Spacecraft in the Shot: A Platform for Deep-Space Cinematography

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Spacecraft In The Shot (SITS) is a breakthrough cross-disciplinary initiative that stands at the intersection of advanced technology and strategic storytelling. It aims to enhance humanity's connection to robotic space exploration by capturing high-definition footage of heroic spacecraft along their journey through deep space. The SITS Imaging Instrument, a self-contained, highly autonomous instrument package can be included in any typical mission payload. The Instrument stores and deploys SITS *imagers*, or camera-carrying nanosats. As a mission approaches a key milestone in the trajectory, the SITS Instrument deploys one or more *imagers* that fly pre-programmed, autonomous trajectories around the host spacecraft. After the footage has been collected and downlinked to the host, the Imagers get decommissioned and left behind as the host spacecraft continues into the depths of space until the next photo opportunity.

Key Words: Nanosats, Footage, Cinematography, Storytelling

1. Introduction

Over the past 60 years the space exploration industry has given humanity valuable insight into our universe, our solar system, and the environmental mechanisms of our own planet. These insights have been communicated to the public through articles, visualizations of data sets, scientific imagery, artist renderings, and more recently, social and web-based media. Despite the success of NASA's social media campaigns, studies show that many of the agency's recent achievements do not resonate as emotionally to the hearts and minds of the present-day younger generation than the Apollo generation. [1] This is especially true for robotic deep space missions, which don't have the natural public figureheads that astronauts are for the human exploration program.

According to a 2008 Scientific American article titled "Robots vs. Humans," NASA's public relations strategy focuses on promoting the program through "entertaining visuals and stories with compelling characters." It's important to note that the characters that resonate with the public are not only astronauts, but rovers and landers that appear anthropomorphized, especially those that have captured in situ "selfies". Smart social media managers at NASA have taken advantage of this to position the mission as a *story* with the robot as the *hero*. Cognitive science has shown that stories activate the hypothalamus and release oxytocin, neurochemicals that are associated with the sense of empathy. [2] Storytelling missions in this way helps bridge the divide between robotic explorers and the humans that sent them.

Along with astronauts and anthropomorphized landers, NASAs robotic spacecraft will continue to journey to novel destinations and push the boundaries of technological and scientific progress. Spacecraft-In-The-Shot (SITS) is offering these future missions the opportunity to viscerally stimulate a new and younger generation. As these spacecraft encounter new and historic firsts in space exploration, SITS will be there to document these moments for the benefit of all mankind.

The Spacecraft-in-the-Shot (SITS) initiative will harness modern filmmaking technology to enable NASA to bring humanity along the most epic interplanetary robotic spacecraft journeys of our time through the eyes of a small team of autonomous *imagers*. These *imagers*, which are a fraction the size of a 1U CubeSat, will deploy away from the host spacecraft to autonomously capture cinematic quality HD footage of the spacecraft operating at location.

Moreover, as operations in space become more and more complex, having an asset such as SITS onboard to monitor key spacecraft events such as deployments, rendezvous, and burns brings a powerful engineering capability to missions. The flexibility SITS offers with its autonomous, free-flying *imagers* gives an extra dimension of possibility to storytellers, engineers and scientists alike.

2. Space Snapshots Over Time

A few of the most profound images throughout the history of human culture were images such as "Earthrise" taken by the Apollo 8 Astronauts in 1968 and the first portrait of the solar system called "Pale Blue Dot" by Voyager 1 spacecraft in 1990.

Fig 1. Earthrise (left) and Pale-Blue Dot (right).

These images, shown in Fig. 1, were not original mission requirements, yet they gave humanity new vantage points into their existence as a species. The impact of these images to our society's morale are indisputable. Spacecraft-in-the-Shot would provide the world with the capability to capture new vantage points: real footage that the general public has only been able to imagine through artist renderings.

2.1. The History of Interplanetary Cameras

To date, there have been 24 interplanetary spacecraft with cameras. [7] Most of these cameras, ranging from New Horizon's Long Range Reconnaissance Imagers (LORRI) to Mars Science Laboratory's MASTCAM, had scientific objectives. Only one mission, JUNO, had the intentions of public outreach as a high priority. Funded by EPO, JUNOCam was not a scientific requirement, but was decided upon because the mission team couldn't imagine not taking visible imagery. However, JUNOCam also had the scientific objective to map the Jupiter's poles in color and low incidence angles. [8]

Despite their good intentions, most of these cameras missed out on the opportunity to contextually put a trace of a man-made object into the picture. With that said, there have been a few missions that have turned the spacecraft's camera around to take interplanetary "selfies." In 2014, the European Space Agency's Philae lander a took a photo of the Rosetta spacecraft's solar panels before landing on the comet 67P / Churyumov-Gerasimenko. [9]

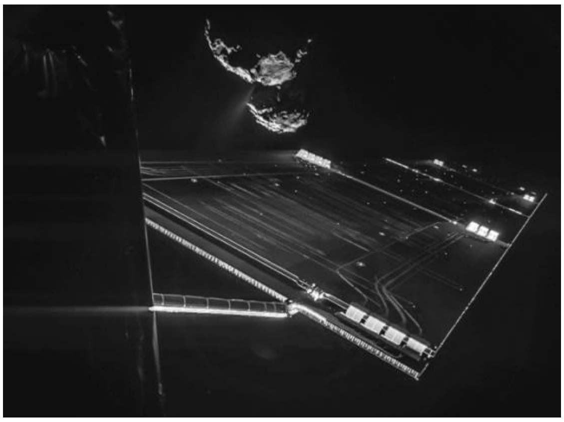


Fig 2. Rosetta selfie with 67P.

Another example is The Planetary Society, which has taken selfies of its solar sail cubesat, called LightSail, to monitor deployment. [10] In 2016, China released Bianxing 2, a formation-flying CubeSat, from their Tiangong 2 Space Lab to monitor the lab's condition using visible and thermal infrared wavelengths. [11] Though the spirit of a "selfie" was there, these images were not conducted with effective storytelling as a priority.

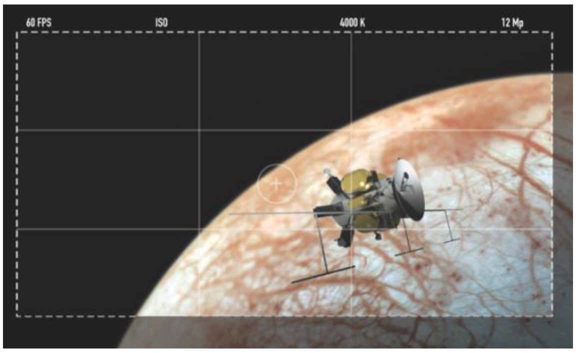


Fig 3. SITS would take high-definition footage of mission milestones.

2.2. Value of Contextualizing Images

Artists have been visualizing the scientific unseen for thousands of years. Within the domain of interplanetary missions today, artistic renderings are crucial to the public's contextual understanding of space exploration. Deep space missions rely on computer and conceptual renderings to show their spacecraft operating at location. However, there is an inherent sense of inauthenticity in artistic renderings of this type.

There is a reason why people go on trips or vacations and have the desire to take photos of themselves in the foreground of beautiful rolling landscapes or the canals of Venice. Researchers are now interested in understanding this method of documentation as a social practice and cultural artifact. [6] Fundamentally, putting people within a photo gives the photo a sense of humanity and context. For example, a National Geographic photo of an ocean is interesting, but capturing a photo of a blue whale jumping out of the ocean creates compelling contextual connection. The same kind of visceral connection can be made to destinations in deep space by capturing mission spacecraft in the foreground. The spacecraft brings an element of the human into an otherwise alien landscape, and allows people back on Earth to see a bit of themselves in the shot.

3. A Payload for Humanity

Over the past six decades, space scientists have contributed to the answers of some of the most fundamental questions about humanity such as: Where did we come from? How did we get here and where are we going? These questions of belonging are not only fundamental questions in NASA literature, but are inherent to what makes us human. While NASA's historical vision is inspiring, instrument payloads on current interplanetary spacecraft have objectives exclusively for the sake of science return. However, there is real value in documenting historical human-made moments and communicating these to the people back home. This value is widely recognized on the ground, as journalists regularly travel the world to document and report on important societal events. The cameras were rolling when Dr. Martin Luther King gave his world shaking "I have a dream" speech, when the Berlin wall fell in 1989, and when SpaceX landed its first reusable first stage rocket in 2017. It's a shame they weren't when Pioneer 10 performed the first encounter of Jupiter or when the NEAR spacecraft first made the first soft-landing on an asteroid.

The Spacecraft-in-the-Shot offers the capability to capture these achievements using the same high-quality cinematography people have come to expect back on Earth Leveraging state-of-the-art camera technology and recent advancements in small satellite hardware, SITS can revolutionize how mission stories are told.

3.1. The Science of Storytelling

Numerous studies have proven that the power of storytelling is a neuroscience. Humans are viscerally carried along with compelling narratives, not only because of cultural tradition, but because of the chemistry in our brains. Paul J. Zak, Director of The Center for Neuroeconomic Studies at Claremont Graduate University, works with his team to study how humans biologically respond to stories. 12) According to his lab's research, he concludes that good stories elicit strong empathetic responses by releasing neurochemicals of oxytocin and cortisol found only in mammals. Oxytocin is nicknamed the "morale" or "cuddle" molecule and is linked to interactions of social bonding.

Stories have been linked to personal transformation for thousands of years. Only recently have scientists found that storytelling is an inseparable part of our DNA and what makes us inextricably human. In 2013, researchers at Emory University published studies in which they detected biological reactions to hearing stories. 13) They found that the primary sensory motor cortex of a human experiences heightened connectivity when experiencing a story. That is why a good narrative has a lingering effect and has the power to shape people's lives and behaviors.

3.2. Why Now

In study conducted by Dr. Richard Felder, over 65% of engineering students were found to be "visual learners." This research became the foundation for a standardized test called the Index of Learning Styles (ILS). 14) The attraction to consuming information by seeing is also reflected in the popularity of social media technology like Instagram and Snapchat, that empower people to easily share visuals of their own life journeys, whether it is vacation photos or throughout their ordinary day.

Right now, the public receives its visuals of humanities journey into deep space primarily from science fiction films and artists. However, NASA has an opportunity to harness this appetite for imagery by cooperating with the powerful storytellers from the film-industry. NASA can capture the cinematic experiences of its robotic deep space probes and transform into fact what is currently only visible in science-fiction.

4. The Journey of a Mission Concept

For decades, spacecraft camera technology has only been utilized where its had high scientific value. Since the primary function of SITS is to take high-definition stills and video to document and communicate historical moments in deep space, it has been challenging to fit it into the current payload paradigm.

In the summer of 2016, after multiple attempts to get funding for SITS through traditional NASA technology proposal calls, Jonathon Smith, a navigator in JPLs Mission Design and Navigation Section, presented the idea to a panel of judges on JPL's Inaugural Pitch Day. Firouz Naderi, former Director of Solar System Exploration at JPL, said it was the best concept he heard that day. Sponsored by The Office of Technology, SITS was finally awarded seed funding to mature the concept within JPL's early formulation center, The Innovation Foundry.

4.1. Early Architecture Study

The Innovation Foundry at JPL is one of NASA's most successful mission system architecture centers. It is a program office that helps foster and mature pre-phase A mission concepts through the field of concurrent engineering. Interdisciplinary core teams of engineers and scientists get together with subject-matter experts and mission clients to conduct rapid mission studies that help to push a concept through to the next phase of the mission formulation lifecycle. The first step for SITS was to conduct a study with the Innovation Foundry's A-Team.

The A-Team or Architecture Team is a group of cross-disciplinary engineers and scientists that grow concepts within the first few levels of concept maturity (CML). They work within the facility of Left Field, a colorful brainstorming room with wall-to-wall white boards and sticky notes. Mission ideas that come to the A-Team range from practical to radically futuristic. Yet even to this seasoned crew, SITS was considered unconventional and a little out of "Left Field." The majority of A-Team core members are made up of engineers and scientists. One of the newest members of A-Team, Jessie Kawata, JPL's Creative Strategist and Lead Industrial Designer, was brought on to lead the study. Jessie had a background of product design and development and was working on the development of strategic storytelling tools already, making her a natural fit to lead the SITS study.

Through the A-Team study, SITS was decomposed, examined and reassembled into its current form. With a sound concept in hand, SITS was ready for the Innovation Foundry's rapid mission development team, TeamX.

4.2. Feasibility Study

TeamX is cross-functional multidisciplinary team of engineers. They utilize concurrent engineering methodologies to complete rapid design sessions with constrained cost, mass, and volume budgets. TeamXc is a specialized group within the broader organization created in response to a rise in demand for SmallSats, NanoSats, and CubeSats.

SITS entered a 3-day TeamXc feasibility study, where engineers worked around their norm to create a point design driven by storytelling requirements instead of science. The result of the session was *SITS Earth-Shot,* a reimagining of the standalone SITS payload instrument appropriate for proposal as an Earth-orbiting NASA Technology Demonstration Mission.

5. Earth-Shot Technology Demonstration

The ultimate goal of this initiative is to design and build a standalone spacecraft instrument that can be carried into deep space as payload on NASA's robotic exploration missions. However, an intermediate goal is currently being pursued to develop a technology demonstration version of the instrument for operation in Earth orbit. The design described below is the *SITS Earth-Shot spacecraft* which has merged the SITS *instrument* into a 12U CubeSat. The resulting spacecraft houses the *imagers* to be used in the demonstration and also has all the subsystems needed for independent flight (comm, GNC, power, thermal, etc). It is important to note that the standalone *instrument* and *Earth-Shot* both share the same concept of operations and key technology drivers, which is of course necessary when designing a technology demonstration.

5.1. Concept of Operations

The SITS Earth-Shot system is designed to collect footage of itself operating in Earth orbit. It does this by tasking an individual *imager* to fly a media collection sortie (Fig. 4). These sorties are designed in advance by the ground team and uplinked to *Earth-Shot*. They identify the time at which the *imager* should be deployed and specify the trajectory and attitude profile that it needs to fly to collect the desired footage. There are three distinct phases involved in executing a sortie.

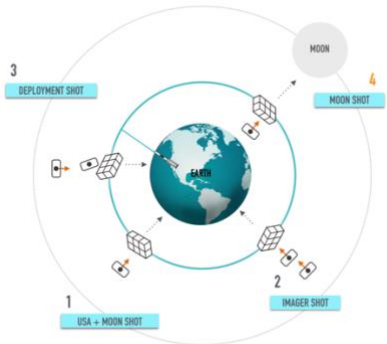


Fig 4. *Earth-Shot* Concept of Operations

5.1.1. Deployment

A sortie is initiated by the ejection of an *imager* from its storage location inside *Earth-Shot*. The *imager* will have been charged and tasked with a trajectory prior to deployment. The ejection mechanism ensures that *imager* clears the immediate physical location of the spacecraft, at which point it brings the host spacecraft within its field of view and initiates a footage stream to the *instrument*. Once the feed has been registered, the *imager* initiates its flight of the media collection trajectory.

5.1.2. Collection

Once clear of the immediate vicinity of *Earth-Shot*, the *imager* begins flight of the media collection trajectory. This trajectory was designed by analysts on the ground to position and point the *imager* to collect the desired footage. The *imager* dead-recons flight of the reference trajectory subject to an *r-plus control law*[1]. An autonomous navigation system onboard the imager allows it to dynamically update its pointing in the contingency that it departs the reference trajectory, ensuring that the desired footage is collected. The *imager* live streams footage directly to *Earth-Shot* where it is stored for downlink.

5.1.3. Decommissioning

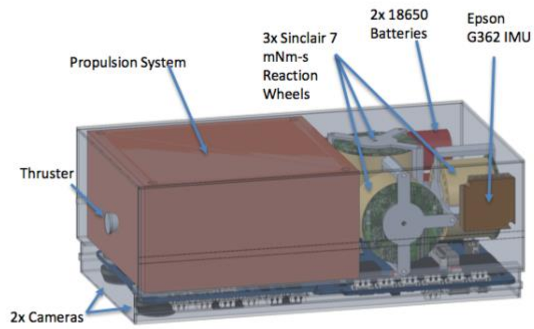
After completing flight of the collection trajectory, the *imager* is prepped for decommissioning. Instead of attempting a potentially hazardous re-docking, the *imager* simply drifts off into space and the r-plus control law assures it permanently leaves the vicinity of the spacecraft. The collected footage is processed by *Earth-Shot*, and chunked for eventual downlink to Earth.

5.2. Technology

The *Earth-Shot* spacecraft has been designed to fit entirely in a 12U CubeSat form factor. This was to make it conveniently packable as a NASA TDM tag-along launch payload. Most of the internal space is occupied by 5 stowed SITS *imagers* and their ejection scaffolding, with the remaining used by spacecraft subsystems. Figure 5 shows an integrated CAD rendering of an *imager* (top) and 5 imagers stowed in a 12U bounding box (bottom).

Design Overview

- *Instrument* merged into 12U CubeSat for free-flying testbed. The resulting spacecraft houses 5 *imagers*, with the remaining space used for spacecraft bus systems.
- Compatible with operations in LEO, GEO, and deep space. *Imagers* maneuver in a 3m - 30m range from the host spacecraft, and have a nominal life span of 15 minutes.
- Use of modern cell phone components (processors, transmitters, batteries, etc.) allows for miniaturization of the free flying *imagers*. Current size is 1/2U and further reduction is possible through reconfiguration of COTS hardware. Because the *imagers* have a short operational life and are disposable, failure of these non-space hardened components is an acceptable risk.



[1] *R-plus* is designed to protect the host spacecraft at all costs, and stipulates that any maneuver performed by an *imager* must have the effect of increasing the distance between the *imager* and spacecraft.

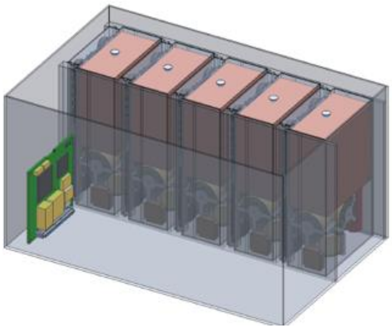


Fig 5. CAD renderings of *imager* (top) and 5 *imagers* in a 12U bounding box (bottom).

The current design is the result of a JPL TeamXc rapid- design session. It identifies all key software and hardware components and verifies that the mission concept is sound, but stops short of the detail needed to begin manufacture. However, the extensive use of COTS and high-TRL technology mean that maturing the design and progressing to hardware development can be done swiftly and safely. Table 1 lists the key system components and their maturity levels.

Table 1. *Earth-Shot* Design Maturity Level

Design Component	Maturity	Description
Overall Design	TRL 3	TeamXc point design for SITS Earth-Shot spacecraft
Hardware:		
Camera Stack	COTS	Cameras (Omnivision) and processors (Snapdragon)
Local Comm	COTS	*Instrument-imager* communication via Qualcom Wifi Chips
GNC	COTS	Sinclair reaction wheels, Epson IMU, DSSP thrusters
Power	COTS	Panasonic Lithium-Ion Rechargeable Batteries
Software:		
Monte	TRL 9	JPL ground software for trajectory design and navigation
AutNav	TRL 9	JPL flight software for autonomous spacecraft navigation

5.2.1. Collecting and transmitting footage

Because the *imagers* are discarded after a single use, emphasis has been placed on reducing both their physical size and cost so that more can be carried from mission start. Hardware is liberally sourced from the commercial cell phone market (Table 2) which invests billions of dollars every year in just these initiatives (miniaturization and cost reduction).

Table 2. Key *Imager* Design Components

Component	Description
Camera	Omnivision 13850 13.2 MP cell phone camera
Processor	Snapdragon 820 Android processor
Wifi Chipset	Qualcom AR9390 Chip 450Mbps
Wifi Antenna	Johanson Technology 2450AT18B100 antenna

Each *imager* is equipped with two cameras that independently stream footage back to *Earth-Shot*. Each camera has a dedicated wifi chipset and antenna to ensure a data-rate high enough to stream 4K video. On the receiving end, *Earth-Shot* has four independent wifi receivers (chipset and antenna) which allows for the simultaneous operation of up to two *imagers* (two dedicated channels for each *imager*). The *imagers* do not store any video; everything is streamed directly to *Earth-Shot* where it is logged in onboard storage and processed for downlink.

Camera Stack Design Summary

- *An S-Band (2.4 GHz) Wifi protocol is used for communication between the imagers and Earth-Shot.*
- Each *imager* has two independent cameras and streaming pipelines capable of processing 4K video (30 fps) or slow-motion 720P video (240 fps).
  - *Imager* streaming pipeline consists of Omnivision Cameras (x2), Snap- dragon Processors (x2), Qualcomm Wifi Chips (x2), Johanson Antennas (x2)
- *Earth-Shot* has four independent receivers capable of supporting two simultaneously operating *imagers*.
  - *Earth-Shot* receiving pipeline consists of Qualcomm Wifi Chips (x4) and Johanson Antennas (x4).
- Footage is saved on board *Earth-Shot* and preprocessed for eventual downlink to Earth.

5.2.2. Autonomous Operation

JPL has an astrodynamic software toolkit called Monte that is used for high-accuracy trajectory design and navigation[2]. The spacecraft trajectories produced by Monte are routinely used by science instrument operators to design their observation profiles. Monte can be configured to do an analogous task for SITS, which is to help operators design *imager* sortie trajectories that capture dynamic cinematic shots of the spacecraft and its surrounding environment. These trajectories will be created well in advance of the actual sortie, and uplinked for the *imagers* to fly autonomously.

After an *imager* has been ejected, it begins flying the sortie only after it has cleared a minimum-operational distance from the host spacecraft. At this point, the *imager* uses its onboard IMU to dead-recon flight of the reference trajectory. JPL's AutoNav flight software is used to adjust the pointing of the *imager* cameras in real time, to ensure the integrity of the shot even if the *imager* departs from its nominal flight plan[3].

After the sortie is complete, *Earth-Shot* will autonomously process the collected footage and segment it for downlink. Initially, only a low-resolution version of the footage will be

2 montepy.jpl.nasa.gov

3 AutoNav has flight heritage on several NASA missions, including Deep Impact and Stardust, where it was used with great success.

returned, allowing operators to prioritize in what order the full-resolution segments will be returned.

6. Growth Potential

The ultimate goal of Spacecraft In The Shot is to create an spacecraft payload instrument that can be included on all future NASA missions. Through the eyes of SITS, the current and next generation can view NASAs robotic deep space program in a completely new light. However, there is no reason that SITS has to stay within the halls of NASA. If SITS realizes its vision of a low-mass, low-cost, and low-risk system package, it will be viable as an option for international space agencies as well as the burgeoning commercial deep space industry. One can easily imagine SpaceX or Planetary Resources bringing along SITS as they start sending spacecraft to interplanetary destinations.

SITS also has the potential to foster new and important partnerships between the space industry and professionals in filmmaking, camera technology, product design, and social media. These new relationships can set the stage for future innovations in deep space cinematography. With the growth of augmented and virtual reality today, it is possible that in the future people could experience SITS footage in an immersive and interactive environment with a holographic headset.

7. Conclusion

SITS has the potential to revolutionize the way that humanity participates in the exploration of our Universe by
take footage of the spacecraft itself.

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