

Development and Testing of Harpoon-Based Approaches for Collecting Comet Samples

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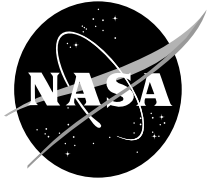
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Supplementary videos are available in a companion document: GSFC Development and Testing of Harpoon-Based Approaches for Collecting Comet Samples, NASA/TM-2017-219018Supplement, accessible online from the NASA Technical Report Server (NTRS) using document link <http://hdl.handle.net/2060/20170004092>.

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Development and Testing of Harpoon-Based Approaches For Collecting Comet Samples

1. Introduction

Comets, having bright tails visible to the unassisted human eye, are considered to have been known about since pre-historic times. In fact 3,000-year old written records of comet sightings have been identified¹. In comparison, asteroids, being so dim that telescopes are required for observation, were not discovered until 1801². Yet, despite their later discovery, a space mission returned the first samples of an asteroid in 2010³ and two more asteroid sample return missions have already been launched^{4,5}. By contrast no comet sample return mission has ever been funded, despite the fact that comets in certain ways are far more scientifically interesting than asteroids.

Why is this? The basic answer is the greater difficulty, and consequently higher cost, of a comet sample return mission. Comets typically are in highly elliptical heliocentric orbits which require much more time and propulsion for Space Craft (SC) to reach from Earth and then return to Earth as compared to many asteroids which are in Earth-like orbits. It is also harder for a SC to maneuver safely near a comet given the generally longer communications distances and the challenge of navigating in the comet's, when the comet is close to perihelion⁶, which turns out to be one of the most interesting times for a SC to get close to the comet surface. Due to the science value of better understanding the sublimation of volatiles near the comet surface, other contributions to higher cost as desire to get sample material from both the comet surface and a little below, to preserve the stratigraphy of the sample, and to return the sample in a storage state where it does not undergo undesirable alterations, such as aqueous.

In response to these challenges of comet sample return missions, the NASA Goddard Space Flight Center (GSFC) has worked for about a decade (2006 to this time) to develop and test approaches for comet sample return that would enable such a mission to be scientifically valuable, while having acceptably low risk and an affordable cost. A harpoon-based approach for gathering comet samples appears to offer the most effective way of accomplishing this goal.

As described below, with a decade of development, analysis, testing and refinement, the harpoon approach has evolved from a promising concept to a practical element of a realistic comet sample return mission. Note that the following material includes references to videos, all of which are contained in different sections of the video supplement identified in the references. Each video will be identified as "SS##", where "SS" means the supplement¹⁰ section and "##" will be the number of the section.

2. Comet Sample Return Studies and Work Prior to 2006

One impetus for starting this GSFC effort in 2006 was the 2003 Planetary Decadal Survey⁷, that stated, “The Primitive Bodies Panel’s second-ranked medium-class mission is the return of samples from a selected surface site on the nucleus of a comet.” Another impetus was the possibility of proposing such a mission in response to the upcoming third NASA New Frontiers (NF) Announcement of Opportunity (AO)⁸ then expected in the 2009-time frame.

When the GSFC work started in 2006 significant work had already been done, in part the result of the 1980 Planetary Decadal Survey⁹ that had stated, “we recommend that studies be carried out to determine the feasibility and cost of automated sample acquisition from asteroids and comets and of their return to Earth in a manner that preserves their integrity”.⁷ Subsequently the NASA International Cometary Explorer (ICE), originally the International Sun-Earth Explorer (ISEE) 3, spacecraft flew through the tail of comet Giacobini-Zinner in 1985. More close-up comet information was obtained from USSR and ESA flybys of the Halley’s Comet in 1986. Figure 1 shows the first close-up image of a comet (Halley) captured by the ESA Giotto mission.

In the 1985 time frame, this new comet fly-by information led to the initiation of a major ESA-NASA joint study of the Comet Rendezvous Asteroid Flyby (CRAF) Mission concept. As its part of the CRAF study ESA developed the Comet Nucleus Sample Return (CNSR) concept, which would have used the NASA-developed CRAF SC. One example of a CNSR concept for a comet Sample Acquisition System (SAS) is shown in Figure 2, which depicts a comet lander that would hold itself on the surface while using a telescoping coring drill to get samples from as far down as 10 meters below the surface.

In the end the CNSR concept did not make it into development because NASA decided not to go ahead with the CRAF mission. However, ESA did use its work on CRAF to provide the basis for Rosetta comet rendezvous and landing (but not sample return) mission, development of which started around 1993. While the Rosetta mission was still in development, the 2003 Planetary Decadal Survey⁷ focused its recommendation on a Comet Surface Sample Return (CSSR) mission whose cost could be compatible with what the NASA New Frontiers (NF) Program could support, i.e., a total cost of something less than \$1B. The Survey felt that a CSSR mission which would be less challenging than a CNSR mission that required deep drilling and cryogenic storage of sample material. However, the 2003 Survey also recommended delaying work on a CSSR mission until after 2005, when the results from the Deep Impact Mission could provide data on the strength characteristics of comet surface material.

In the meantime, the Rosetta mission finished its development and was successfully launched in 2004. Much of the CNSR research was able to be used and further advanced by Rosetta because its Philae Lander daughter-ship was designed, among

other things, to obtain and analyze comet surface samples. Thus, ESA scientists had to develop workable concepts for dealing with the expected range of comet surface properties in order to remain on a comet surface and acquire surface samples, and this work was able to later contribute to the GSFC harpoon development efforts.

3. Initial GSFC Concept Development

The GSFC Internal Research And Development (IRAD) effort began by reviewing earlier work related to comet sample return and looking for ways to improve on it. Like the ESA CNSR mission concept, the GSFC IRAD initially assumed that a comet lander would obtain multiple subsurface samples and keep them at cryogenic temperatures to preserve volatiles. However, the GSFC IRAD tried to improve on the CNSR concept by seeing if it could be accomplished at a low enough cost to fit into the NF Program.

This focus on cost reduction led to the GSFC harpoon concept for acquiring comet surface samples. Given the low gravity of a comet, plus comet outgassing and the reactive upward force resulting from drilling down, a sample-gathering comet lander normally requires some way of anchoring itself to the surface during drilling, such as by using thrusters. The GSFC concept was that a single sample-gathering harpoon could serve both as anchor and as a means of obtaining surface and subsurface samples. The sample-gathering harpoon would contain a cavity to hold sample material, and a door in front of the cavity that would close when the harpoon reached the end of its travel. The harpoon would fire close to the moment of touchdown, essentially transferring some amount of the lander's downward momentum to the harpoon. Just before liftoff of the lander, the harpoon would be retracted. Figure 3 shows a very early 2006 concept for the comet sample-gathering harpoon. The potential advantages of this sample-gathering concept included:

1. Dispensed with the cost of a separate anchoring system
2. Making use of the downward momentum of the lander whether the lander was the main SC itself or a separate daughter ship.
3. Ability to penetrate the hardest expected comet surfaces by giving the harpoon enough kinetic energy via increased mass or velocity
4. Ability to accommodate arbitrarily soft comet surfaces by giving the harpoon tether enough strength to bring the harpoon to a stop even if the surface was too soft to dissipate any of its kinetic energy
5. Get a sample very quickly (seconds) if desired
6. Keep the lander on the surface indefinitely if desired
7. Be capable of being instrumented to measure surface hardness versus depth profile via accelerometers and subsurface temperatures via thermocouples

Having settled on the harpoon approach as worth further study, GSFC conducted some literature research which found that the Philae Lander for the Rosetta Mission incorporated the extensively tested and fully developed harpoon system shown in Figure 4. This harpoon was designed mainly to keep Philae on the surface but it could also provide deceleration and temperature measurements. Adapting some of

the design concepts for the Philae harpoon, in 2008 to 2009 GSFC developed an ambitious CNSR mission concept with:

1. A daughter-ship comet Lander with 3 sample-gathering harpoons and capable of multiple landings (Figure 5)
2. A harpoon subsystem (Figure 6) that would retrieve a fired harpoon from the comet, encapsulate the harpoon in a sealed container on the Lander, with the encapsulated harpoon later (after the Lander had return to the Carrier mother ship) able to be moved by a robot to a cryogenic storage container (shown in expanded form in Figure 7.) that would be located in an Earth Return Capsule.
3. A rendezvous and docking approach to get the Lander back on the mother ship (Carrier SC shown in Figure 8) based on the successful 2007 DARPA Orbital Express Mission shown Figure 9
4. A robot arm (Figure 8) on the Carrier SC to transfer the encapsulated samples, along with an ion propulsion (Figure 10) capable of performing a round trip mission from Earth to Comet 4015 WH (Figure 11) and then back to fly by Earth. During the Earth fly by, the Earth return vehicle (Figure 8) with the sample storage system (Figure 7) would separate, reenter the Earth's atmosphere, land and keep the samples at cryogenic temperatures until they were placed into cryogenic laboratory freezers after their return to the surface of the Earth.

This approach, which eliminated the risk of landing a SC with the large solar arrays needed for ion propulsion, proved to have strengths and weaknesses. It did show that a sample-gathering harpoon could be an effective element of a very capable end-to-end comet sample return mission concept, but a mission cost analysis showed that a lander plus mother ship approach appeared too expensive for a NF mission, which resulted in this mission concept not being proposed in response to the 2009 NF AO.

4. GSFC Technology Development and Mission Refinement

Even though the Lander plus mother-ship approach was judged too costly for a NF mission, the intrinsic advantages of the harpoon approach (speed, simplicity, and the ability to deal with a wide range of comet surface hardness) led to continuing GSFC efforts to develop this technology and to see if there were a different comet sample return mission architecture that could fit into the NF cost cap. One of these efforts was the production of a computer graphic simulation (Video SS02) to illustrate how a harpoon sampling mission might operate.

The technology effort first resulted in the design and construction of a laboratory mechanism, the "ballista" shown in Figure 12. Its initial goal was to test the penetrative capabilities of dummy harpoons with different geometries into different test materials representing the expected range of compressive strengths of comet surface material, as Video SS03 documents. As shown in Figure 13, a variety of

dummy harpoon tip geometries were tested by ballista firings to determine their penetrative ability. However, as shown in Figure 14, the effect of tip geometry was found to be much less significant than harpoon mass, velocity and cross-sectional area.

The architecture development effort led to the 2011 development of a different GSFC mission concept (illustrated in Figure 15) to eliminate the need for a lander by firing the harpoon from the mother ship at a safe standoff distance (order of 10 m) above the comet. This mission architecture indicated that a sample-gathering harpoon could enable a comet sample return mission with acceptably low risk and the ability to fit within the NF cost cap. In 2012, this GSFC “standoff” harpoon concept was incorporated into an Applied Physics Laboratory (APL)-led effort to develop an end-to-end comet sample mission concept called COMet Rendezvous, Sample Acquisition, Investigation, and Return (CORSAIR) planned to be proposed in response to the next NF AO, then expected to appear in the 2016 timeframe.

Being part of the CORSAIR mission led to designating the GSFC harpoon as the Sample Acquisition And Retrieval Projectile (SARP) and the overall GSFC harpoon subsystem as the Sample Acquisition System (SAS). As part of the overall CORSAIR mission design, the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), had also been brought on as a partner to provide both a space robot to move as required the sample cartridge within the SARP and a Launcher for the SARP, to be based on heritage from developing the Launcher for the harpoon of the Rosetta Philae Lander.

5. Initial SAS Development for the CORSAIR Mission Concept

Being part of a supported NF proposal effort mission allowed the continuation and expansion of the GSFC ballista testing work. One initial effect was to move the ballista from inside a GSFC laboratory to the top of an existing but unused external GSFC concrete tower structure, which had been made available to provide a more realistic environment for SAS testing. As shown in Figure 16, a shed was placed on top of the tower to protect the ballista from the elements. Figure 16 also shows a new ground shed that was acquired to provide a workshop area, as well as a surplus GSFC van that was turned into office space. This overall facility was designated the Tower Test Facility (TTF). The course of this initial SAS work for the CORSAIR mission also led to changes in the SARP and, as described further below, to the following two major additions to the SAS.

1. A compact end-effect, the Kinematic End-Effector (KINEE), that allowed the DLR robot to grasp and release the sample cartridge contained within a retrieved SARP. This enabled the SARP sample cartridge, after being fired and retrieved, to be removed and inserted into any intermediate Sample Handling Station (SHS), and finally transferred from the SHS to an Earth Entry Vehicle (EEV)

2. A Dual Carpenter's-tape Tether (DCT) which, along with its with its deployment and retrieval features, came to be called the Tether Extension and Retraction Mechanism (TERM). This allowed a fired SARP to be retrieved and its sample cartridge extracted by the KINEE and DLR robot, which together came to be called the Sample Transfer System (STS).

When these elements were developed and integrated together, it became possible (as shown in Figure 17 and documented in Video SS04) to use the TTF to fire the SARP down into containers of different target materials located about 6 m below the ballista launcher, and then retrieve the SARP back up to the ballista using the DCT and TERM.

5.1 SARP

With the earlier laboratory tests showing that a SARP with a sample chamber cross-section of about 2.5 by 2.5 cm could penetrate the hardest expected cometary surface to a minimum depth of about 25 cm with a velocity of a few tens of meters per seconds, an initial SARP concept (shown in Figure 18) was developed for the CORSAIR mission consisting of a sheath enclosing a removable sample cartridge with a stainless steel foil door. As shown in Figure 19, this initial concept was further refined to incorporate a spring to close the cartridge door and then built into testing hardware that was used to test the ability of the cartridge door to close after using the ballista to fire the SARP into a variety of test materials, such as sand, gravel, and ice.

However, as a result of becoming part of the CORSAIR mission, a number of changes were gradually made to both the design and development of the SARP. First, as shown in Figure 20, the SARP was significantly resized to meet CORSAIR mission requirements, which were for each SARP to provide a sample capacity of 250 cc with a sample chamber of about 5 x 5 x 10 cm. This new form factor was needed in order for the sample cartridge to fit within the storage space allocated on the CORSAIR Earth Entry Vehicle (EEV).

Finally, the SARP design was reconfigured to provide a means for it to be grasped and moved by the DLR robot with the KINEE described below. Initially, as shown in Figure 21, the SARP sample cartridge was given two robot interfaces on its side and back, with the expectation that the KINEE would initially grasp the sample cartridge by the side interface, move it to an intermediate location for examination, then release it and grasp it from the rear interface for transfer to the EEV, as shown in Figure 22.

5.2 KINEE

Since the DLR robot was not equipped with a SARP-compatible end-effector, this led to the development of the GSFC KINEE-end effector to be mounted on the DLR robot arm. KINEE was the result of an innovative GSFC end-effector design that

permitted not only a very compact end-effector but also a very compact grasping interface on the object to be grasped and released. As shown in Figure 23, the key KINNEE end-effector innovation was a “gripper” that expanded rather than contracted, and a grasping interface that surrounded the expanding “gripper” rather than being inside a contracting gripper. When tightly fastened to the gripping interface, KINNEE was drawn into a kinetic mount (the source of its name) shown in Figure 24. The KINNEE concept began with having a camera and target to align with the cartridge (also shown in Figures 23 and 24), and a latch actuator (shown in Figure 24) to decouple the cartridge from the “de-coupler” plate at the back of the SARP. The KINNEE also had a second camera shown in Figure 25 to align itself with the EEV.

5.3 TERM

The original concept (Figure 15) for the standoff harpoon envisioned retrieving the harpoon with a flexible cable similar to that used for the anchoring harpoon of the Philae Lander (Figure 4) and subsequently also incorporated into the Lander for GSFC CNSR concept (Figure 6). However, further analysis indicated that better control of the SARP during retrieval was desirable and this led to the (DCT) shown in Figure 17. The TERM mechanism for deploying and retrieving the SARP with this stiffer tether is shown in Figure 26, along with an indication of how the TERM would interface with the DLR launcher.

The DCT had the advantages of not only increased tether stiffness but also of being able to be placed on either side of the launcher guide barrel. This arrangement allowed the filled sample cartridge to be brought directly back to the end plate of the Launcher piston rod by the DCT and their motors. Once in this position, the cartridge could be grasped by the KINNEE and then transported by the DLR robot to a storage location.

Following concept development, the dual carpenter’s-tape TERM was carried through detailed design, fabrication and testing. Figures 27 shows more design details of the TERM retraction and braking motors, and Figure 28 shows the approach for mounting the TERM to the ballista and the ballista in the shed on top of the concrete TTF tower shown in Figure 16. Figure 29 shows progress being made in assembling the mechanical and electrical components of the TERM. When all of these elements were developed and integrated together, it became possible (as shown in Figure 30) to fire the SARP a distance of about 6 m into a container of target material and then retrieve the SARP back to the ballista launcher using the TERM.

The testing program using the carpenter tape version of the TERM allowed the accomplishment of numerous test objectives, including validating the overall usefulness of the TTF and the mechanical and electrical

capabilities of individual SAS elements, such as the SARP and the TERM. Video SS05 documents an early test of the SARP and its mechanisms in the TTF.

Another result of developing the TERM was that it allowed DLR to develop and test a TERM-compatible Launcher as documented in Video SS12.

6. Second Phase of SAS Development for the CORSAIR Mission Concept

As detailed below, the second phase of SAS development for the CORSAIR mission consisted of a mixture of both the continued development of existing design concepts, (such as the SARP mechanisms) and changes in the SAS design to meet CORSAIR requirements. Examples of changes were the incorporation of the flip hinge into the SARP, the resulting changes in the KINEE, the replacement of the ballista by the Variable Impulse Pressure (VIPr) Launcher, the use of FOAMGLAS to simulate cometary materials, and the replacement of the TERM by the Triangular Rollable And Collapsible (TRAC) boom and the Boom Retraction And Deployment (BRAD) Mechanism. With the completion of this second phase of SAS development, the resulting SAS appears able to meet CORSAIR mission requirements.

6.1 SARP Mechanisms

The TTF made it possible to develop and test remotely controlled, electrically operated mechanisms to close the door of the sample cartridge and separate the outer sheath from the cartridge before retrieving the cartridge back to the ballista.

Figures 31 and 32 illustrate an initial test version of the SARP with the two spring-loaded mechanisms released by simple burn wires. With the ballista and TERM in the TTF, plus the burn-wire triggers, a successful and remotely-controlled test, (as shown in Figure 30) was conducted of firing the SARP, triggering the two mechanisms within the SARP, and retrieving the closed and separated cartridge filled with sample material. Video SS05 also documents using this equipment for an early test of the TERM and of the mechanisms in the SARP that release its outer sheath and close the door on its sample cartridge.

However, the burn wire technique was not appropriate for the design of a flight SARP because of (among other things) the time required (tens of seconds) to sever the Vectran thread. This led to the GSFC development of the magnetically actuated Bi-Stable Pin-Puller (BSPP), shown in Figure 33, which was compact enough, exerted enough force, and could be actuated in a fraction of a second. Video SS09 documents the operation of the BSPP. Another SARP effort, shown in Figure 34, was to equip a SARP with electronics to power a LED blinking at known rate, which enabled viewing cameras to more accurately determine the velocity at the moment of impact.

The final issue uncovered was that the existing coil spring design for actuating the cartridge door was not strong enough to cut through a sample of the hardest expected cometary material, represented by FOAMGLAS with a compressive strength of 2.4 MPa. As shown in Figure 35, a torque wrench was used to determine the spring force required to cut this material. Then this requirement was addressed through the design, fabrication and testing of a new heavy-duty spiral coil spring shown in Figure 36 that (when used in pairs) had sufficient force to close the cartridge door under these worst design-case conditions. The compressed spiral spring is designed to be released by the BSPP, which is in turn activated by a timer in an electronics package in the SARP de-coupler plate that starts counting down when the SARP is fired. Figure 37 shows the assembly of the SARP control electronics, de-coupler plate, outer sheath, sample cartridge, spiral spring and BSPP. Videos SS10 and SS11 document the operation of the spiral spring at room and cryogenic temperatures, respectively.

Another change to the SARP was to remove the complexity resulting from the KINEE having to switch from side interface (used to remove the cartridge from the SARP de-coupler plate) to the rear interface (required to insert the cartridge into the EEV, as shown in Figures 21 and 22). A redesign, shown in Figure 38, got rid of the need for a side interface (and the switching of mating surfaces) by mounting the cartridge on a flip hinge, which had the added benefit of providing the KINEE with a clean mating surface.

This latest version of the SARP appears to have all of the basic capabilities required for the flight SARP.

6.2 Kinematic End Effector (KINEE)

The use of the SARP flip hinge (shown in Figure 38) with a cartridge detent allowed the KINEE to be further simplified by eliminating the need for its latch actuator shown in Figure 24. Ongoing discussions with DLR enabled another simplification in the KINEE design by eliminating the cameras due to the ability of the DLR robot to align itself using its built-in force feedback capabilities. To increase the reliability of using force feedback, the KINEE grasping interface was given some tapers (shown in Figure 39) to help the DLR robot “feel” its way in. The KINEE shape was modified slightly (as shown in Figure 40) to accommodate the new interface design. Figure 41 illustrates how the KINEE interacted with the new cartridge interface.

Following these changes, the electrically-powered test version of KINEE (shown in Figure 42) was built and sent to DLR where it was used by a test version of the DLR robot, as shown in Figure 43, to successfully demonstrate the transfer of a cartridge from the SAS to a storage location.

So far, this version of the KINEE has met all CORSAIR mission requirements.

6.3 FOAMGLAS

Another issue was that the sample materials used to date did not have hardness (compressive strength) properties that were both consistent and in the range of the hardest expected cometary surface which had been estimated to have a compressive strength of about 2 MPa. This need was addressed in an innovative fashion by making use of a building insulation material called FOAMGLAS made by Pittsburgh Corning Corporation and which could be obtained with various compressive strengths going up to 2.4 MPa. Figure 44 illustrates the results of one of the SARP firing tests done into FOAMGLAS. An additional benefit of using FOAMGLAS was that, because of the consistent (about $\pm 10\%$) FOAMGLAS compressive strength, it was possible to find, as shown in Figure 45, that there was satisfactory correlation between measured penetration into FOAMGLAS and penetration estimated with a fairly simple model used for the Rosetta Philae harpoon.

6.4 VIPr Launcher

In terms of changes, the initial TTF tests also pointed out the inability of the ballista to achieve SARP impact velocities of more than ~ 20 m/s, which was short of the 30 m/s velocities estimated to be required to penetrate the hardest expected comet material. This limitation of the ballista was addressed by replacing the ballista in the TTF with the GSFC-developed Variable Impulse Pressure (VIPr) Gas Launcher shown in Figure 46. Video SS06 documents an early and not entirely successful test of the VIPr. The VIPr eventually proved capable of imparting SARP impact velocities of ~ 35 m/s, sufficient for demonstrating that the SARP could penetrate far enough into any expected comet surface material. Videos SS07 and SS08 document more successful tests of using the VIPr and TERM to cause the SARP to adequately penetrate FOAMGLAS with different compressive strengths and impact angles.

6.5 Boom Retraction And Deployment (BRAD) Mechanism

The final and largest change in the SAS resulted from an analysis of the differential velocity between the SC and the comet surface and by the SARP gaining even more differential velocity due to the possibility of being deflected off an unexpected hard and angled object hidden just below the comet surface. This analysis showed that the DCT did not have sufficient stiffness to prevent a SARP being retrieved from possibly swinging around and contacting the CORSAIR SC due to differential horizontal velocities between the SC and the SARP.

The insufficient stiffness of the DCT was addressed by extensive redesign in order to use a single composite Triangular Rollable And Collapsible (TRAC) boom (shown in Figure 47) as the tether. The TRAC concept was developed

by the Air Force Research Laboratory (AFRL) as a boom or mast that is flexible when stowed laying flat on a reel but becomes stiff when deployed by unreeling and expanding into a triangular cross-section, as illustrated in Figure 47. As shown in Figure 48, the adequacy of TRAC boom stiffness was verified by first measuring its stiffness and then putting these measured stiffness characteristics into a dynamic model using the Automated Dynamic Analysis of Mechanical Systems (ADAMS) software. As documented in Video SS13, this effort showed that the TRAC boom tether would exercise sufficient control over the SARP while being retrieved from comet under worst case conditions. Based on the success of these simulations, the BRAD, shown in Figure 49, designed to accommodate a TRAC boom, replaced the TERM. In support of the change to the BRAD, DLR developed new design for a launcher that featured a “birdcage” piston that went around the TRAC boom and its BRAD drum. Video SS14 documents a DLR test of the new launcher.

7. END-TO-END SAS Design and Tests

With the design changes and tests described above, it became possible to firm up the design of the overall flight SAS. Figure 50 shows all of the SAS elements on the CORSAIR SC in their stowed configuration, and Figure 51 shows these same SAS elements in one of their deployed configurations.

Thus, the objective of the current and ongoing SAS testing is to verify the end-to-end operation of the SAS. Integrated ground testing of all of these SAS elements is not practical at this time because two of the major SAS elements (launcher and robot arm) continue to be developed in Germany while the rest of the SAS is being developed in the US. Therefore the end-to-end test will consist of a series of separate tests. There are planned to be the following 4 separate tests to cover the end-to-end SAS test:

1. DLR Launcher with Birdcage
2. GSFC BRAD in TTF
3. GSFC SARP in FOAMGLAS
4. DLR Robot with GSFC KINEE, sample cartridge and flip-hinge

7.1 DLR Launcher with Birdcage.

As will be described in the DLR Launcher section, the new Launcher with Birdcage will be test fired in Germany to the maximum required velocity (~ 50 m/s) with a dummy mass that is equivalent to maximum expected effective mass of the BRAD drum and SARP (~ 5 kg)

7.2 GSFC BRAD in TTF.

Figures 52 and 53 illustrate the basic BRADD actions that will be exercised in the TTF to satisfy the End-to-End test goals. Basically, a 6 m TRAC boom (already delivered with end fittings) will be integrated in the BRAD, which is currently in the late stages of fabrication and assembly. Once the BRAD is complete and functional, it will be mated to the dummy “birdcage” shown in Figures 52 and 53 and then to the VIPr on the TTF. This setup will be used to fire a dummy SARP at 30-to-50 m/s into target material and then retrieve the SARP back up to the

birdcage. Video SS15 documents an early test where the SARP and TRAC boom was allowed to drop down from, and then be retrieved back to, the Transfer Stand (an early and partial test version of the BRAD) – followed by the manual release of the flip hinge. Again using the Transfer Stand, Video SS17 documents that contamination (cometary material adhering to the back of SARP) does not prevent the SARP from making a sufficiently rigid connection to the birdcage piston when retrieved. Video SS18 then documents a drop test (as was done in Video SS15) except that Video SS18 documents a test with the BRAD as opposed to the Transfer Stand. Videos SS19 and SS20 show top and bottom views, respectively, of the SARP, TRAC boom and BRAD being fired by the VIPr in the TTF.

7.3 GSFC SARP in FOAMGLAS.

As shown in Figure 44, the ability of the SARP to adequately penetrate the hardest expected cometary material has already been successfully tested. The remaining SARP test will be along the lines of Figure 34, where the main objective will be to show that the Cartridge door (with its spiral spring and pin-puller) can be electrically triggered and cut through the 2.4 MPa FOAMGLAS that represents the hardest expected cometary surface material. Video SS21 documents the VIPr firing the BRAD and TRAC boom at a high enough velocity for the SARP to penetrate FOAMGLAS.

7.4 DLR Robot with GSFC KINEE, Sample Cartridge and Flip-Hinge.

As shown in Figure 43, one of the most significant of the separate SAS ground tests has already been successfully conducted, namely using the KINEE and a robot arm to extract a sample cartridge from the flip-hinge held against a birdcage. The robot arm is a commercial KUKA arm, but its design was derived from the DLR flight arm design and so it replicates the significant capabilities of the DLR flight arm. Video SS16 documents this demonstration.



Figure 1. First Flyby Image of a Comet (Halley) Captured by ESA Giotto Spacecraft in 1986

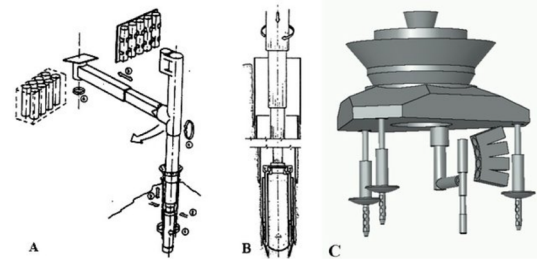
CNSR- SAS-3M (88-90)

In the Comet Nucleus Sample Return (CNSR) scenario, the Sample Acquisition System (SAS) had to perform the following tasks:

- Anchoring the S/C on the comet (to counteract the drilling and other force/torque);
- Sampling of materials, to acquire:
 - surface sample, i.e. 1 to 5 kg;
 - a core sample, down to a depth of 3 m;
 - a volatile sample at the bottom (10-100 g).
- Manipulation and handling samples and tools: the core sample, of diameter 10 cm, had to be cut in segments of 0.5 m long for storage in the Earth Return Container.

The requirement of sampling down to 3 m led to rather complex items; a single corer was impractical, and a corer device held on a telescopic tube was selected.

The total mass of the samples was superior to 15 kg, and their volume about 25 l.



SAS-3m for Rosetta/Comet Nucleus Sample Return

Several system studies were performed. The figure A and B depict a concept of SAS-3m Telescopic Drill developed by Tecnospaio. The figure C shows the schematics of accommodation of the Telescopic Corer Drill on a Lander from Matra study; coring elements are brought successively deeper by a telescopic tube carried by a manipulator arm. The companies NGI in Norway and Diamant Boart in Belgium performed parallel corer studies. Finally, the CNSR SAS-3m remained at the stage of a conceptual study (Eiden M., Coste P. 1991).

Figure 2. 1990 Concept for a Comet Sample Acquisition System for the ESA Comet Nucleus Sample Return (CNSR) Mission

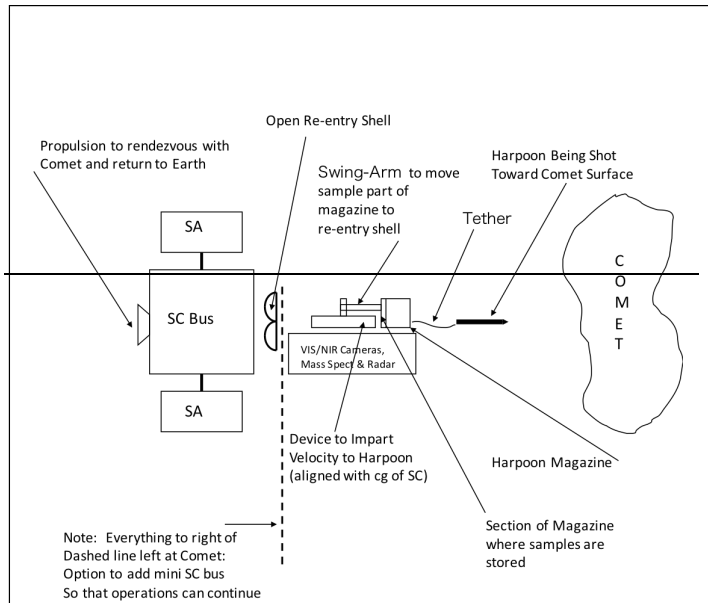


Figure 3. Initial 2006 Concept for GSFC Comet Sample Gathering Harpoon

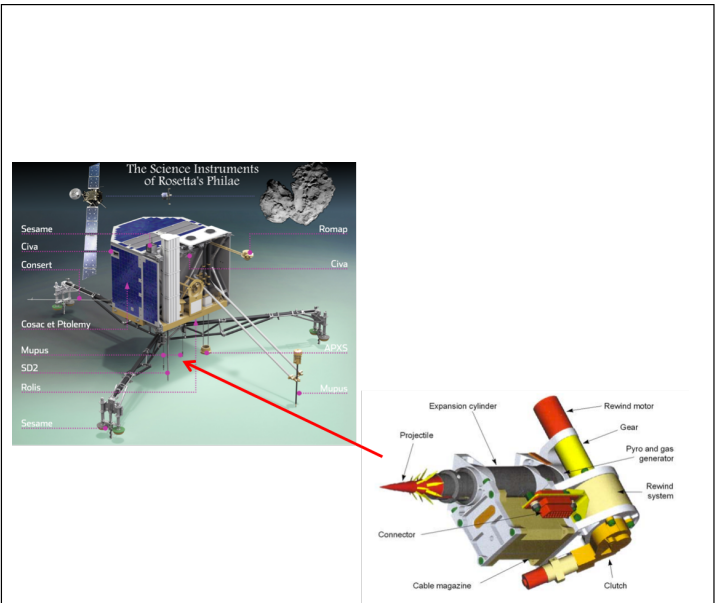


Figure 4. Philae Lander for ESA Rosetta Mission (upper left) and blowup of Lander Anchoring Harpoon (lower right)

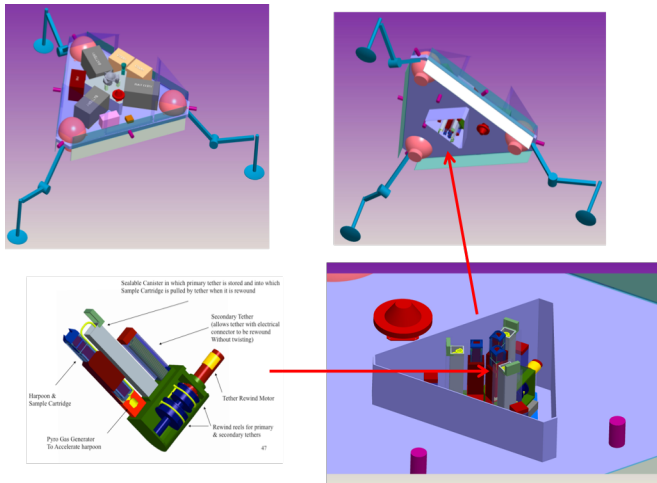


Figure 5. Concept for GSFC Comet Lander with 3 Sample-Gathering Harpoons

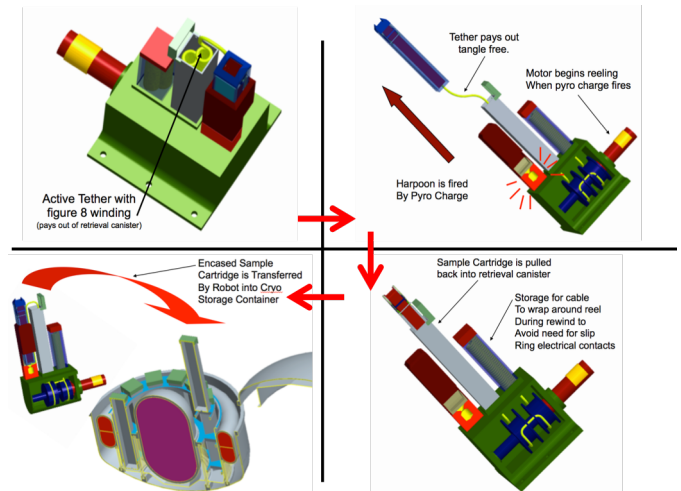


Figure 6. Operation of GSFC Comet Sample-Gathering Harpoon

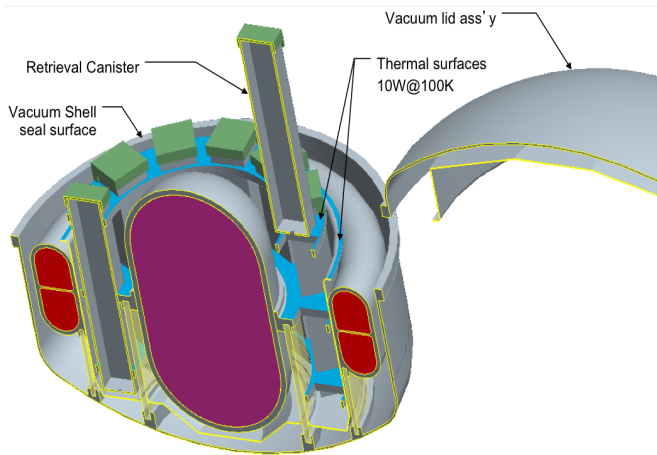


Figure 7. GSFC Concept for Cryogenic Storage of Comet Samples on Earth Return Capsule

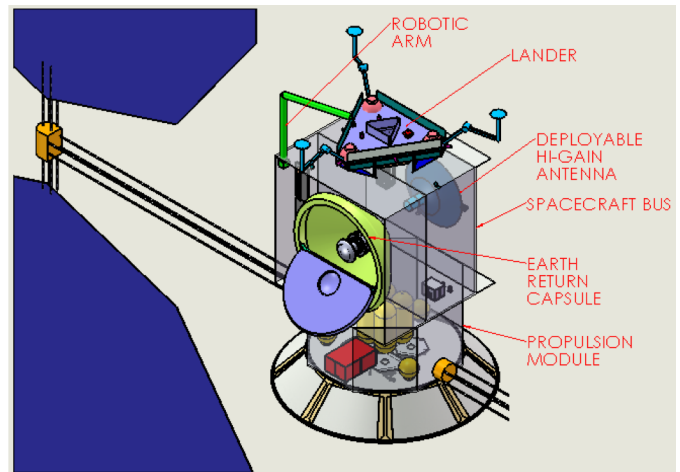


Figure 8. Concept for GSFC Carrier Ship (Mother-ship) for Comet Sample Return Mission



Figure 9. DARPA Orbital Express-Based Concept for how GSFC Comet Lander would Rendezvous and Dock with Carrier Ship

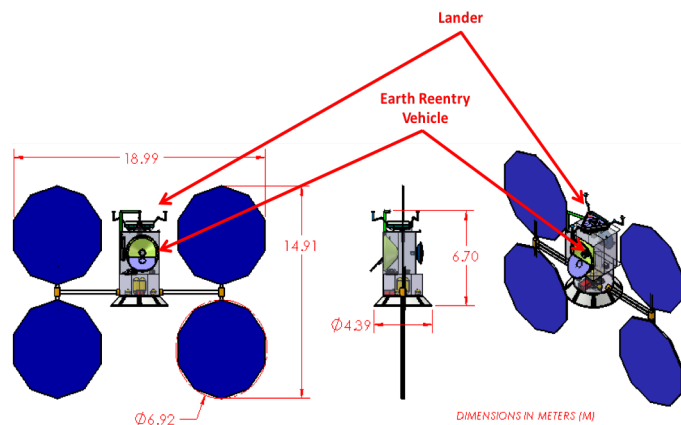


Figure 10. GSFC Concept for 37 kW Ultra-flex Solar Arrays to Power Ion Engines on Comet Sample Return Carrier Ship

4015WH Round-trip Low-thrust Trajectory

- Launch**
 - August 21, 2015
 - $C3 = 10.95 \text{ km}^2/\text{s}^2$
 - Mass to injection = 1852 kg
 - Delta IV 4040-12
- SEP System**
 - NEXT 2+1
 - $P_0 = 20 \text{ kW}$
- Large Thrust and Coast Arcs**
 - Transfer time = 2.7 yrs
- Arrival at Wilson-Harrington**
 - May 1, 2018
 - Mass = 1491 kg
- Departure from W-H**
 - May 1, 2019
 - Mass = 991 kg (500 kg drop)
- Large Thrust and Coast Arcs**
 - Transfer time = 3.5 yrs
- Return to Earth**
 - August 26, 2022
 - Mass = 967 kg
 - Entry Velocity = 15.3 km/s



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Figure 11. Low Thrust Roundtrip Trajectory for GSFC Carrier Ship to Acquire and Return Samples from Comet 4015 Wilson-Harrington

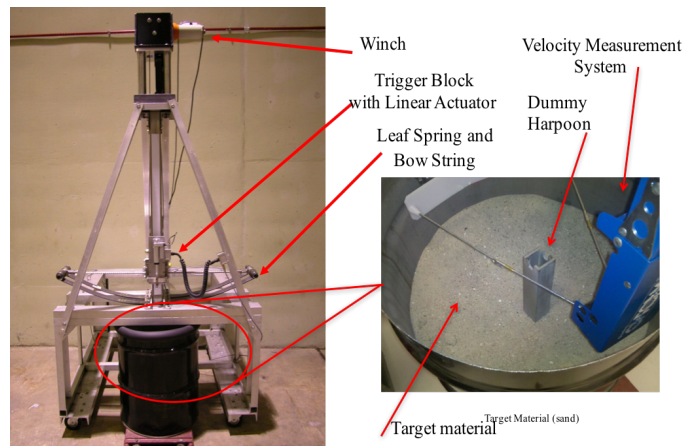


Figure 12. GSFC Laboratory "Ballista" for Firing Test Harpoons into materials representing expected range of comet surface properties

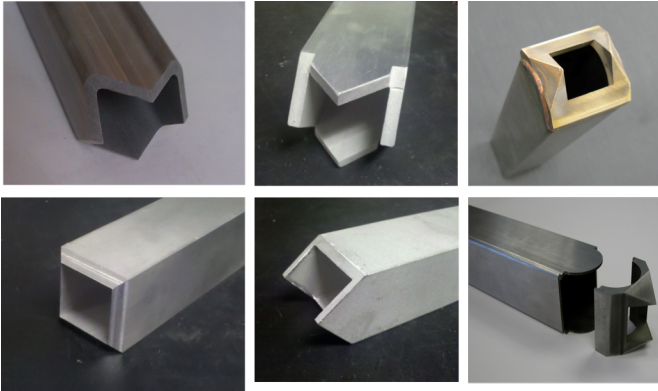


Figure 13. Some Sample-Gathering Harpoon Tip Geometries Tested by Having Ballista Fire Them into Different Materials

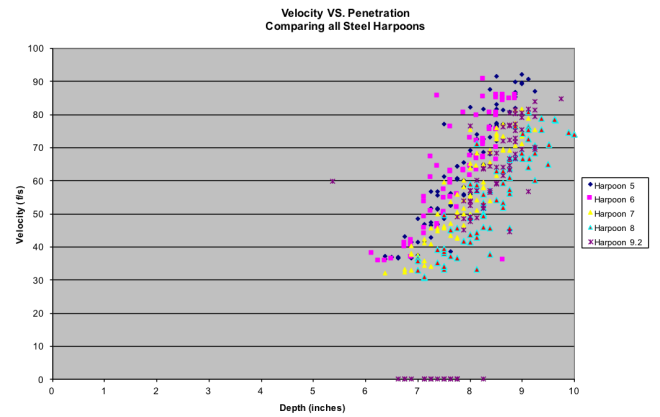


Figure 14. Test Harpoon Penetration Depth vs. Velocity for Varying Tip Geometries

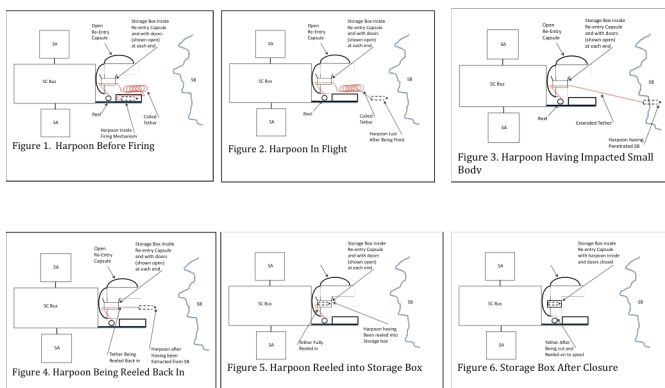


Figure 15. Concept from 2011 GSFC IRAD Proposal to Study a Standoff Sample Acquisition System (SSAS)



Figure 16. SAS Tower Test Facility (TTF) with Protective Shed on Top of Tower, New Work Shed on Ground and Re-purposed EMC Test Van



Figure 17. Barrel of Comet Material Simulant Installed in TTF Showing Dual Carpenter's Tape Tether and SARP Having Penetrated and Then Extracted from Simulant

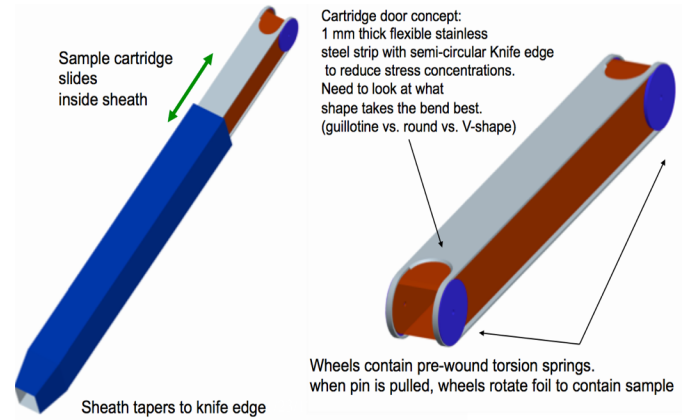


Figure 18. Initial Concept for SARP Sample Cartridge and Sheath

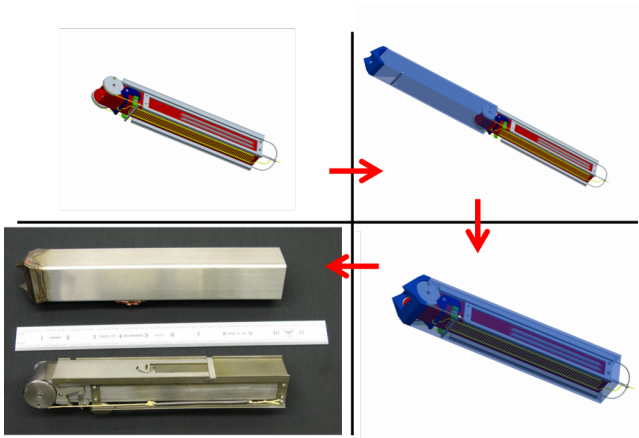


Figure 19. Initial Concept and Test hardware for Spring Loaded Door for SARP Sample Cartridge

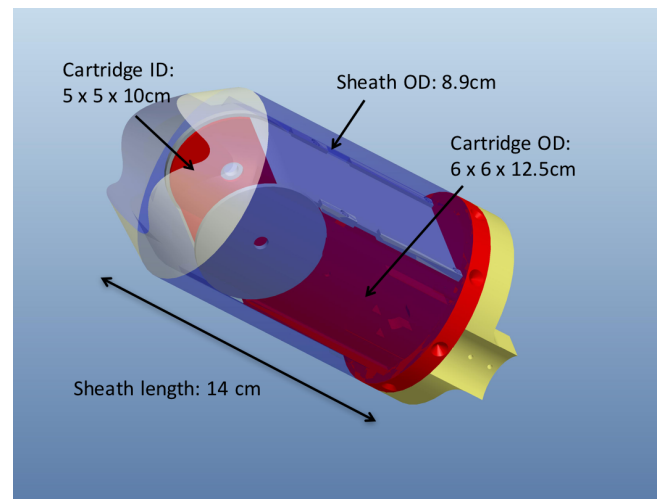


Figure 20. New SARP Dimensions after Reconfiguration to meet CORSAIR Requirements into Different Materials

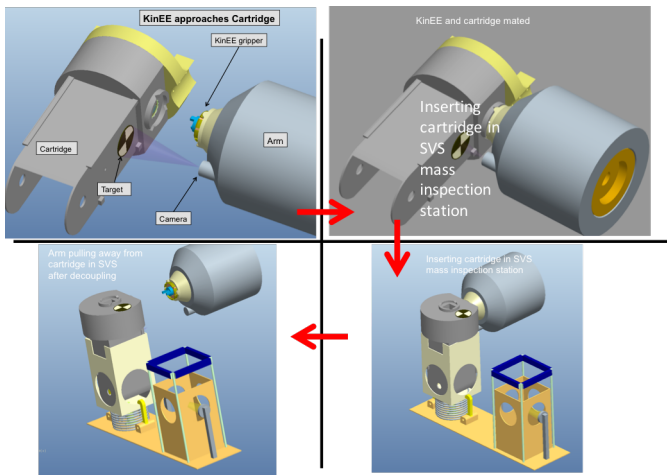


Figure 21. SARP with 2 KINEE Interfaces being Grasped and Released from Side Interface

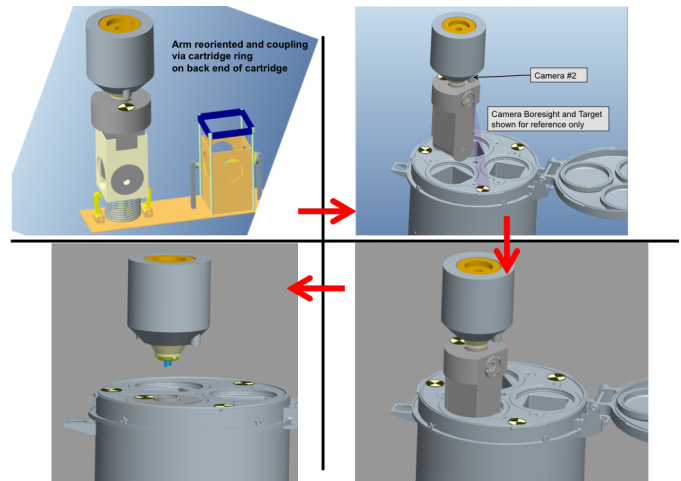


Figure 22. SARP with 2 KINEE Interfaces being Grasped and Released from Rear Interface

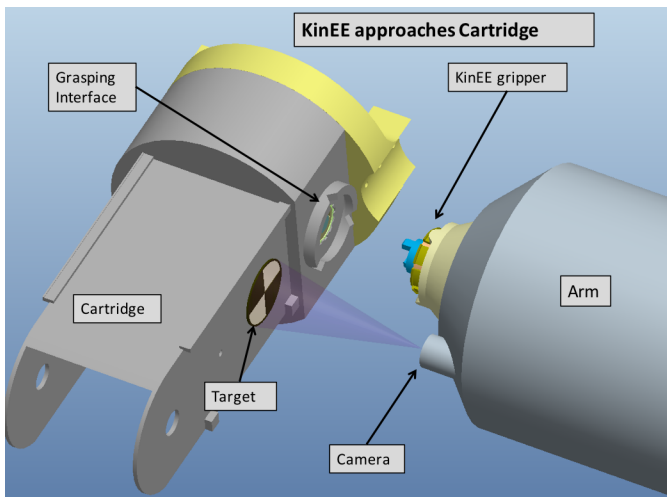


Figure 23. Initial KINEE Concept with Camera and Alignment Target on Side of Sample Cartridge

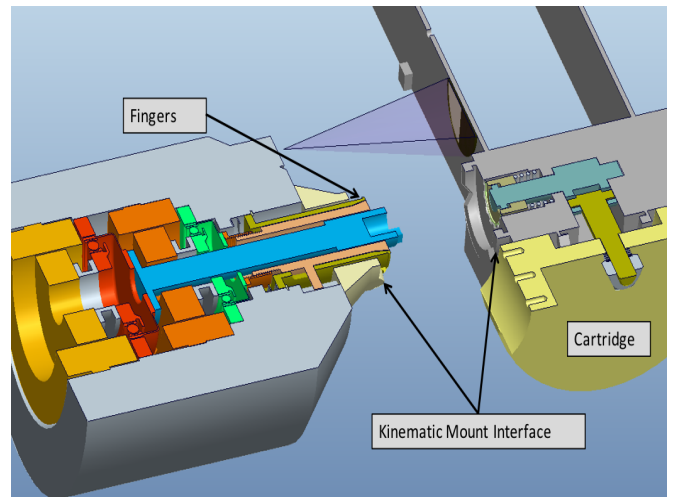


Figure 24. Details of Latching Mechanisms for Initial KINEE Concept

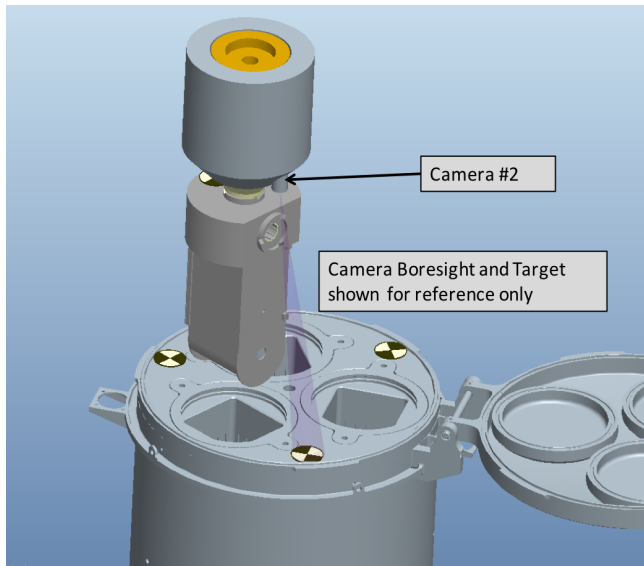


Figure 25. Initial KINEE Concept with Second Camera, plus Alignment Target on Sample Storage System (SSS) in Earth Entry Vehicle (EEV)

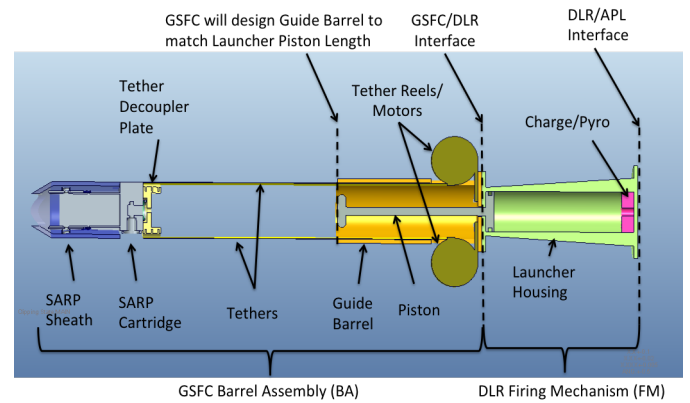


Figure 26. Initial Concept for TERM to Operate with DLR Launcher and Dual Carpenter's Tape Tether (DCT)

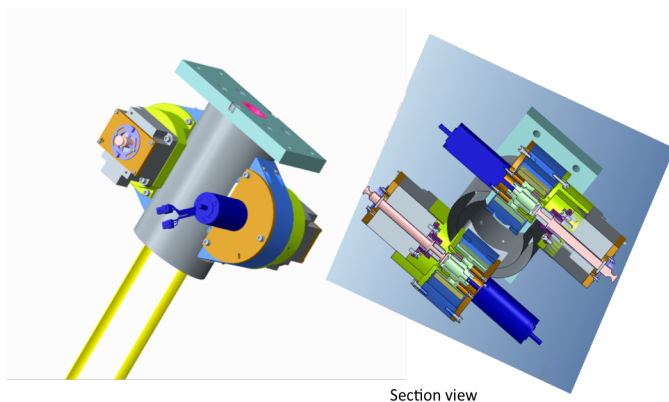


Figure 27. TERM Design Details

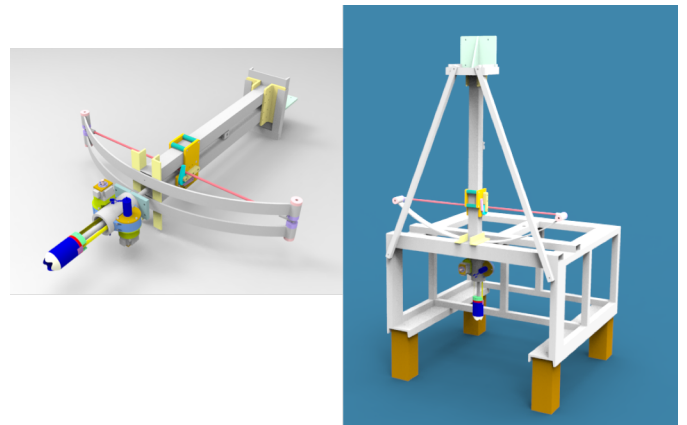


Figure 28. Concept for TERM Mounted on Ballista and Ballista Mounted on Stand to be Placed on Top of TTF

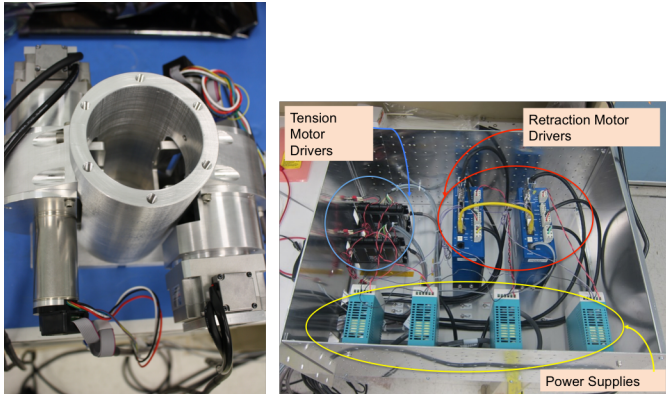
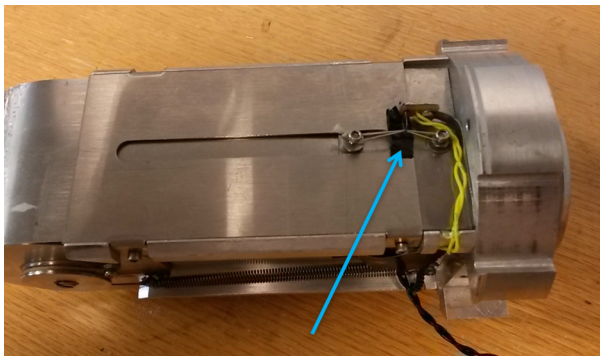


Figure 29. Initial KINEE Concept with Second Camera and Alignment Target on Sample Storage System (SSS) in Earth Entry Vehicle (EEV)



Figure 30. Test SARP Penetration Start and End, Followed by Electronically Triggered Release of Outer Sheath and Start and End of Extraction



Nichrome wire burns through Vectran "rope" when signal is received.

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Figure 31. Initial Test SARP with Burn Wire to Release Cartridge Door



Band clamp holds sheath to cartridge (currently - not flight) and is released by burn wire to decouple the cartridge from the sheath.



Part features without band clamp

Figure 32. Initial Test SARP with Burn Wire to Release Outer Sheath

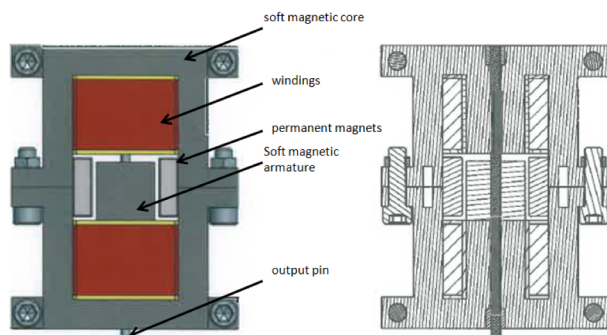


Figure 33. GSFC-Develop Bi-Stable Pin-Puller to Trigger SARP Mechanisms

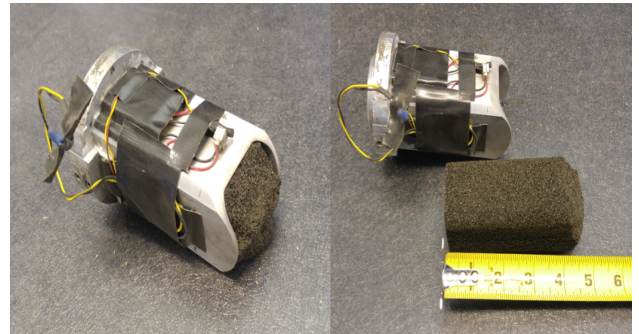


Figure 34. SARP Instrumented with Blinking LED to Enable High Speed Cameras to Accurately Measure SARP Velocity at Moment of Impact

- Bench top sample capture door experiments were conducted to measure the torque required to consistently cleave and capture a sample in 2.4 MPa foamglas. On Average less than 100 in*lbs (11.3 N*m) was required.

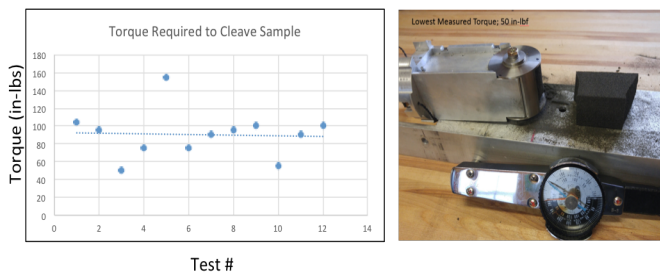


Figure 35. Measurements and Setup of Torque-Wrench Tests to Determine Force Required to Cut Through Hardest (2.4 MPa) FOAMGLAS

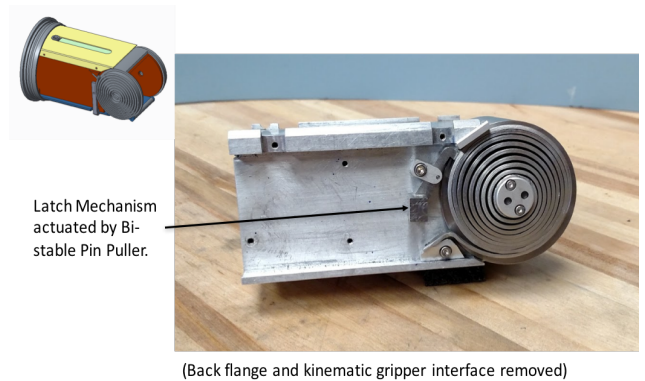


Figure 36. Initial Setup of Spiral Spring with Enough Torque for Pair of Spiral Springs to Push Sample Cartridge Door through Hardest (2.4 MPa) FOAMGLAS

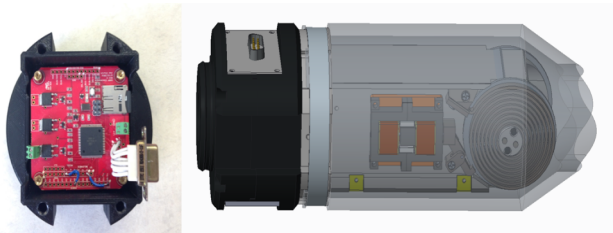


Figure 37. Full SARP Assembly Containing Black De-Coupler Plate With Control Electronics on Red Circuit Board, Transparent Grey Outer Sheath and Shaded Sample Cartridge with Bi-Stable Pin-Puller and Spiral Spring

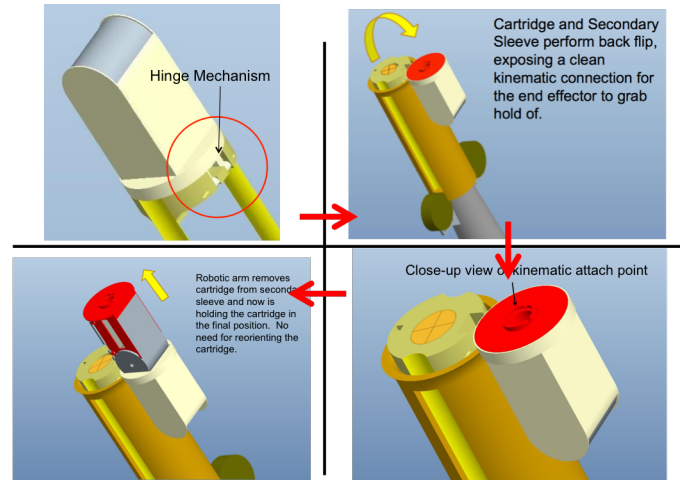


Figure 38. SARP on Flip-Hinge in Closed and Open Positions, with Open Position Showing KINEE Interface on Back of Sample Cartridge

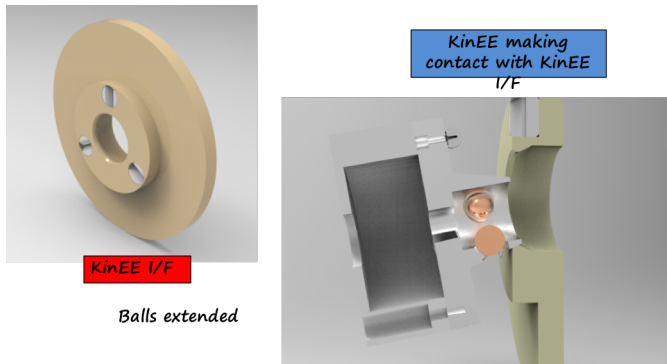


Figure 39. KINEE Grasping Interface with Tapers to allow KINEE to be aligned by Robot with Force Feedback

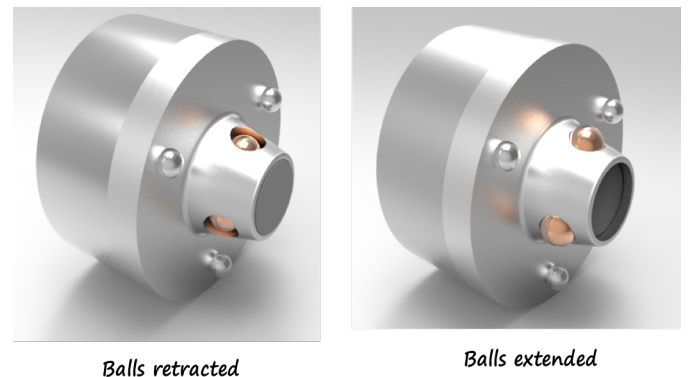


Figure 40. KINEE Grasping Mechanism with Tapers to Allow for Force Feedback and Showing Locking Balls in Retracted and Extended Positions

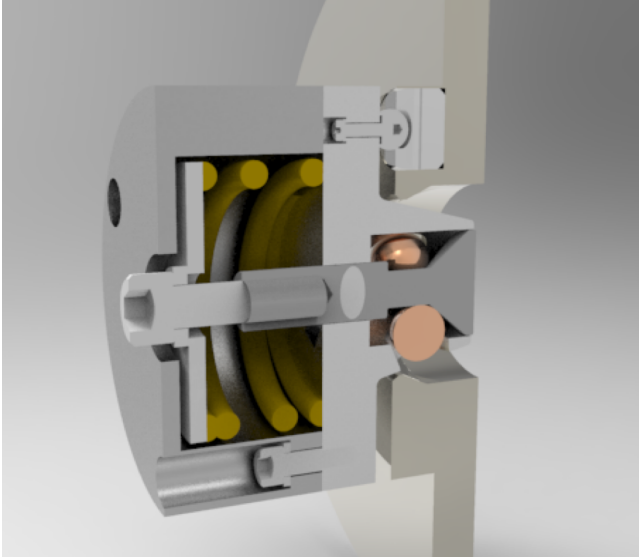


Figure 41. KINEE moving into Grasping Interface (left) and Locking Tight by Pushing Balls Outward (right)



Figure 42. Versions of KINEE and SARP Developed for Testing with DLR Robot

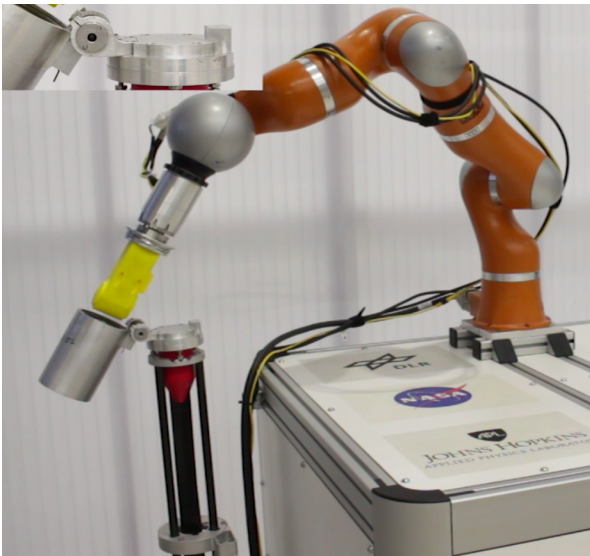


Figure 43. DLR Test Robot Extracting Sample Cartridge From SARP on Open Flip Hinge

Test 13:
Target: 2" layer of 2.4 MPa FOAMGLAS on 15" of 800
FOAMGLAS
SARP: fired at 900 psi; impact velocity 33.4 m/s; penetrated
5.75" (14.6 cm)

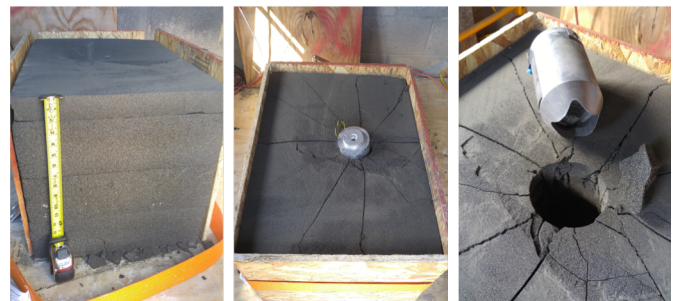
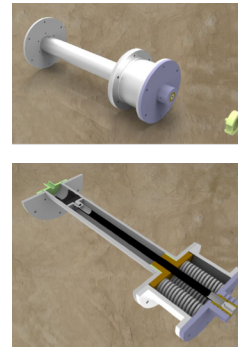


Figure 44. SARP Penetration of ≥ 10 cm into Hardest (2.4 MPa) FOAMGLAS

	Inputs	Comments
Width of Sample Cavity (cm)	5.00	
Depth of Sample Cavity (cm)	5.00	
Height of Sample Cavity (cm)	10.00	
Cross Sectional Area of Sample Cavity (cm sq)	25.00	
Cross Sectional Area of Sample Cavity (m sq)	2.50E-03	
Volume of Sample Cavity (cc)	250.00	
Volume of Sample Cavity (m³)	2.50E-04	
Diameter of Harpoon (in)	3.75	Increased diameter from 3.5 inches to make room for inner sheath
Diameter of Harpoon (m)	9.518E-02	
Cross Sectional Area of Harpoon (m sq)	7.13E-03	
Cross Sectional Area of Harpoon minus cross sectional area of sample cavity (m sq)	4.63E-03	
Cross Sectional Area of Harpoon minus cross sectional area of sample cavity (m sq)	7.17	Roughly agrees with Wegel e-mail of 7/2/2013, 10:21 AM
Required Penetration Depth of Harpoon (m)	0.10	
Volume of Material to be Displaced (m³)	4.63E-04	
Mass of Harpoon (kg)	3.062	From SARP MEL developed with Don W. in Aug 2015
Max Expected Compressive Strength of Comet Surface in Pascals (N/m²)	2.00E+06	From SAS Level 3 Requirements in Stu Hill E-mail of 10/24/13, 10:35 AM
Energy to Displace Required Volume of Comet Surface in Joules (Nm)	925.11	
Required Harpoon Velocity (m/s)	24.58	From Equation 13 of "Using the anchoring device of a comet lander to determine surface mechanical properties"

Figure 45. Measured and Modeled Penetration of SARP in FOAMGLAS



VIPr uses compressed helium gas to provide acceleration.

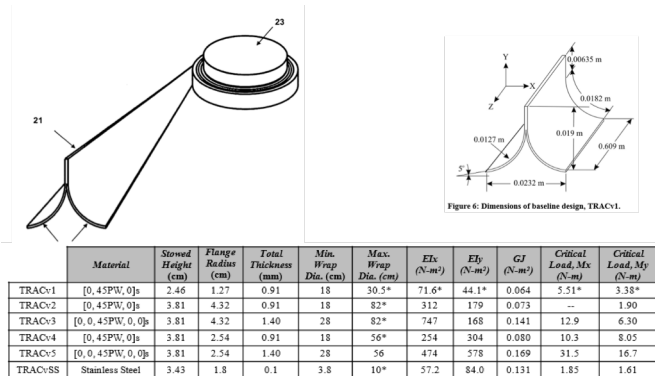
Initial testing of VIPr was done outside of TTF.

Launcher has since been integrated into tower.



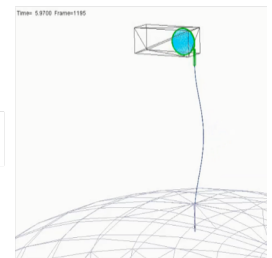
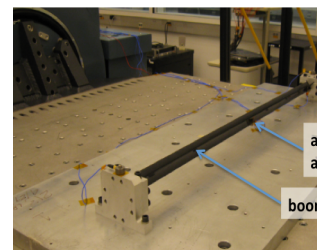
46

Figure 46. Variable Impulse Pressure (VIPr) Launcher



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Figure 47. Triangular Rollable And Collapsible (TRAC) Boom with Properties for Different Versions (V5 used)



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Figure 48. APL Measurement of TRAC Boom Stiffness and Image from APL simulation of TRAC Boom Behavior using ADAMS Software

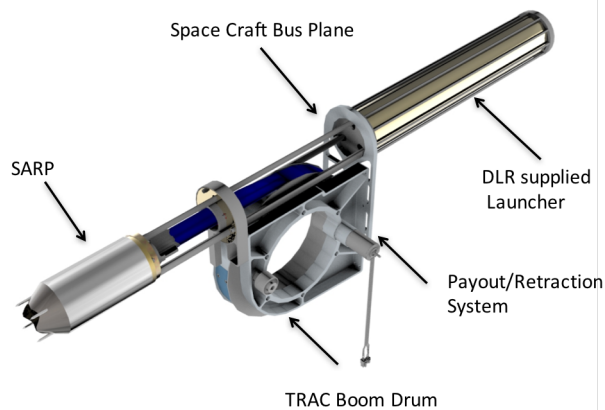


Figure 49. 1 of 4 Identical SAS Assemblies (SARP, TRAC Boom, BRAD and DLR Launcher)

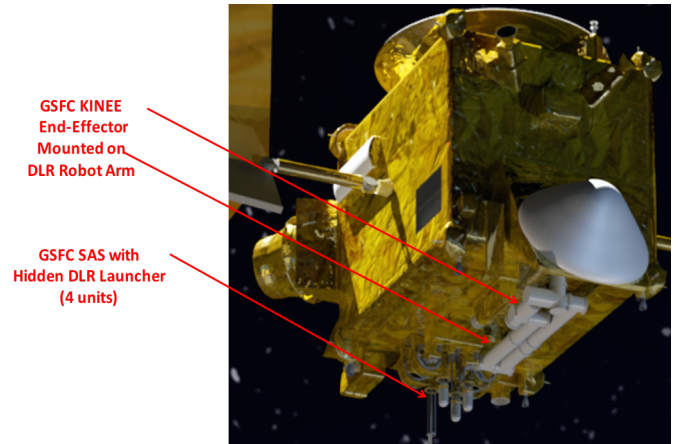


Figure 50. Four (4) SAS Assemblies and KINEE on CORSAIR SC In Stowed Flight Configuration

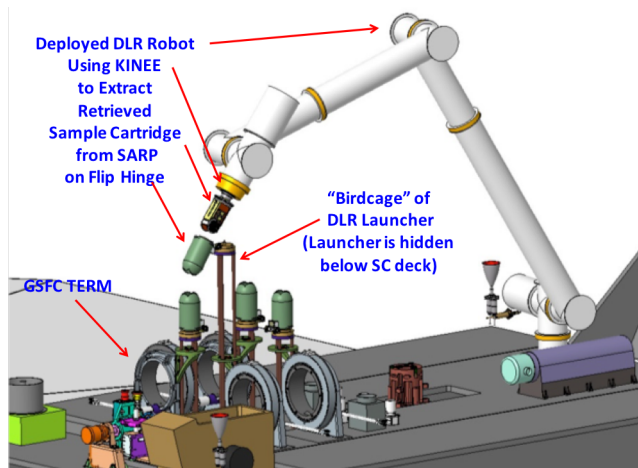


Figure 51. CORSAIR Flight Configuration of Deployed DLR Robot Removing Sample Cartridge from SARP on Open Flip Hinge

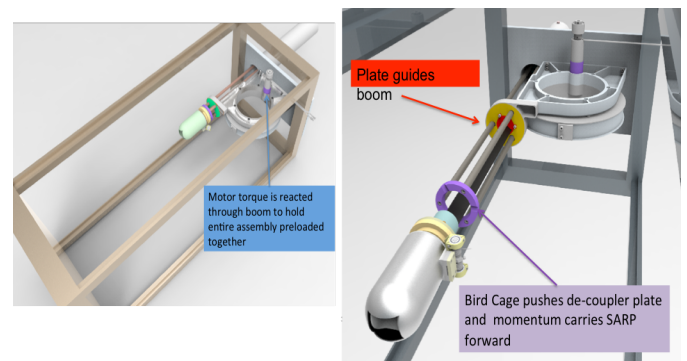


Figure 52. Setup for End-to-End SAS Test in TTF Showing Configuration Just Before Firing (left) and just after Firing (right)

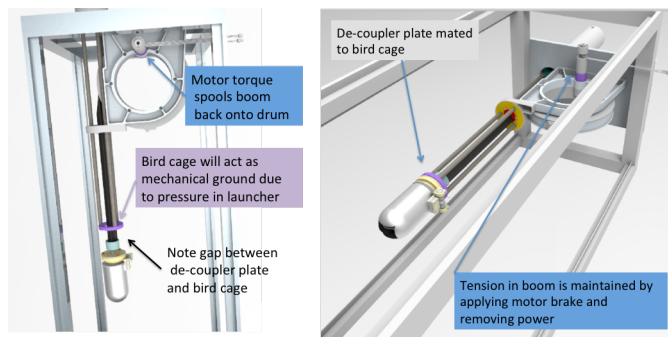


Figure 53. SAS Configuration in TTF End-to-End Test as SARP is being retrieved (left) and just after SARP is full Retrieved (right)

References

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2. <https://en.wikipedia.org/wiki/Asteroid>
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7. <https://www.nap.edu/download/10432>
8. <https://science.nasa.gov/researchers/sara/grant-solicitations/new-frontiers-announcement-of-opportunity>
9. <https://www.nap.edu/read/12372/chapter/10#78>
10. NASA Technical Report Server (NTRS) document link:
<http://hdl.handle.net/2060/20170004092>

