Science and Technology Drivers

The ISIS mission provides tremendous dividends across a wide range of planetary science disciplines, as well as meeting significant objectives of human exploration and technology demonstration. Because of this there are potential stakeholders across a correspondingly broad swath of the space science and exploration community.

4.1. Asteroid Impact Mitigation Demonstration

The ISIS impact would change the orbit of 1999 RQ36 in a minute but detectable way. However, the change in velocity ΔV due to the impact is difficult to predict because it depends on unknown asteroid properties. Depending on the internal structure and mechanical properties of the asteroid, there could be a very substantial boost to the momentum transfer due to escaping ejecta from the impact area. This so called momentum enhancement is represented by β, a scaling factor on the input momentum from the impactor [1]. If $\beta=1$ then there is no enhancement from ejecta and we have what is termed an inelastic or plastic collision. If $\beta=2$ then there is as much ejecta momentum as spacecraft momentum, and the response is like an elastic collision. The momentum enhancement is thought to be in the range of $1.5<\beta<3$ for porous bodies, such as 1999 RQ36. Stronger bodies could see significantly higher values of β.

The prediction challenge represented by uncertainty in β is perhaps the most critical challenge that future engineers and scientists will face in designing and implementing a real kinetic deflection mission. It is difficult to design a deflection mission when there is a factor of 2-3 on the uncertainties in how much mass and velocity are required for a kinetic impactor. Just making sure that the impact is "big enough" is a possible – though very clumsy – solution, but that approach could come at a significant penalty in terms of cost and mission complexity. Moreover, pushing the asteroid too much in a completely uncontrolled way could actually deflect it onto a different impact trajectory, a so-called keyhole trajectory with an impact in the decades following the impact just avoided. The kinetic impact deflection approach will be much more robust if we have a better idea of how asteroids respond to such an impact.

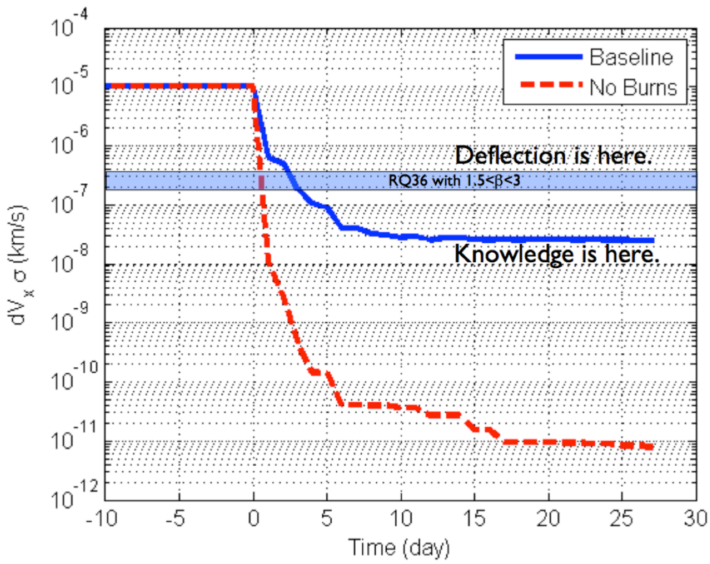

Figure 3. Uncertainty in the estimated asteroid deflection, i.e., change in velocity, due to a kinetic impactor [3]. This example is for a generic observer spacecraft station keeping near an asteroid similar to 1999 RQ36. The plot depicts a "Baseline" case with rather conservative assumptions on maneuvers and other activities that tend to corrupt the estimate. The "No Burns" case provides a lower bound for a very clean spacecraft that is not maneuvering.

If we conservatively assume β in the range 1.5 to 3 then the ISIS impact would lead to ΔV of 0.15-0.30 mm/s for an impactor mass of 420 kg. An orbiting spacecraft, in this case OSIRIS-REx, would measure the deflection on the asteroid. The precision of the ΔV

estimate is still to be determined, but a previous study [3] indicates that precisions of order 0.02 mm/s or better are feasible (Figure 3). The technique is standard radio science, where optical navigation images of the asteroid provide an estimate of the position of the spacecraft with respect to the asteroid. At the same time radio measurements, which include ranging, Doppler and Delta-Differential One-way Range (Delta-DOR) from Earth to spacecraft afford a precise estimate of the position of the spacecraft with respect to the Earth. The combination of all data types places the asteroid in the solar system with an accuracy of several meters. Accumulating such measurements over a period a few weeks gives enough information to estimate the asteroid deflection and hence β with a precision of ~10% or better.

4.2. Terminal Guidance Technology Demonstration

The second aspect of an asteroid deflection demonstration, besides measuring ΔV and β, is the testing of terminal guidance technology. This technology has been demonstrated to a large extent by the Deep Impact (DI) mission, which collided with comet 9P/Tempel 1 in July 2005. The technique involved the use of an onboard closed loop autonomous navigation system (called AutoNav). In addition to DI, AutoNav has also been used on all recent comet flyby missions (Deep Space 1, Stardust, Stardust-NExT, and EPOXI) to maintain closed-loop tracking during the flyby for high-resolution imaging. Thus, the technology is proven and mature, and the enhancements needed for the ISIS mission are modest and do not require revolutionary advancements to accomplish.

Bhaskaran and Kennedy [4] have conducted a preliminary study on the accuracy of the impact for the ISIS mission. Using a standard onboard navigation camera to image the target on approach, AutoNav determines the spacecraft trajectory relative to the asteroid and computes and executes maneuvers to impact the surface. The study indicates that 99% confidence targeting accuracies of 100 m or better are feasible. As the spacecraft design matures, higher fidelity simulations will be performed to optimize the targeting accuracies based on various hardware factors such as the thruster performance, and ability of the attitude control system to determine and control the spacecraft's attitude.

The Bhaskaran and Kennedy study [4] simply targeted the center of figure of the asteroid, but a more refined approach to the deflection problem calls for an oblique impact to achieve greater control on the ΔV vector. This requires targeting an off-center location, as was done on DI where the final images and maneuvers were used to bias the impact site away from the center of light. The advantage of oblique targeting for a kinetic impactor is that, while the input momentum from the spacecraft is oriented along the incoming relative velocity vector and so cannot be manipulated without dramatic changes to the mission trajectory, the ejecta momentum is directed normal to the surface at the impact location. Thus the ejecta momentum can in fact be directed in an optimal way by selecting an impact location that has the desired surface orientation. As an example, it is a classical result that the optimal asteroid deflection is aligned with the asteroid's heliocentric velocity vector because this yields the maximum position change at the epoch of impact. However, the celestial mechanics of interplanetary transfers can often make it difficult to optimally align the spacecraft inbound velocity vector. Even so, the impact location can be selected so as to align the ejecta momentum in an optimal way and thereby achieve greater efficiency than would otherwise be possible. This approach does require somewhat better terminal guidance accuracy than a direct hit, but affords greater design and schedule flexibility in the impactor trajectory design process, and thereby allows deflection options not otherwise available.

4.3. Science Investigations

There has so far been a single hypervelocity impact of a spacecraft into a small solar system object, namely the highly successful Deep Impact collision with comet 9P/Tempel 1. In that mission the observer spacecraft was on a fast flyby trajectory, and thus had only a few minutes to observe the collision. During the impact, fine dust with low transparency obscured the crater, and the spacecraft was unable to linger in order to image the crater after the dust cleared (although the Stardust-NExT mission did obtain low-resolution images of the crater area 5-1/2 years later). Moreover, Tempel 1 is large, with a diameter around 5.5 km, meaning that even if the spacecraft had remained in the area it would not have been possible to measure the ΔV associated with the impact, let alone discriminate impact-momentum effects from cometary outgassing that may have been associated with the impact.

In contrast to the Deep Impact mission, the ISIS mission would employ the OSIRIS-REx spacecraft to make a host of observations of the target asteroid in the months following the impact. The longer-term presence of a capable observer spacecraft opens up a wide range of exciting science investigations that would engage a broad range of the planetary science community. Because of its prime mission, which includes a detailed characterization of 1999 RQ36, the OSIRIS-REx spacecraft has an impressive suite of instruments with which to observe the ISIS impact. Of particular importance are the following instruments:

- The OCAMS imaging suite, which includes the wide-field SamCam (22° FOV), the general-purpose MapCam (4° FOV), and the narrow-field PolyCam (0.8° FOV). The SamCam would be used for optical navigation and to provide context, while the MapCam would be used for mapping the asteroid surface after the ISIS impact. PolyCam provides the highest resolution in the vicinity of the ISIS impact crater.

- The OSIRIS-REx spacecraft plans two spectrometers, the visible/near-IR OVIRS instrument (0.4-4.3 μm) and the mid- to far-IR OTES instrument (4-50 μm). These provide mineralogical information about the surface material, while OTES would also provide constraints on the thermal properties of the surface.
- The OSIRIS-REx Laser Altimeter (OLA) is a scanning altimeter that is planned to provide precision topographic maps of the asteroid surface.

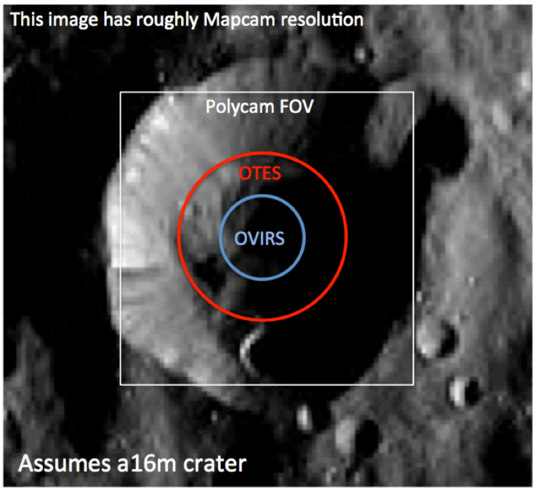

Figure 4. Overlay of instrument footprints at 1 km.

Figure **4** depicts the instrument footprints relative to a notional 16 m crater at a range of 1 km. These instruments, along with radio science, would facilitate numerous science investigations, some of which would be aided by the thorough characterization of the asteroid conducted during the baseline OSIRIS-REx mission prior to the ISIS impact. Some key examples include the following:

- The real-time imaging of the cratering event, estimated to take ~10^3 s for the crater to finish forming assuming lunar-like regolith cohesion, would reveal the mechanical properties of the surface and subsurface material and the particle dynamics during the ejecta formation process.
- The impact would induce seismic waves that travel through the body and reflect off boundaries and come to focus at the antipode. Such waves are expected to trigger landslides, topple boulders, and likely would loft material far from the impact site, all of which would allow strong constraints on the deep interior structure of the asteroid. This part of the study would be facilitated by images showing the dynamic effects of the impact, as well as through the comparison of pre- and post-impact high-resolution imagery.
- The study of the trajectories and sizes of the ejected material would shed light on the meteorite formation process.
- After the debris has cleared, over a period of ~1-2 weeks (allowing for re-impacting collisions generating further ejecta), high resolution imaging of the crater interior would reveal the subsurface geology and constrain the crater formation process. In addition, any exposed material could be examined for the presence of volatiles.
- Spectra of the pristine material from depth would provide added context for the OSIRIS-REx sample and reveal the extent to which the asteroid surface is altered by long term exposure to the space environment.
- OTES would provide estimates of the thermal inertia of the recently disturbed areas for comparison with previously mapped values, providing insight into the porosity and bulk density of the re-accumulated material.
- OLA would produce before and after topographic maps of the impact site, allowing a detailed assessment of the volume of material excavated by the impact and an estimate of how much of the ejected material re-accumulated in the vicinity of the crater.
- The particulate environment produced by a range of disturbances, from high energy at the impact site to minor disturbances far from the impact point would be observed.
- Depending on the selected impact site, the asteroid's spin state could be altered, and in particular, it could become excited into a non-principal axis rotation state. A detection of this effect appears feasible and would directly constrain the asteroid's moments of inertia, representing an independent constraint on the object's interior structure.
- The change in the asteroid's velocity from the impact (~0.15-0.30 mm/s) would be measureable through radio science observations with signal-to-noise ratio ~10. This would reveal the momentum enhancement factor β, shedding light on the geotechnical properties of the interior and surface materials, as well as greatly informing any future asteroid impact deflection efforts.

4.4 Small Body Exploration Strategic Knowledge Gaps

In support of NASA's initiative for human exploration of near-Earth asteroids, A Special Action Team of the Small Bodies Assessment Group (SBAG) has prepared a list of Strategic Knowledge Gaps (SKGs) for the exploration of NEAs [5]. SKGs identify gaps in knowledge or information required to reduce risk, increase effectiveness, and improve the design of robotic and human space exploration missions. The ISIS mission squarely addresses a number of SKGs, many designated as "Critical."

The SBAG SKG report identifies a few overarching themes, including understanding how to work on and interact with a small body surface, and understanding the small body environment and its potential risks to crew and equipment. Within these themes, categories are provided, and ISIS would provide highly relevant information for several of these categories, including the following:

- Surface mechanical properties – Besides providing desired information on the macro-porosity of the asteroid interior, ISIS would reveal the geotechnical properties of the surface material. This would include information on the compressive strength of the surface at small and large scales. The relevance to exploration relates to the need to understand how the surface responds when attempting to contact the body with a vehicle or tool. These properties also have relevance to the feasibility of using tethering devices to facilitate exploration.
- Particulate environment near the body – The dust environment around a small asteroid is not understood at the present time, and this has obvious relevance to human and robotic proximity operations. ISIS would provide vital constraints on the particulate environment following a disturbance. Not only would the question of debris clearing time for large disturbances be resolved, but across the body there would be lower energy disturbances from seismic activity, enabling an understanding of the amount of particulates that may be raised by disturbances across a wide range of energy levels.
- Local and global stability of small bodies – Again, the seismic activity would disturb the surface, with energy inputs ranging from highly disruptive at the impact site to more moderate and slight disturbances farther from the point of collision. The seismic activity could change the landscape by toppling fragile structures and boulders, and creating landslides on steeper sloped areas. The amount of change to the surface would provide key insights on how safe it would be for an astronaut or robotic explorer to interact with the surface.

5. Flight System Design

The ISIS flight system design is constrained by a number of driving requirements. These include:

- Low cost and development risk
- Ability to develop complete flight and mission system on a very tight schedule
- Design which does not impact InSight primary payload
- Mass maximized for impact, but fitting within ~1000 kg available on InSight launch
- Navigation accuracy and agility to ensure targeting

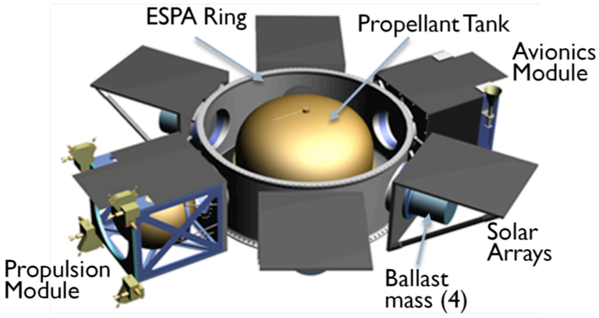

Figure 5. ISIS spacecraft configuration.

These requirements have led to a simple free flying spacecraft design that is based on the space-qualified EELV Secondary Payload Adapter (ESPA). This further minimizes the cost and development risk of the flight system primary structure, and introduces no significant impact to InSight Launch Vehicle (LV) integration. The standard ESPA provides a cylindrical ring installed between the EELV Standard Interface Plane and the primary payload, passing EELV mechanical and electrical interfaces to the primary payload in an identical configuration to the EELV.

This design (shown in Figure **5**) allows the spacecraft to make maximum use of the loading capability of the ESPA ring to deliver an impactor with optimal mass at impact. In the ISIS configuration, all six payload-attachment positions on the ESPA ring are occupied by modules that remain attached to the ring throughout the mission. The modularity of the design and its use of ESPA standard interfaces greatly simplify development and integration while minimizing impact to the InSight LV process flow. Integration in the launch stack is shown in Figure **6**.

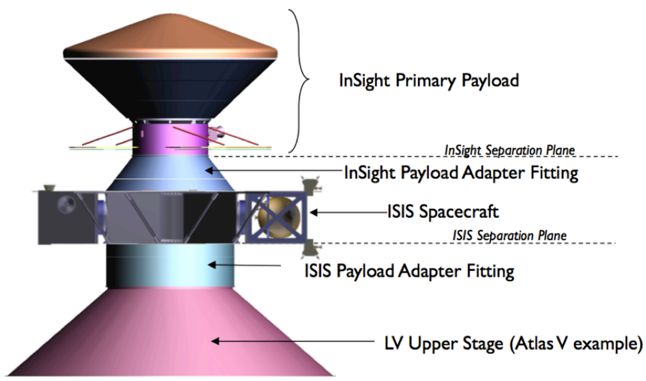

Figure 6. ISIS/InSight launch configuration.

The active components of the flight system are contained in two modules: Avionics and Propulsion, which are attached to the ring at two of the standard payload interface points. The Avionics Module contains the Command and Data Handling (C&DH),

Guidance, Navigation and Control (GN&C), including the optical navigation camera, and Telecom and power electronics subsystems, while the Propulsion Module incorporates all components of the primary and Reaction Control System (RCS) propulsion subsystems other than the propellant tank, which is mounted in the inner part of the ring. Power during cruise is provided by six fixed solar array panels, two of which are attached to the two active spacecraft modules, with the four additional panels mounted to the four open ESPA attachment points. Solar arrays and modules are connected to each other through an external power and signal harness.

The four secondary payload positions on the ESPA ring not occupied by the Avionics and Propulsion Modules are used to mount ballast mass elements. These elements, the mass of which can be adjusted to accommodate the final mass and balance of the spacecraft, allow maximization of the impact energy of the impactor.

Table 2. ISIS Flight System Master Equipment List

	CBE Mass (kg)	Contingency (%)	Total Mass (kg)
C&DH	9.9	14%	11.3
Power	25.2	9%	27.3
Telecom	10.4	18%	12.2
Structures	208.7	17%	243.8
Thermal	8.0	30%	10.4
Propulsion	58.8	28%	75.1
GN&C	10.3	10%	11.3
Spacecraft Total	**331.3**	**18%**	**391.6**
System Margin			28.5
Dry Mass Total		**43%**	**420.0**
Propellant			382.7
Wet Mass Total			**802.8**
LV Mass Allocation			1142.0
Launch Mass Margin			339.2

The ISIS design is based on the use of existing, flight-proven hardware to ensure the lowest cost and risk, as well as helping to accommodate the need for an expedited development schedule. A summary of the Master Equipment List (MEL) is shown in Table **2**. Masses are estimated from existing equipment with each subsystem carrying a contingency reflecting design maturity in accordance with JPL Flight Project Practices. The spacecraft wet mass totals 802 kg, which includes the ESPA ring (~125 kg). Given a LV mass allocation of 1142 kg (the estimated performance margin for the InSight launch on a Falcon 9, the smallest available LV), up to 340 kg would be available for ballast. However, ΔV requirements may be the limiting factor for the ballast mass. The masses (with contingency) of the Avionics and Propulsion (wet) modules are 106 kg and 60 kg, respectively, leaving large margins against each attachment point's maximum allowable mass of 180 kg.

6. Summary and Conclusions

The ISIS mission concept leverages NASA's investments in both the OSIRIS-REx mission and the InSight launch to provide Discovery-level science returns, address critical Strategic Knowledge Gaps for human exploration, and demonstrate asteroid impact mitigation technology, all for a small fraction of the cost of a Discovery mission. The New Frontiers-class observer spacecraft provides the ISIS mission with an impressive suite of instruments that are unlikely to be available if this mission is attempted later with a low-cost observer spacecraft. Given the low frequency of asteroid rendezvous missions, the fortunate convergence of the OSIRIS-REx schedule and the InSight launch represents an extraordinary but time-critical opportunity that will not be repeated soon.

7. Bibliography

[1] J.D. Walker, S. Chocron, D.D. Durda, D.J. Grolsch, N. Movshovitz, D. Richardson, E. Asphaug (2013), "Momentum enhancement from aluminum striking granite and the scale size effect", Int. J. Impact Engineering **56**, 12–18
[2] Benz, W. and E. Asphaug (1999). Catastrophic disruptions revisited. *Icarus* **142**, 5-20.
[3] S. Bhaskaran, S. Chesley, R. Park, A. Petropoulos, J. Sims, D. Yeomans, Navigation Challenges of a Kinetic Energy Asteroid Deflection Spacecraft, in: Proc. AIAA/AAS Astrodynamics Specialist Conference, held 18-21 August 2008, Honolulu, Hawaii.
[4] S. Bhaskaran, B. Kennedy, Closed Loop Terminal Guidance Navigation for a Kinetic Impactor Spacecraft, Proceedings of the 2013 IAA Planetary Defense Conference (2013). Paper number IAA-PDC13-04-02.
[5] NEO/Phobos/Deimos Strategic Knowledge Gaps Special Action Team Final Report, November 28, 2012 http://www.lpi.usra.edu/sbag/documents/FinalReport_112812.pdf

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