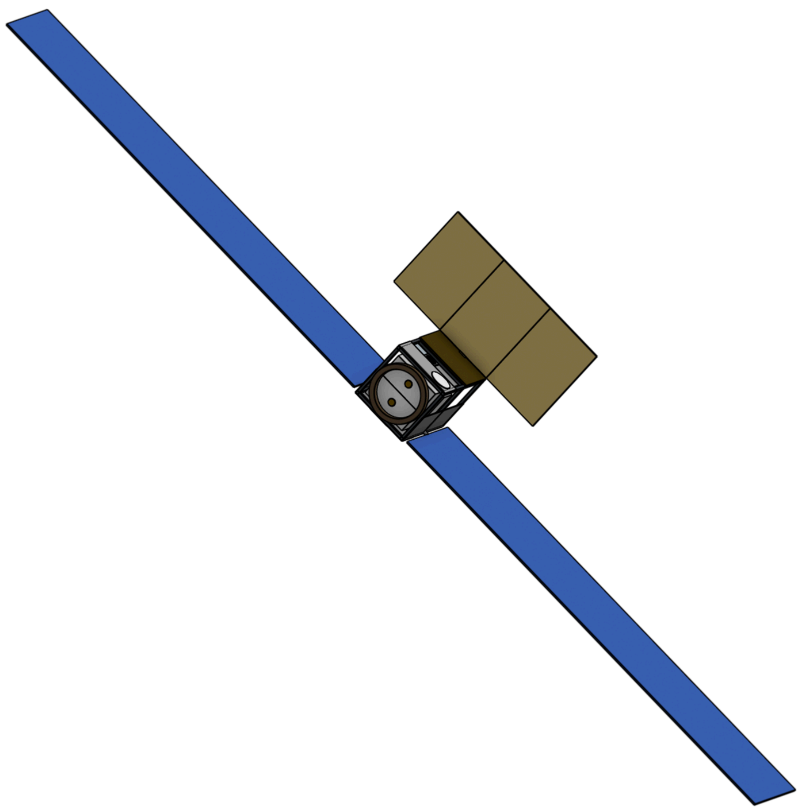
IZIHAMBO-1

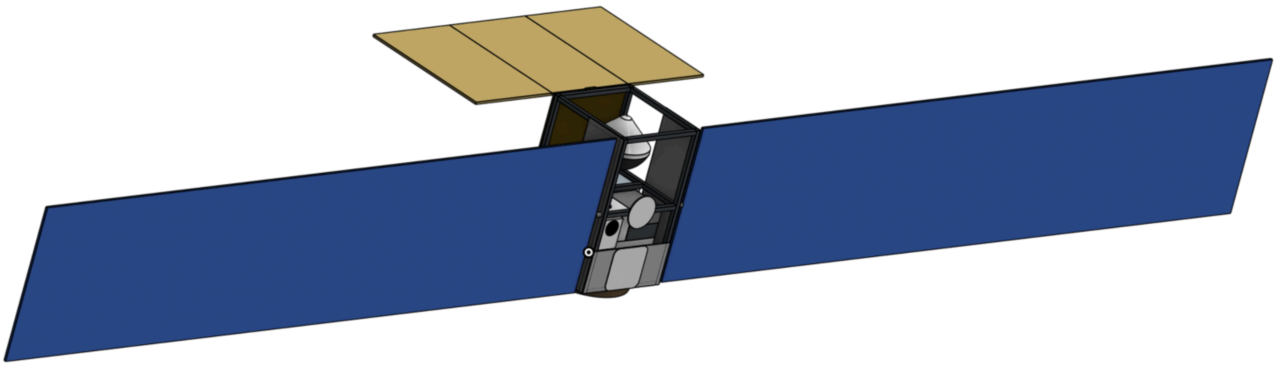
MOON - MARS - ASTEROID

DEEP SPACE CUBESAT MISSION



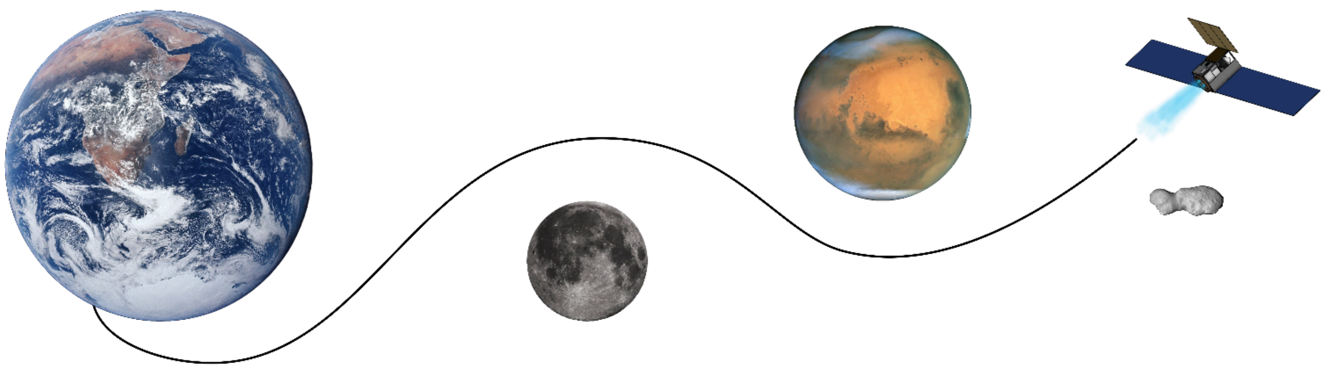
A PROPOSAL BY ALEXANDER BUICK

Izihambo, a Zulu word meaning Journeys, Travels, or Expeditions



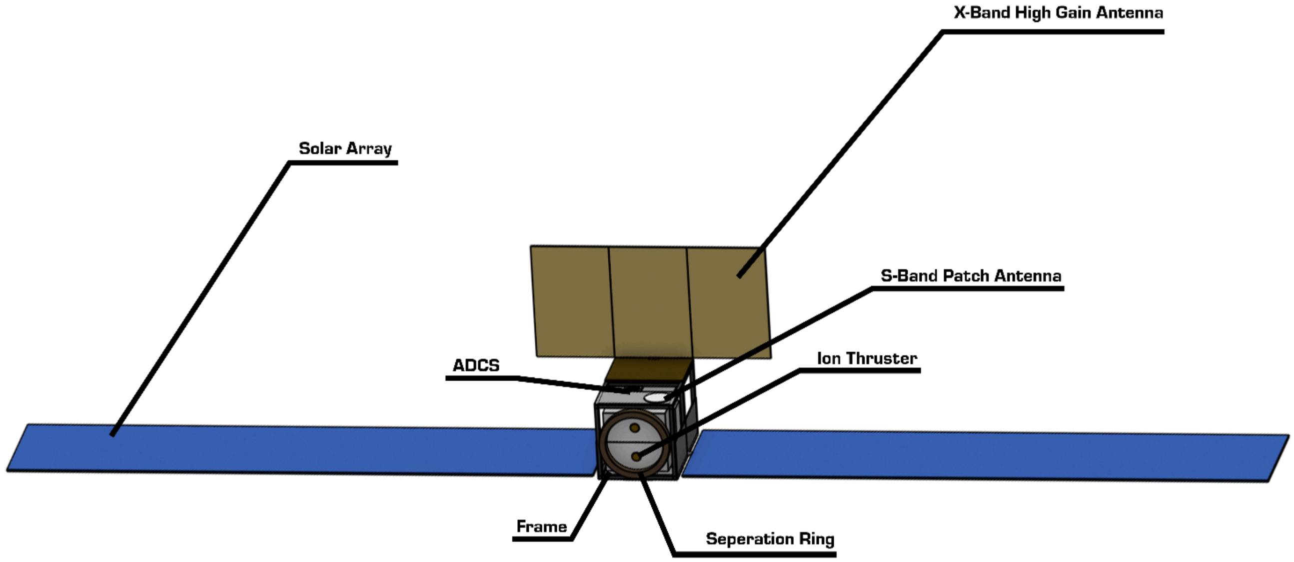
What are the goals of IZIHAMBO-1?

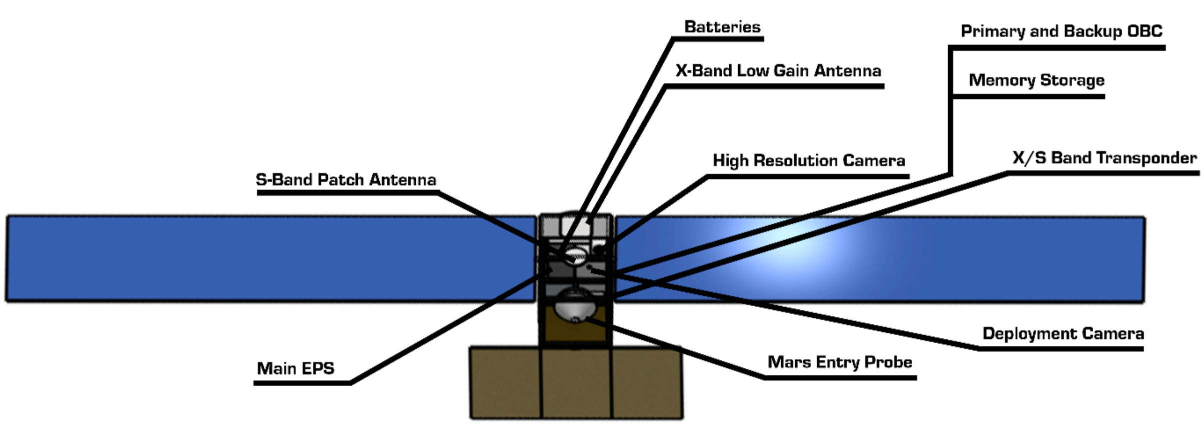
- Demonstrate that interplanetary space can be accessed cost efficiently while still enabling valuable scientific return.
- Capture high resolution imagery of the Moon, Mars, and a Near Earth Asteroid.
- Deploy a sub-2kg mini probe to enter the Martian atmosphere to validate the viability of small scale Mars EDL (Entry, Descent, and Landing)
- Position South Africa as the world's 4th nation to land hardware on Mars.



Mission Overview

IZIHAMBO-1 is a cost efficient 12U deep space CubeSat mission designed to demonstrate access to interplanetary space while maintaining meaningful scientific capability. IZIHAMBO-1 will be placed on a Trans-Lunar Injection (TLI) trajectory by a launch provider. Its lunar flyby serves not only as a scientific opportunity, but also as a gravity assist that injects the spacecraft into heliocentric orbit. From there, IZIHAMBO-1 will perform a long, low-thrust burn to place it on a trajectory that will initially encounter the Martian atmosphere. Approximately a few weeks prior to arrival, the Mars Descent Probe will be released, after which the primary spacecraft will execute a divert maneuver to avoid atmospheric entry. During the Mars encounter, IZIHAMBO-1 will image Mars, conduct scientific observations, and act as a communications relay for the Mars Descent Probe. Following the Mars flyby, the spacecraft will perform course corrections to place it on a trajectory to encounter a Near-Earth Asteroid (NEA).





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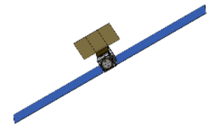
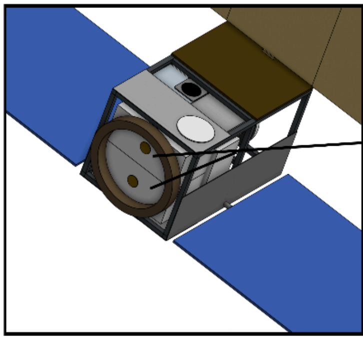
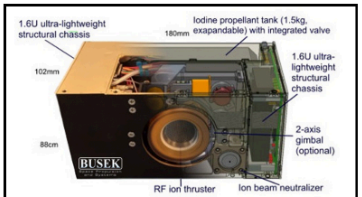
Spacecraft Architecture



Propulsion



Credit: Busek



Credit: Busek

Credit: Busek

2x Bit-3 Ion Thrusters with gimbal

Dry Mass: 1.40kg Each (Total 2.80kg)

Wet Mass: 2.90kg Each (Total 5.80kg)

Power: 56-75 W Each (Total 112-150 W)

Delta V (14kg Cubesat): 2.39 km/s Each (Total 4.78 km/s)

Thrust: Up to 1.1 mN Each (Total 2.2 mN)

Specific Impulse: Up to 2,150 s

Gimbal: 2-axis, ±10° (capable of desaturating reaction wheels)

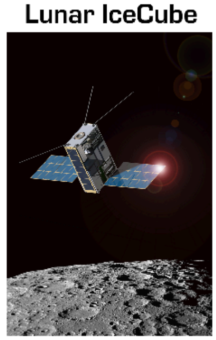
Manufacturer: BUSEK Space Propulsion and Systems

Cost Estimate Guess: $150,000 - $250,000 (ZAR 2,567,452.55 - 4,279,087.59) Each (Total $300,000 - $500,000

[1][2][3]

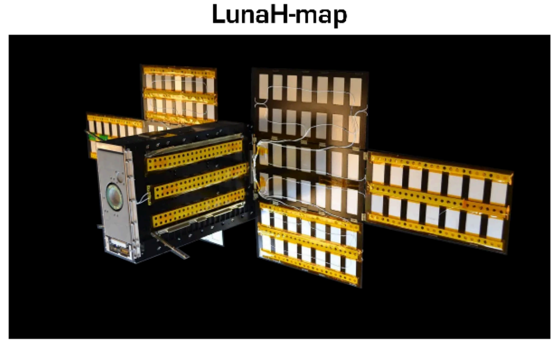
Flight Heritage

Lunar IceCube



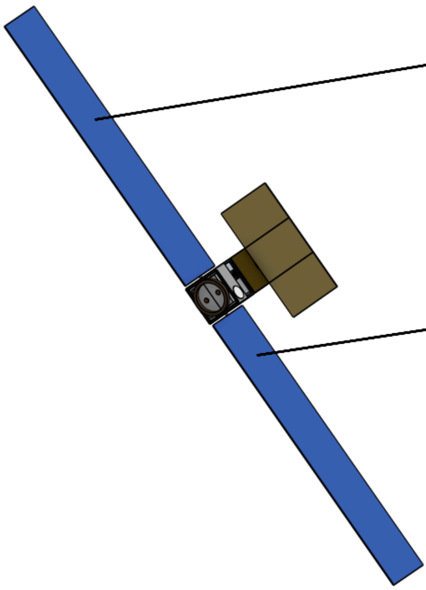
Credit: Morehead State University

LunaH-map



Credit: NASA/Arizona State University

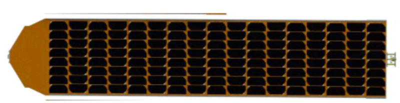
Power



2x ExoTerra 150 W Solar Arrays

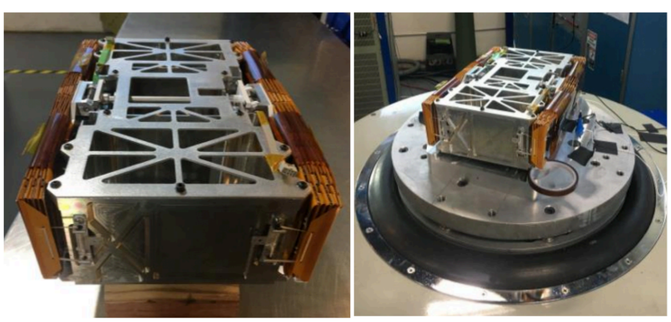
Mass: 1.07kg Each (Total 2.14 kg)
Cell Efficency: 29.5%
Power At Earth: 150W Each (Total 300 W)
Power At Mars: 54-79 W Each
(Total 108-158 W)
Length: Each 1.7m
Volume: 0.85 U stowed
Voltage: 28 or 150 V
Specific Power: 140 W/kg
Manufacturer: ExoTerra
Cost Estimate Guess: $50,000 - $120,000
(ZAR 855,103.46 - 2,052,248.31) Each
(Total $100,000 - $240,000
(ZAR 1,710,206.92 - 4,104,496.62))

[4]

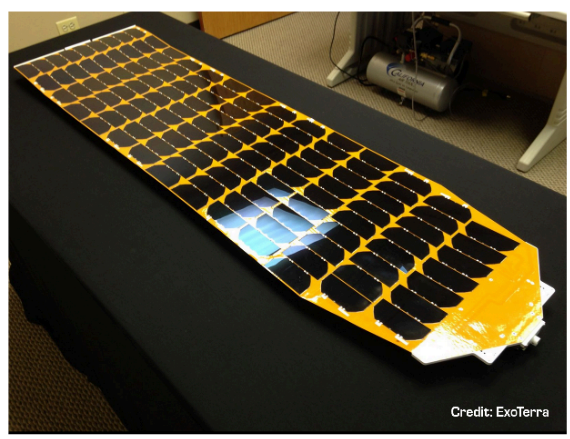


Credit: ExoTerra

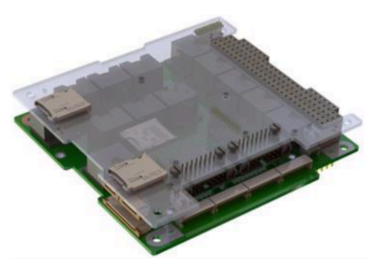
150W Array Stored



Credit: ExoTerra



Credit: ExoTerra



Communication

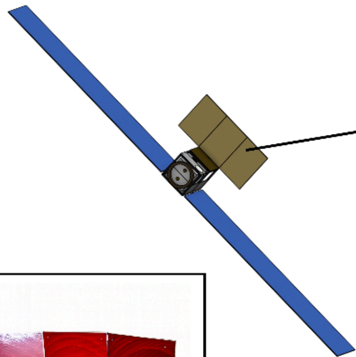


Image Credit: Anywaves

X- Band Reflectarray Antenna

Data Rate: TBD
Power: TBD
Mass: TBD
Gain: Up to 40 dB
Manufacturer: Anywaves
Cost Estimate Guess: $50,000 - $120,000 (ZAR 855,103.46 - 2,052,248.31) Each (Total $100,000 - $240,000 (ZAR 1,710,206.92 - 4,104,496.62))

[5] [6]

Flight Heritage

MarCO-A and MarCo-B

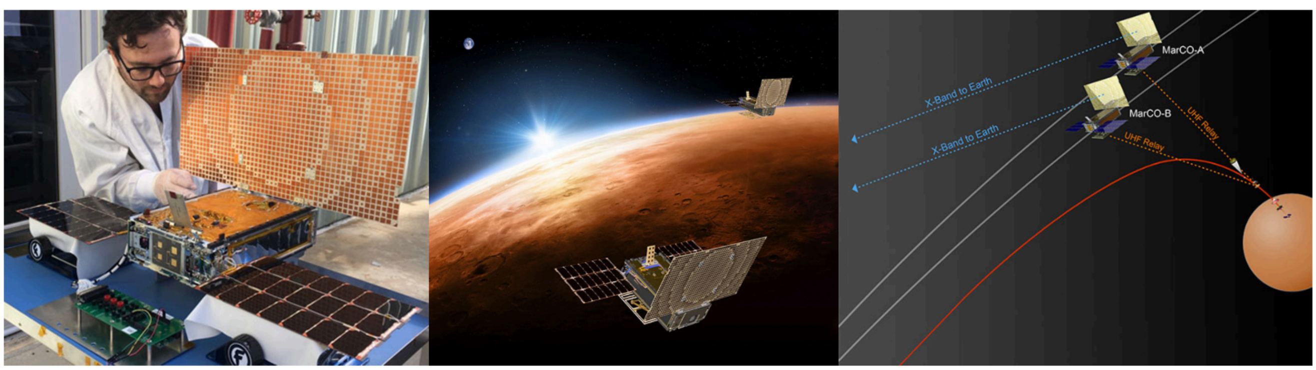


Image Credits: NASA/JPL-Caltech

Data Rate

IZIHAMBO-1's primary antenna will use a foldable X-Band Reflectarray antenna similar to the one used by NASA's MarCO cubesats to communicate with the Earth from Mars. This antenna can be sourced from Anywaves a company that specializes in manufacturing antennas for the space environment. Anywaves claims this antenna has a gain of up to 40dB, but to be safe let's use the gain of the MarCO antenna which was ~29.2 dB. With this antenna NASA was able to achieve a downlink data rate of 8 kb/s from the MarCO cubesats at Mars [6].

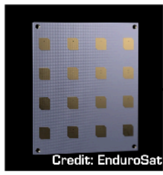
However, this data rate was achieved with the DSN's 70m antenna, a resource we most likely won't have access to. To communicate with it we would likely have to rent time on a KSAT antenna or through their partner network that offers antennas with a range of 13-32m [7]. If using a 32m antenna its data rate would fall to ~1.7 kb/s using the formula $\Delta G = 20 \log_{10}(32/70) \approx -6.8$ dB to calculate its gain loss, then we can plug that into this equation to find out the Linear Power ratio $10^{(\Delta G / 10)} = 10^{(-6.8 / 10)} \approx 0.21$. Now that we have its linear power ratio we can calculate its new data rate $(8 \text{ kb/s} \times 0.21) \approx 1.7$ kb/s.

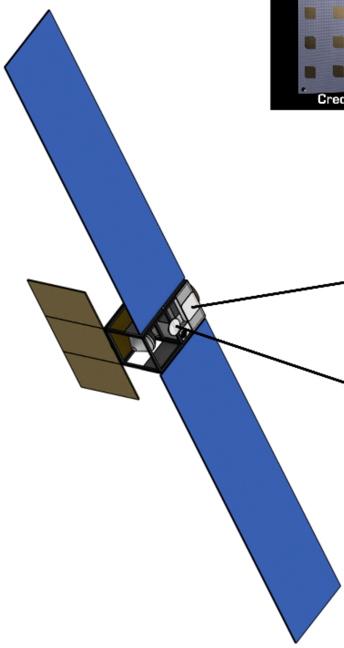
But this 1.7 kb/s data rate is assuming MarCO's transmission power of 5 watts, where limited solar panels resulted in power being a constraint. To its advantage the ExoTerra solar arrays give us a far greater power margin. So if we increase its power by a factor of 5 to 25 watts then we get a new data rate of $(1.7 \text{ kb/s} \times 5) \approx 8.5$ kb/s. If we increase its power to 50 watts by that same logic its data rate would increase to 17 kb/s. At that rate it would take 16.3 hours of continuous transmission to send back 1 gigabit of mission data.

Data Rate

If we have difficultly getting time on a 32m antenna and have to resort to a 13m antenna (assuming 5 watts of transmission power) its data rate would fall to ~0.28 kb/s. If we increase its power to 50 watts its data rate would increase to ~2.8 kb/s. At that rate it would take 4.13 days of continuous transmission to send back 1 gigabit of mission data.

With all this being said, these data rates will not remain constant throughout the duration of the mission and will vary greatly depending on Izihambo-1's position relative to the Earth throughout its mission.





EnduroSat X-Band 4x4 Patch Array

Mass: 0.052kg

Gain: 16 dBi

Dimensions: 82.6 mm x 98 mm x 7 mm

Power: 4w

Manufacturer: EnduroSat

Cost Estimate: $24,499 (ZAR 410,953.13)

[8]

2x Anywaves S Band Antenna

Mass: 0.077kg Each (Total 0.154kg)

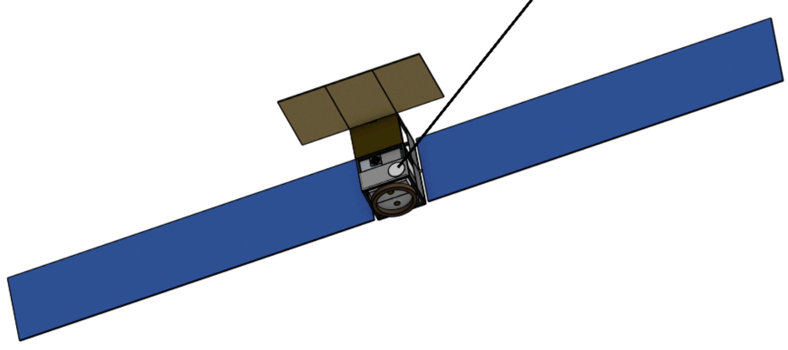
Dimensions: 70.9 x 70.9 x 9.78 mm^3

Power: 20w

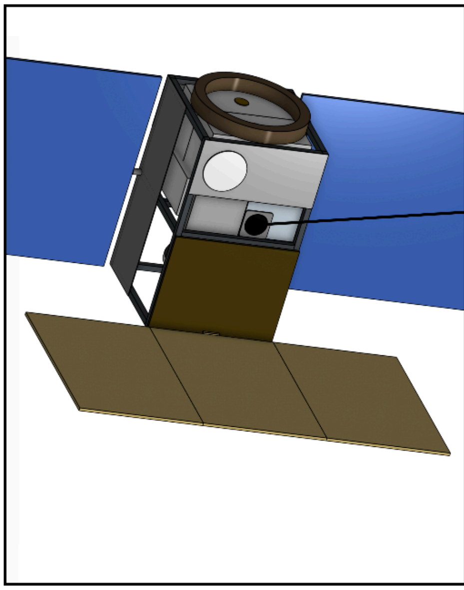
Manufacturer: Anywaves

Cost Estimate Guess: $3,000 - $8,000 (50,313.66 - 134,169.77 ZAR) Each (Total $6,000 - $16,000 (ZAR 100,627.33 - 268,339.53))

[9]



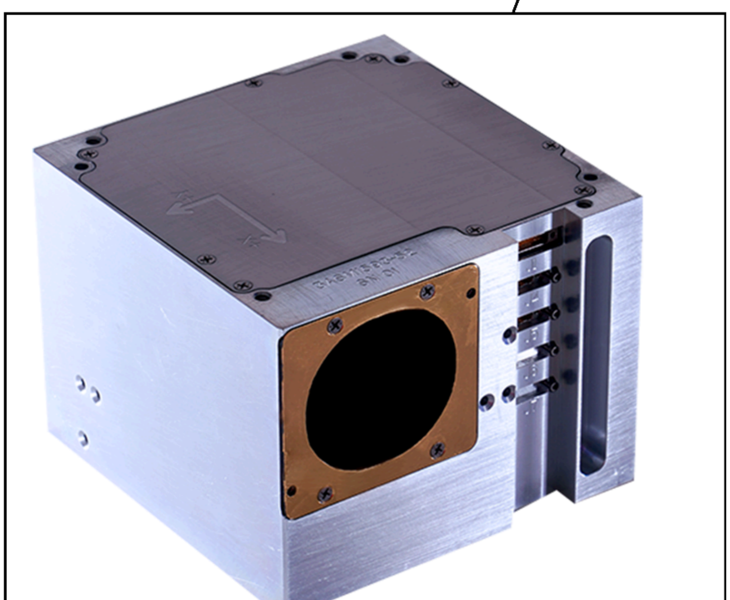
Attitude Control



Blue Canyon XACT-50 ADCS

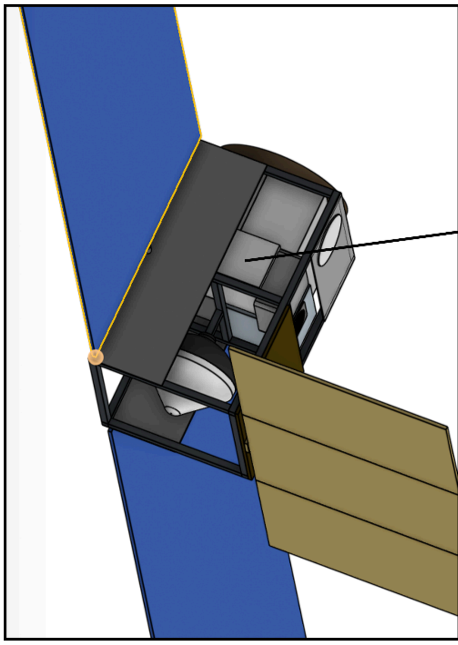
Mass: 1.23Kg
Volume: 0.75U
Dimensions: 10 x 10 x 7.54 cm
Momentum Storage: 50 mNms per axis
Max Torque: 0.006 Nm
Pointing Accuracy (1-sigma): ±10 arcsec for 2 axes; ±25 arcsec for 3rd axis
Slewing Cross-Boresight Error (@ 1 deg/sec) (1-sigma): Gen 2: 15 arcsec
Slewing Around -Boresight Error (@ 1 deg/sec) (1-sigma): Gen 2: 200 arcsec
Voltage: 12v
Manufacturer: Blue Canyon Technologies
Cost Estimate: $150,000 - $200,000 (ZAR 2,515,534.38 - 3,354,045.84)

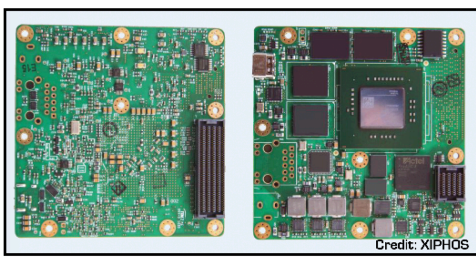
[10] [11]



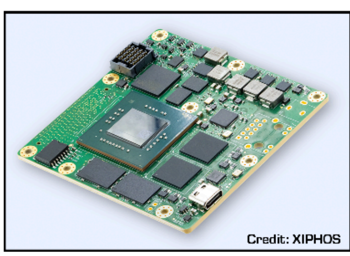
Credit: Blue Canyon

Primary Onboard Computer





Credit: XIPHOS



Credit: XIPHOS

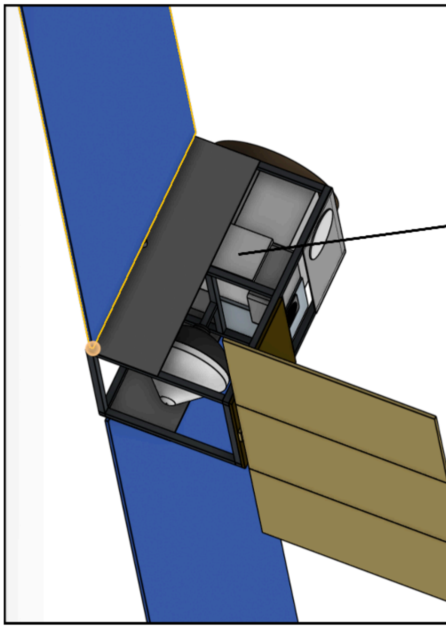
Included In Flight Model

- Triple mode redundancy in Control FPGA
- EDAC-protected RAM
- Upset and multi-current monitoring
- Overcurrent protection (multiple)
- FPGA bit stream scrubbing
- Software watchdog [12]

Primary OBC - Xiphos Q8S

Mass: 0.056 kg
Power: 5w
Memory: 4 GB of LPDDR4 RAM (with ECC), 2 x 256 MB QSPI Flash (NOR), and 2 x 128 GB eMMC.
Interfaces/Info: Gigabit Ethernet, USB 2.0 & 3.1, serial, multiple high speed I/O via mezzanine connector, including GPIO, LVDS, and GTR multi-Gbps transceivers for SATA or PCI Express (PCIe Gen 2)
Linux SDK
Radiation effects mitigation & 30krad TID lifetime
Voltage: 5v to 9v
Multi Processor:
-Xilinx Zynq UltraScale+ XCZU7EG
-Quad core ARM Cortex A53 Application Processing Unit at up to 1.2 GHz
-Dual core ARM Cortex R5 Real Time Processing Unit at up to 500 MHz
-ARM Mali 400 GPU at up to 600 MHz
-504,000 system logic cells
-461,000 flip flops (FF)
-274,000 lookup tables (LUT)
-1,728 DSP slices
Form Factor: 85.8 mm x 80 mm x 22.6 mm, 64 g (with RJ45 and power connectors) 80 mm x 80 mm x 11.2 mm, 56 g (without connectors)
Manufacturer: XIPHOS
Cost Estimate Guess: $25,000 – $60,000 (ZAR 419,178.16 - 1,006,027.58)
[12] [13]

Backup Onboard Computer

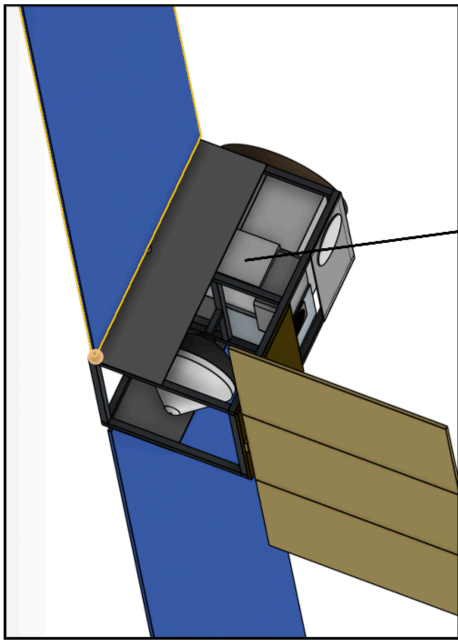


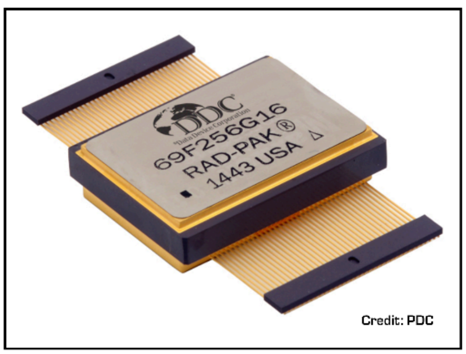
EnduroSat Backup OBC

Mass: 0.123 kg
Voltage: 12v
Processor: ARM Cortex M7
Program Memory Size: 2 MB Flash Memory
Mass Storage: 2x 16 GB Embedded SD NAND Flash Memory
External FRAM Memory: 2x 2MB FRAM with ECC capability
Clock Type: Real Time Clock
PPS Signal: Single-Ended
GPIO Signals: 16x Payload Enable / Disable / Feedback
Payload Interfaces : 1x CAN-FD, 1x RS-422, 1x RS-485, 1x SPI, 1x UART, 1x 100BASE-TX Ethernet
Manufacturer: EnduroSat
Cost Estimate: $16,000 (ZAR 268,268.61)

[14]

Data Storage





Credit: PDC

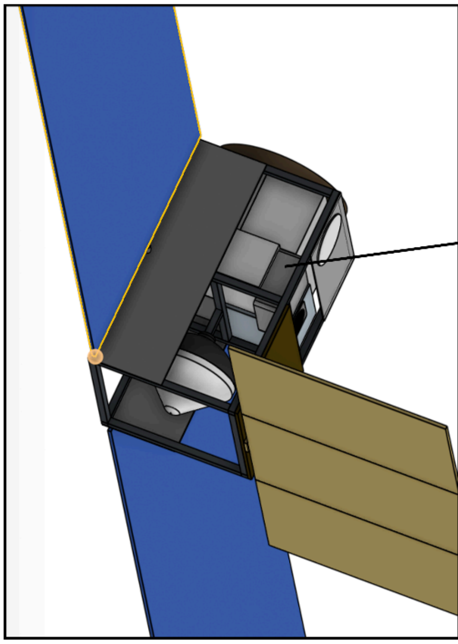
4× DDC 69F256G16 RAD-PAK NAND

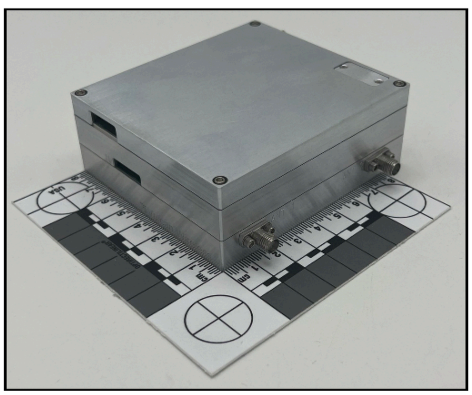
Mass: N/A
Storage: 64, 128, or 256 Gb Each
Speed: Up to asynchronous timing mode 5 (50MT/sec)
Endurance: 60,000 cycles typical
Operating Voltage: VCC 3.0 to 3.6V Each VCCQ 1.7 to 1.95V or 3.0 to 3.6V Each
Radiation Dose Tolerance: >100 krads(Si)
Manufacturer: Power Device Corporation
Cost Estimate Guess: $15,000 - $30,000 Each (ZAR 251,515.58 - 503,031.16) (Total $60,000 - $120,000 (ZAR 1,006,062.31 - 2,012,124.63))

[15]

IZIHAMBO-1 can use 4 of the DDC 69F256G16 RAD-PAK NAND devices for its data storage. In the 256 Gb configuration it would yield a total storage capacity 1024Gb. Though this may be viewed as excessive, it serves for both redundancy and flexibility. Additionally, it could enable the collection of a vast amount of scientific data. Mission data could be classified into primary mission data and secondary mission data. The primary data would be considered the objective of the mission and have priority for transmission back to Earth. The secondary data would be treated as bonus data, transmission of this data back to Earth will not be necessary for mission success. This data could wait for when the spacecraft is closer to the Earth to get better data rates. Possibly in an extended mission phase an Earth flyby could be considered for transmission of this data. This idea is not entirely novel, in the past JPL has explored the concept of using a spacecraft cycling between the Earth and Mars to ferry data [16].

Transponder



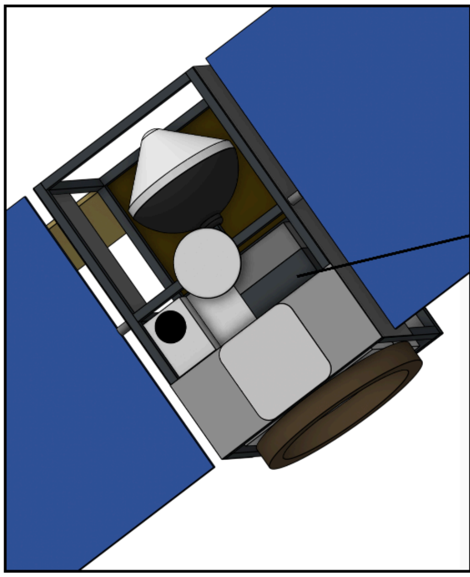


Vulcan Wireless NSR-SDR-X/S

Mass: N/A
Downlink Speeds: Low Mbps to >500Mbps
Uplink Speeds: Low Mbps to >500Mbps
Encryption: Embedded Software-Based Encryption with optional Integrated TSAB (Type-1) Encryption
Compatibility: AWS, SSC, KSat, Atlas Space, MC3, CCSDS, NASA NEN, SCN
Manufacturer: Vulcan Wireless
Cost Estimate Guess: $120,000 - $250,000 (ZAR 2,012,014.60 - 4,191,697.08)

[17]

Electrical Power System



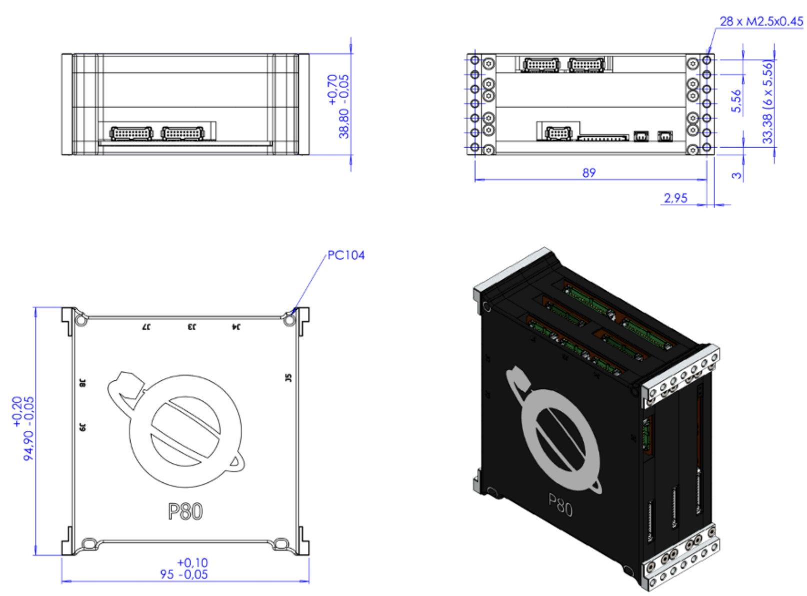
GomSpace NanoPower P80

Mass: N/A
Power: Up to 300w
Battery Pack Capacity: 4
Max Current: 12A
ACU: 12 MPPT boost converters (12x1A)
PDU: 12 low voltage LUP channels
Manufacturer: GomSpace
Cost Estimate Guess: $70,000 - $120,000 (ZAR 1,173,675.18 - 2,012,014.60)

[18] [19]

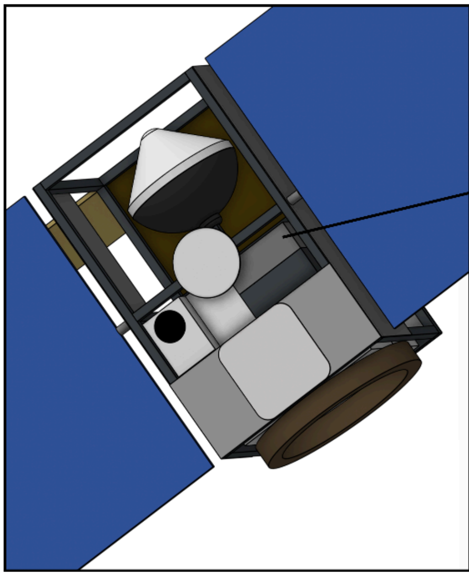
Credit: GomSpace

Credit: GomSpace



Credit: GomSpace

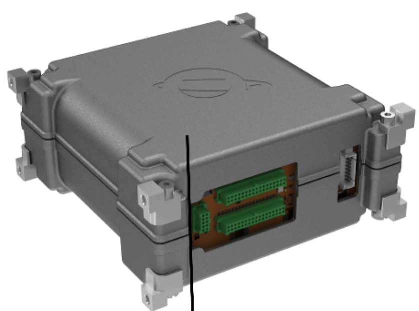
Battery



GomSpace NanoPower BP8

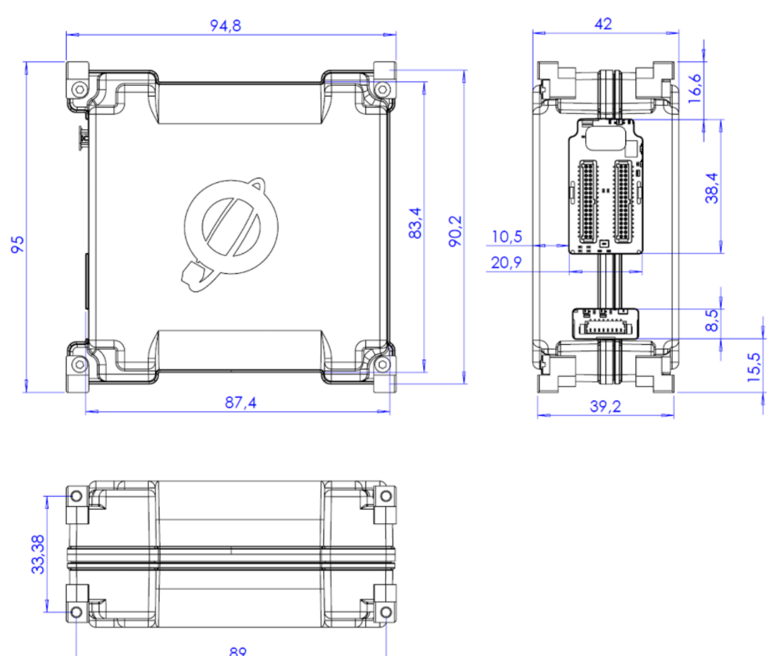
Mass: 0.486 kg
Dimensions: 94.8mm x 95mm x 42mm
Power: 100 Wh
Battery: 18650 Lithium Ion Cells
Nominal Voltage: 28.8 V
Max current discharge: 4 A
Manufacturer: GomSpace
Cost Estimate Guess: $20,000 - $30,000 (ZAR 335,335.77 - 503,003.65)

[20] [21] [22]



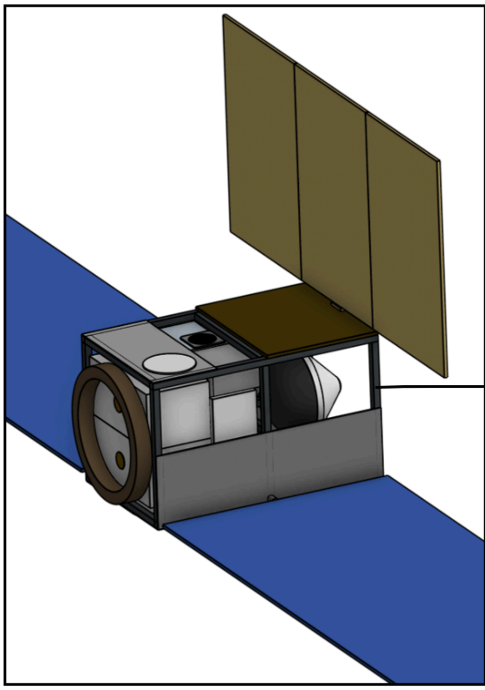
Credit: GomSpace

Credit: GomSpace



Credit: GomSpace

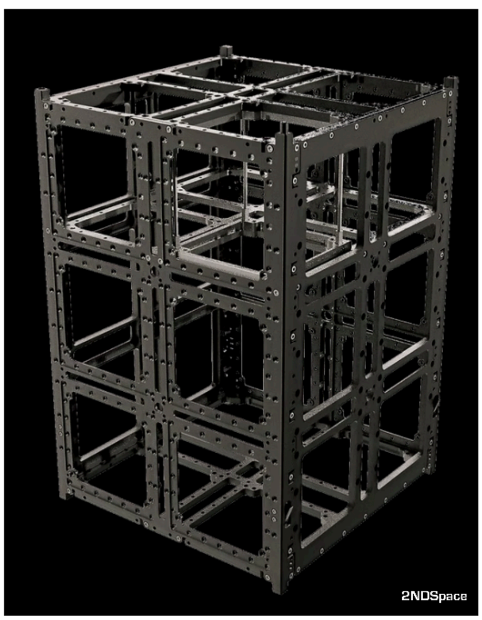
Structure



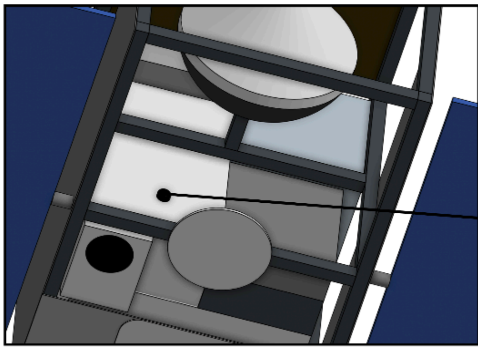
Verse 12 Structure

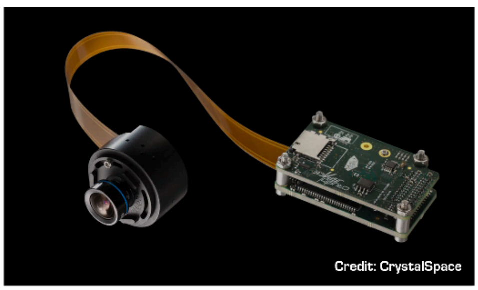
Mass: 1.190 kg
Form factor: 12U
Dimensions: 226x226,3x366
226x226,3x340,5
Vibration and Mechanical Shock Test Qualification: NASA GEVS: GSFC-STD-7000A
ESA ECSS-E-ST-10-03C
Manufacturer: 2NDSpace
Cost Estimate Guess: $15,000-$50,000
(ZAR 251,555.72 - 838,519.07)

[23] [24]



Deployment Camera





CrystalSpace CS-101 Kikas

Mass: 0.05 kg
Dimensions: 42mm × 25mm × 45mm
Resolution: 5 MP
TRL: 9
Manufacturer: CrystalSpace
Cost Estimate Guess: $40,000 - $100,000 (ZAR 670,813.18 - 1,677,032.95)

[25] [26]

Flight Heritage

Thales Aeros MH-1 Mission

Image Credit: CEiiA

ESTCube-1

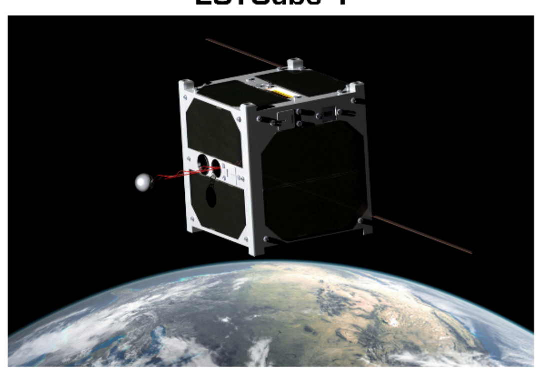
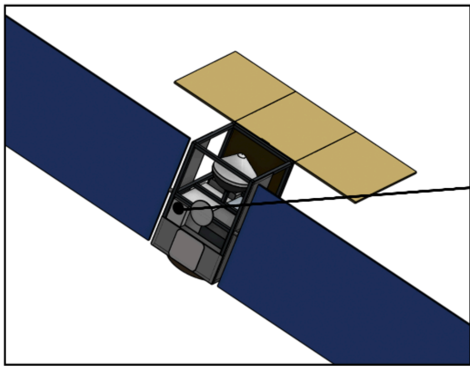


Image Credit: University of Tartu, ESTCUBE team CC BY 3.0

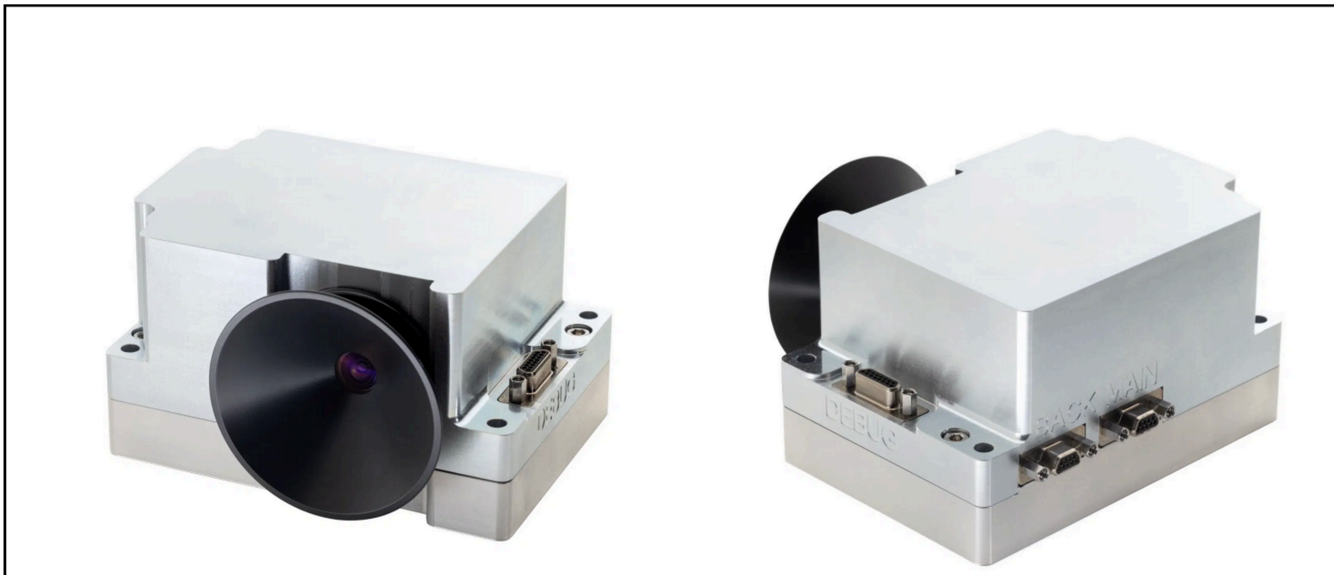
High Resolution Camera



CrystalSpace CS-292 Suupistri-EO

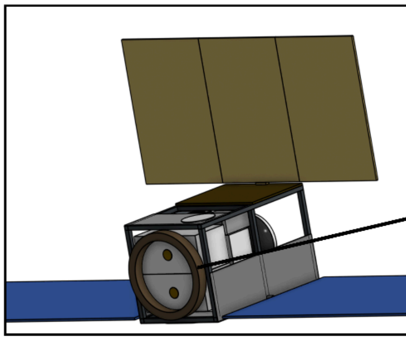
Mass: 0.3 kg
Dimensions: 82mm X 88mm X 39mm
Resolution: 67 MP
GSD: < 1 Meter
Wavelength: 350-850 nm
Manufacturer: CrystalSpace
Cost Estimate Guess: $60,000 - $250,000 (ZAR 1,006,471.24 - 4,193,630.18)

[27] [28]



Credit: CrystalSpace

Spacecraft Seperation



8in mount ring

Mass: N/A

Manufacturer: Rocket Lab

Cost Estimate Guess: $25,000 - $40,000 (ZAR 419,366.86 - 670,986.97)

[29]

Notes

The current design of IZIHAMBO-1 features an 8-inch diameter separation ring based on a model offered by Rocket Lab [29]. This should not be considered a permanent fixture of the spacecraft, but rather an optional deployment approach.

The primary advantage of using the 8-inch diameter separation ring is that it eliminates the need to use a CubeSat dispenser. This approach is supported by multiple launch providers such as SpaceX [30]. It would also enable IZIHAMBO-1 to take on a slightly more irregular geometry, reducing constraints on the placement of components. The primary drawback to using a separation ring is that it would add additional mass to IZIHAMBO-1.

Alternatively, IZIHAMBO-1 could be deployed from a standard 12U CubeSat dispenser, such as the one manufactured by Exolaunch, as shown below. The main advantage provided by this approach is no additional mass will be added to IZIHAMBO-1. The downside is that the spacecraft will have to strictly conform to the 12U standard.

Credit: Exolaunch

Credit: Exolaunch

EXOpod

Mass: N/A

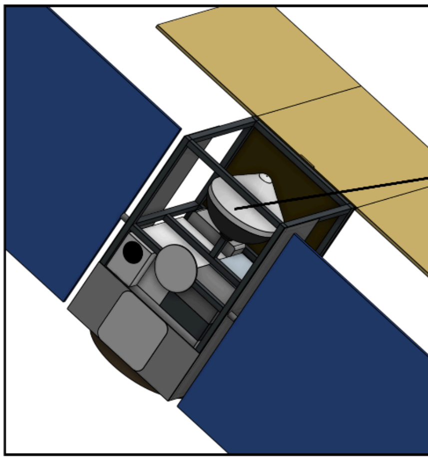
Flight Heritage: 33 Missions

Manufacturer: Exolaunch

Cost Estimate Guess: $150,000 - $300,000 (ZAR 2,474,641.43 - 4,949,282.86)

[31] [32]

Mars Descent Probe

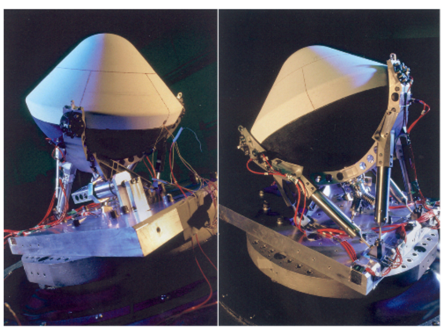


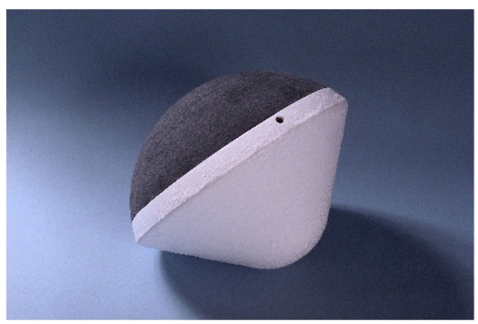
Mars Descent Probe

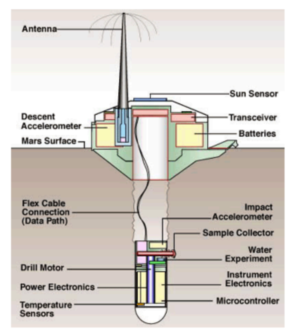
Mass: 1 - 2.4kg
Communication: S-Band
Manufacturer: In House
Cost Estimate Guess: $500,000 - $1,500,000 (ZAR 8,387,260.36 - 25,161,781.07)

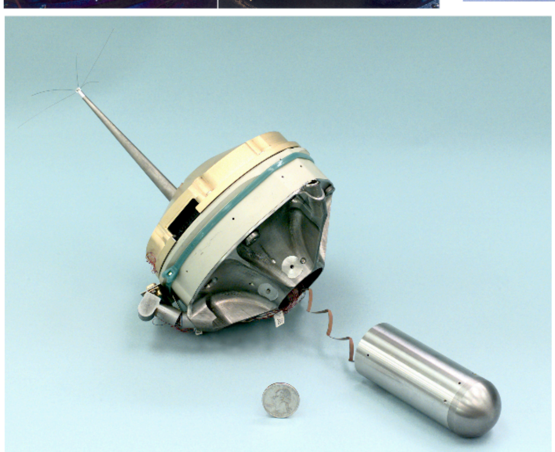
Flight Heritage

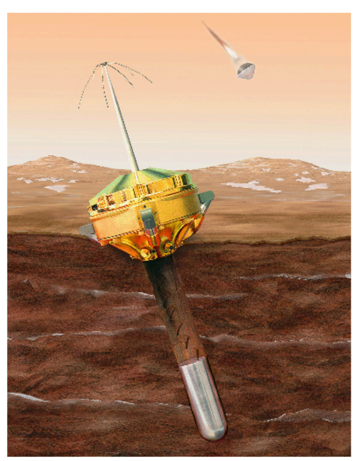
Deep Space-2











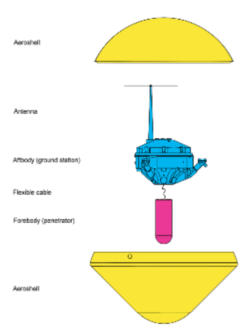
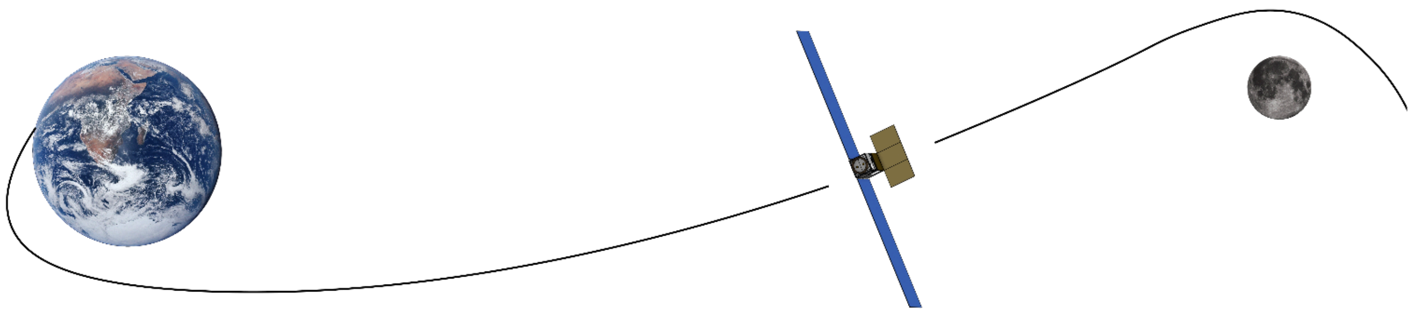


Image Credits: NASA/JPL

Flight Plan

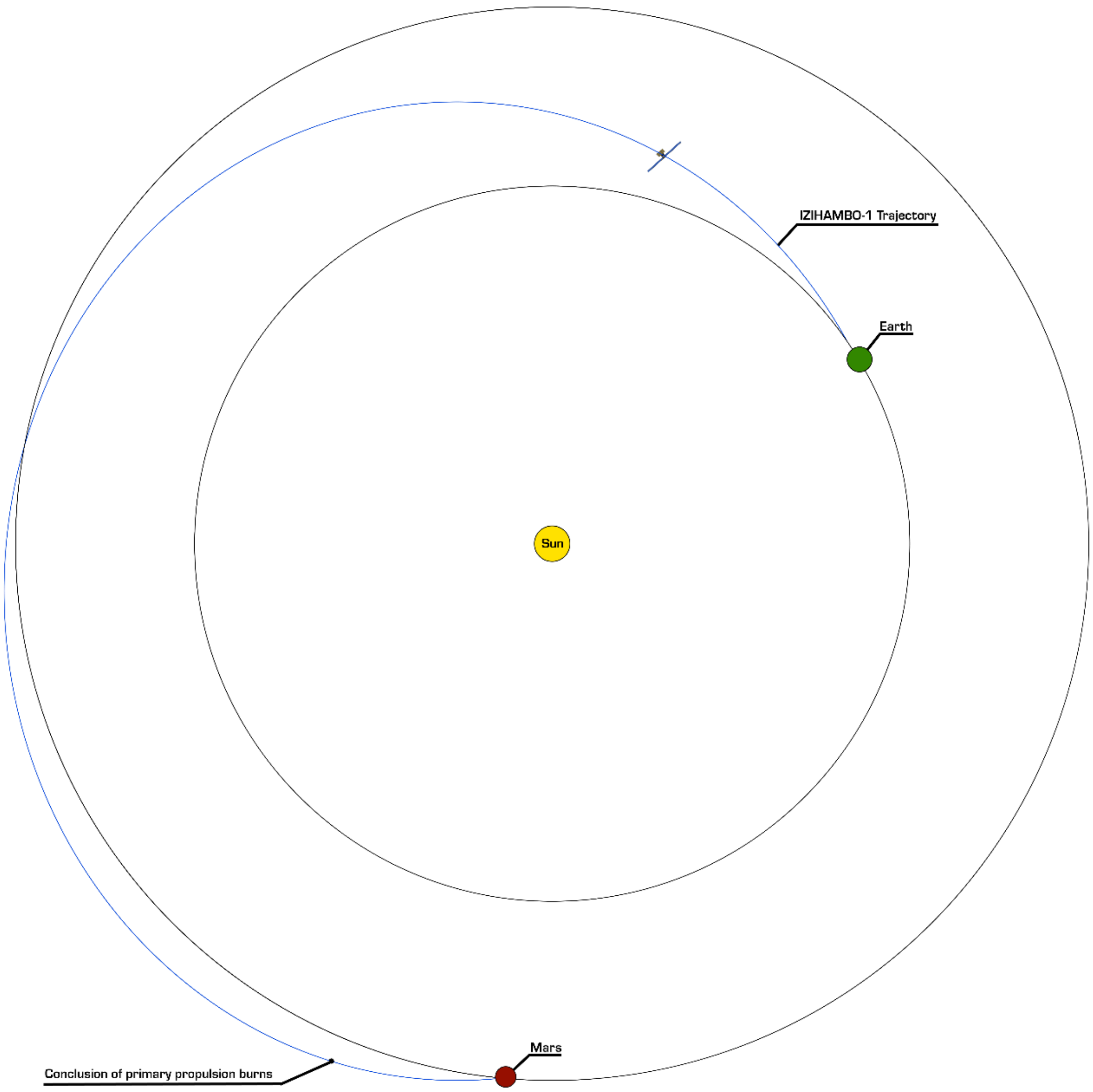


IZIHAMBO-1 will be placed directly onto a Trans-Lunar Injection (TLI) trajectory. An earlier concept considered initially deploying the spacecraft into Low Earth Orbit (LEO), followed by gradual orbit raising using the spacecraft's BIT-3 ion thrusters until reaching TLI. This approach was ultimately discarded.

The primary limitation is thrust. The BIT-3 ion thrusters provide a combined thrust of approximately 2.2 mN, meaning delta-V is accumulated gradually over long periods rather than impulsively over minutes, as with chemical propulsion. While ion thrusters offer excellent specific impulse and propellant efficiency, their low thrust prevents effective use of the Oberth effect. For those unfamiliar, the Oberth effect enables maximum energy gain when a velocity change occurs at very high speed deep within a gravity well, such as near Earth. Without this benefit, the total delta-V required to escape Earth increases substantially, thinning the mission's delta-V margin and leaving IZIHAMBO-1 with a concerningly narrow margin to reach Mars.

Direct insertion onto a TLI trajectory avoids this penalty. It reduces mission complexity, shortens the time to heliocentric escape, preserves an acceptable delta-V margin, and aligns with available commercial rideshare opportunities [33].

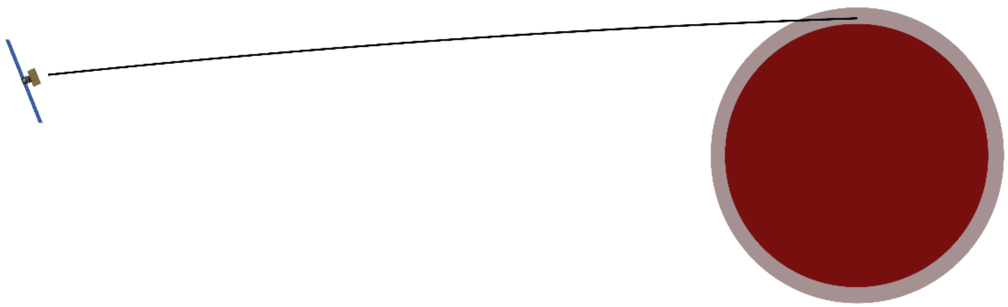
Additionally, South Africa's memorandum of understanding to collaborate with China's International Lunar Research Station (ILRS) program introduces a potential pathway for IZIHAMBO-1 to be manifested as an additional payload [34]. China has previously allocated mass for international payloads, such as the approximately 200 kg offered to international partners on Chang'e-8 [35][36]. Historically, however, China's approach has been to integrate international payloads as hosted instruments rather than deploy them as independent spacecraft. As such, while this opportunity should not be ruled out, it should not be considered essential to the mission.



Being placed directly onto a Trans-Lunar Injection (TLI) trajectory allows IZIHAMBO-1 to use a lunar gravity assist to transition into heliocentric orbit. This approach is directly based off of NASA's BioSentinel CubeSat, which launched as a secondary payload aboard Artemis I. BioSentinel used a lunar flyby to enter heliocentric orbit in order to meet its mission objectives [37][38][39]. From it's launch, IZIHAMBO-1 is expected to enter heliocentric orbit after approximately one week.

Once in heliocentric orbit, IZIHAMBO-1 requires approximately 3.0–3.5 km/s of delta-V for a Mars encounter. Assuming a spacecraft mass of 14 kg and a combined thrust of 2.2 mN from its pair of Bit-3 ion thrusters, this delta-V would be accumulated over 221–258 days of continuous thrust. Under these assumptions, IZIHAMBO-1 would be placed on a Mars-intercept trajectory, resulting in arrival approximately 9–12 months after entering heliocentric orbit.

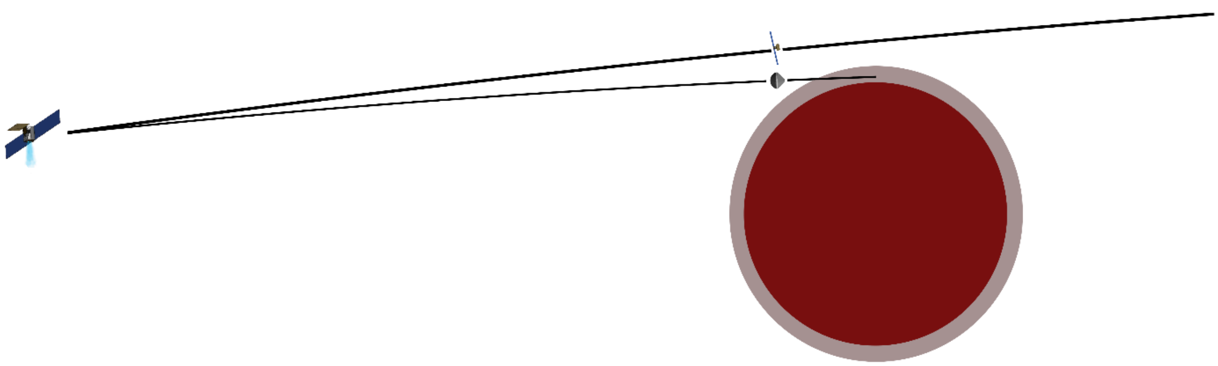
This timeline assumes both ion thrusters operate at a 100% duty cycle. In practice, duty cycle limitations, launch window constraints, trajectory correction maneuvers, and operational considerations may shift the actual arrival date. For reference, the resulting low-thrust interplanetary trajectory closely resembles that of NASA's Dawn mission, which used ion propulsion to conduct a Mars flyby [40][41][42].



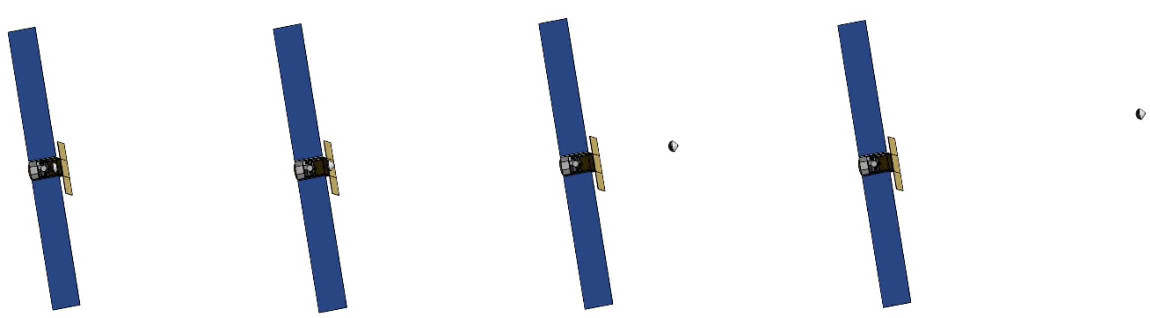
Following IZIHAMBO-1's primary thrust phase, the spacecraft will be placed on a trajectory that initially intersects the Martian atmosphere. Several weeks prior to Mars encounter, IZIHAMBO-1 will release its Mars Descent Probe.

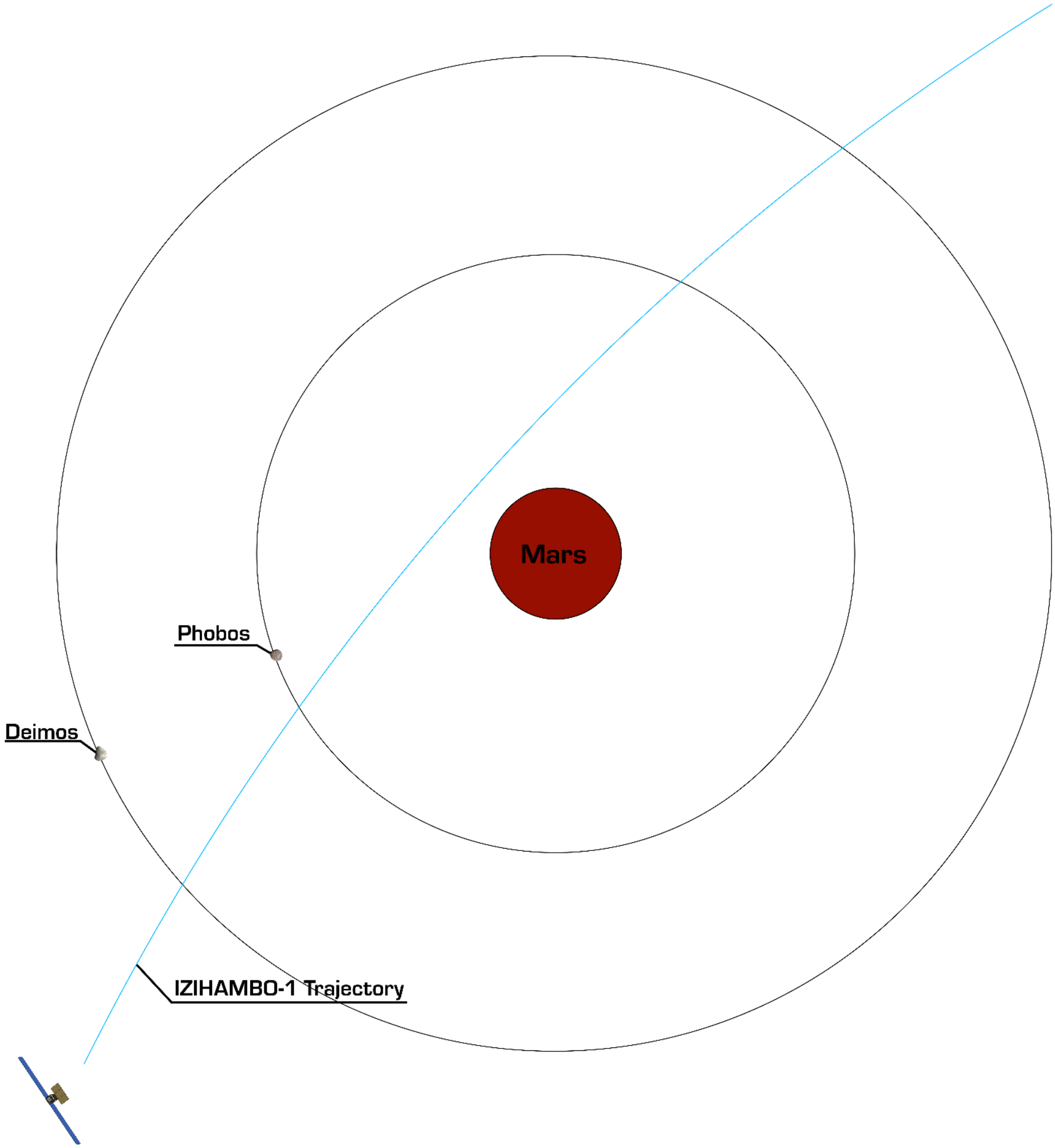
Direct atmospheric entry by IZIHAMBO-1 would result in a rapid unscheduled disassembly of the spacecraft. To avoid this, IZIHAMBO-1 will execute a small trajectory correction maneuver to ensure a safe atmospheric miss while maintaining a close flyby of Mars.

After separation, the Mars Descent Probe will remain on its atmospheric intercept trajectory and proceed into a ballistic descent through the Martian atmosphere. The probe's entry and descent profile is closely analogous to that of the Galileo atmospheric probe deployed at Jupiter [43][44][45].



Mars Descent Probe Deployment



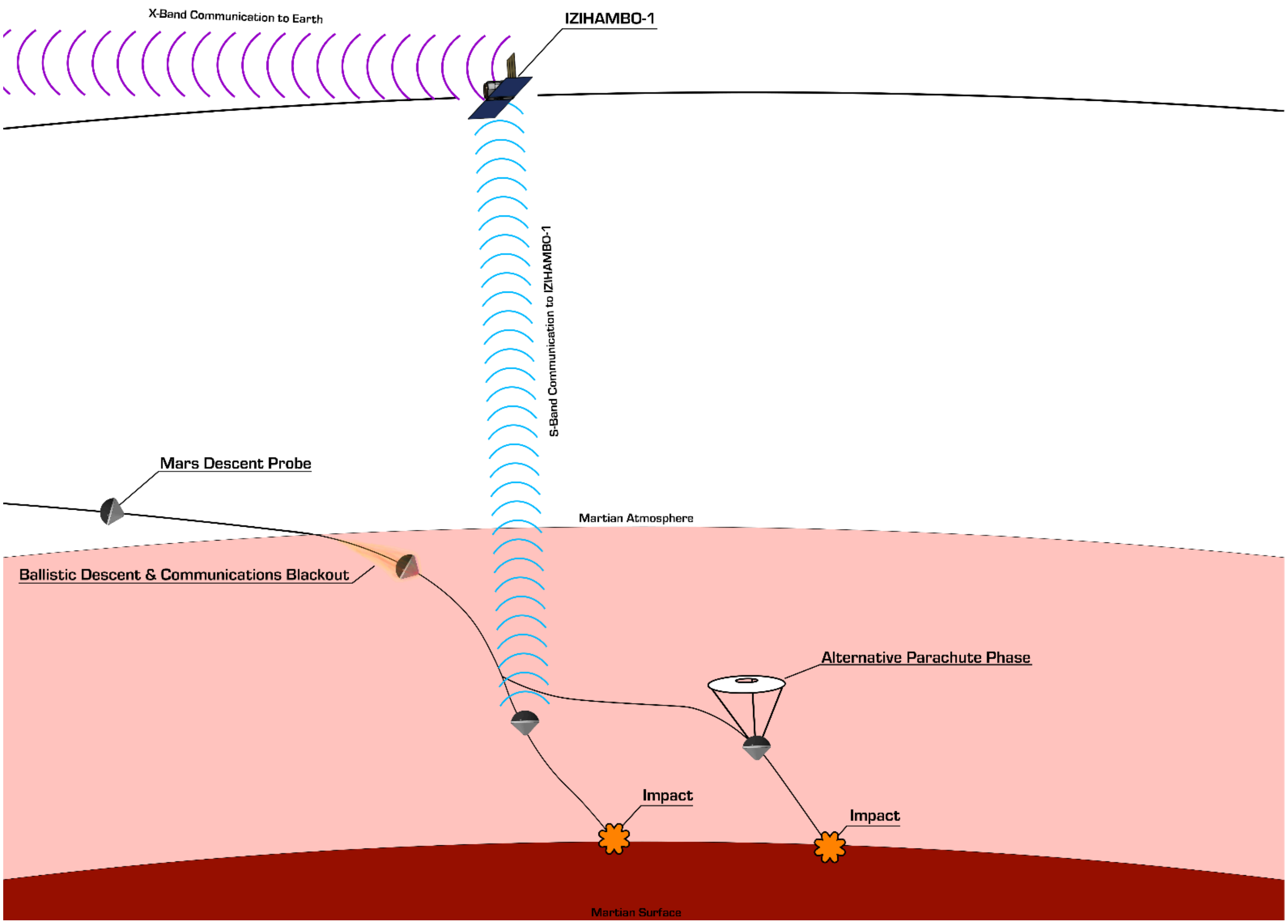


It should also be noted that, depending heavily on IZIHAMBO-1's trajectory and arrival at Mars, an opportunity may exist for close encounters with the Martian moons Phobos and Deimos. A similar opportunity presented itself during the Mariner 6 and Mariner 7 flybys [46][47]. Additionally, such observations could provide valuable complementary data in support of JAXA's upcoming Martian Moons eXploration (MMX) mission [48][49][50].

Upon entry into the Martian atmosphere, the Mars Descent Probe will initially lose communications for a few minutes, as ionized plasma generated by its high-velocity ballistic descent prevents radio signals from reaching IZIHAMBO-1. Once the probe exits the plasma blackout region, it will begin transmitting telemetry and science data to IZIHAMBO-1 over S-band, with IZIHAMBO-1 relaying that data to Earth via X-band.

This communications architecture closely mirrors how the MarCO CubeSats relayed information during the InSight lander's atmospheric entry and descent [51][52][53]. In that case, InSight communicated with MarCO using UHF rather than S-band. Many Mars missions employ UHF during entry and descent because it is significantly more tolerant of pointing errors, atmospheric effects, and rapidly changing flight dynamics, providing the highest probability of receiving at least partial data during the most violent phases of flight. The primary drawback of UHF is its lower data rate when compared to S-band.

For this reason, it is recommended that the IZIHAMBO-1 Mars Descent Probe incorporate both UHF and S-band communications. UHF antennas are lightweight and can provide additional redundancy while maximizing the likelihood of maintaining continuous contact with the probe throughout descent. Later in the descent phase, when plasma effects and dynamic instabilities diminish, S-band can be used to transmit larger volumes of data, such as images and higher-rate sensor measurements.



For mission success, the Mars Descent Probe is treated strictly as a short-duration technology demonstration and is not expected to survive impact with the Martian surface. This assumption significantly reduces mission complexity, as the probe's components do not need to be designed to withstand extreme deceleration loads associated with surface impact. Even in the unlikely event of survival, the probe would remain within communications range of IZIHAMBO-1 for less than one day. As a result, there is no requirement for long-term survivability or power generation systems such as solar arrays. All systems can instead be powered solely by onboard batteries, further reducing complexity.

Optionally, a small parachute may be incorporated into the descent probe design. The primary purpose of this parachute would be to prolong the descent phase in order to increase total data return, rather than to enable survival upon surface impact. While post-impact survival should be treated as an unlikely scenario, the inclusion of UHF communications would, in such a case, enable the possibility of data relay through Mars orbiters such as the Mars Reconnaissance Orbiter, which routinely supports UHF relay for surface missions[54][55].

A Mars Descent Probe designed to survive impact and operate on the Martian surface should be reserved for IZIHAMBO-2.

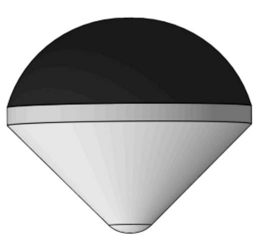
Designing The Mars Descent Probe

As briefly mentioned earlier in the spacecraft architecture section, the Mars Descent Probe will be loosely based on NASA's Deep Space 2 mission [56][57][58][59], primarily mirroring its heat shield and aeroshell design. Unlike Deep Space 2, however, the Mars Descent Probe is not intended to survive impact with the Martian surface. Deep Space 2 had a mass of 2.4 kg, and it is plausible that the mass of the Mars Descent Probe can be significantly reduced by removing the requirement to survive surface impact and the associated extreme g-loads. It should also be noted unlike the Mars Descent Probe, Deep Space 2 incorporated a penetrator that would burrow into the Martian surface. In addition, Deep Space 2 was designed nearly 30 years ago, making further mass reduction likely through the use of modern components.

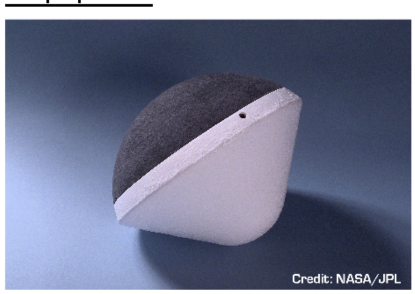
An important consideration for manufacturing is the Mars Descent Probe will reach the Martian surface. As a result, the mission falls under planetary protection Category IV [62]. This classification requires substantial measures be taken to minimize the risk of contaminating the Martian environment with organisms from Earth.

Even if the Mars Descent Probe were removed from the IZIHAMBO-1 mission, the spacecraft would still fall under Category III planetary protection requirements. As its Mars flyby could pose a contamination risk in the event of a navigation error resulting in unintended atmospheric entry. To those unfamiliar, such precautions may appear excessive for a flyby mission. However, the Mars Climate Orbiter incident in which a unit conversion error between metric and imperial systems caused the spacecraft to enter the Martian atmosphere demonstrated that these risks are real and well founded [63].

Mars Descent Probe

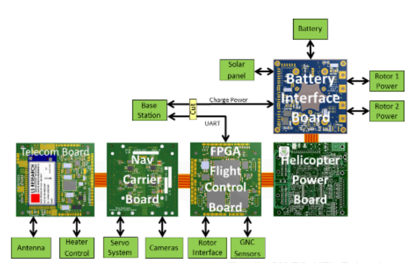


Deep Space 2

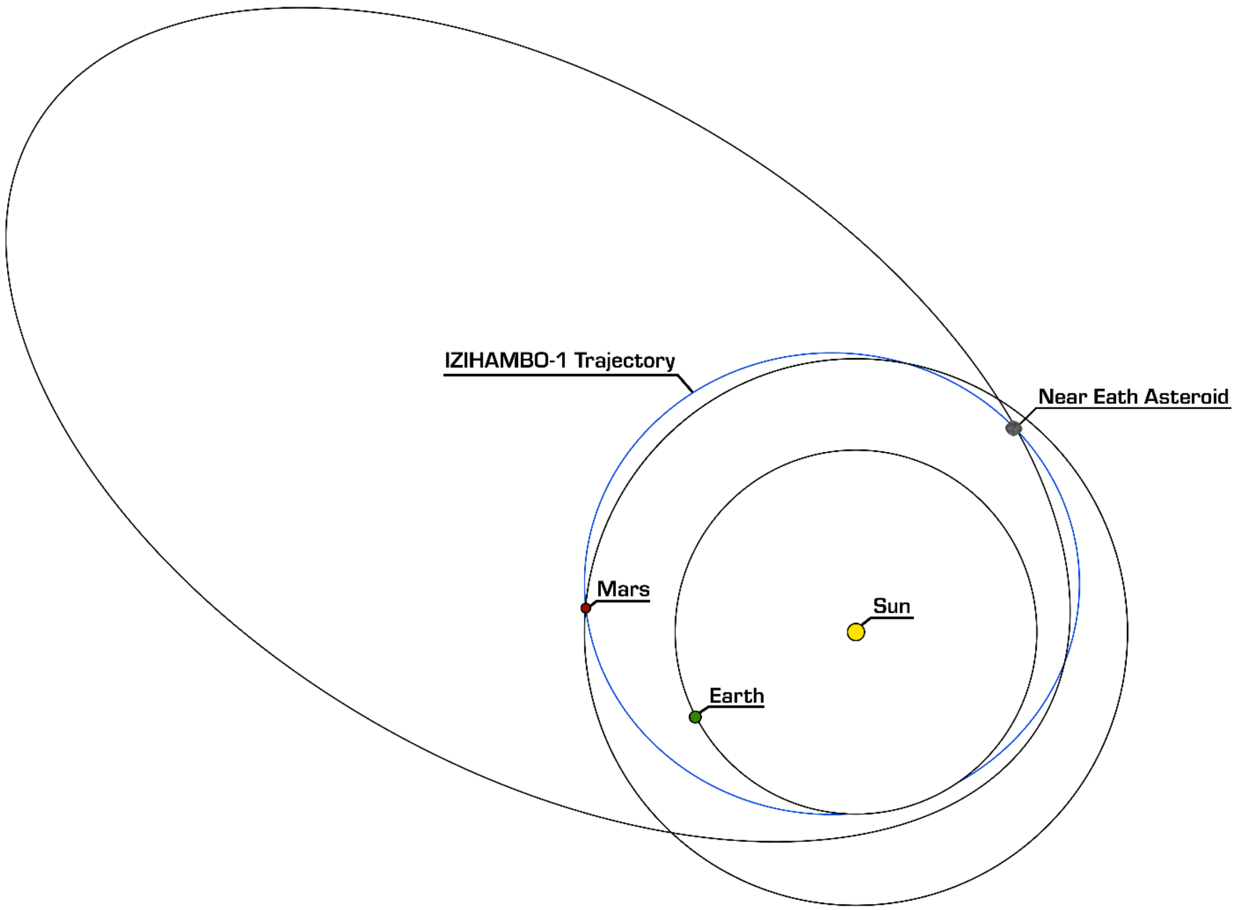


Credit: NASA/JPL

Ingenuity Hardware Architecture



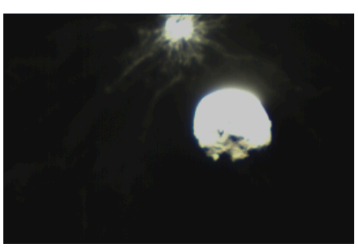
Credit: NASA/JPL-Caltech



LICIACube

Credit: NASA/Johns Hopkins APL/Ed Whitman

Image Captured By LICIACube



Credit: NASA/ASI

Following IZIHAMBO-1's Mars encounter, its new orbit will sit in a range roughly between the orbits of the Earth and Mars. Its remaining delta-V should be in excess of 1km/s, which is more than enough to alter its trajectory to a new target. Such a target that could be considered is a Near Earth Asteroid (NEA), these are asteroids that pass within 1.3 AU. Luckily for IZIHAMBO-1, there are currently in excess of 40,000 that have been discovered [64]. This makes it incredibly likely that IZIHAMBO-1 will be able to encounter one with minimal course corrections. The concept of using a CubeSat to study an asteroid is not new. In the past, the LICIACube, a CubeSat built by the Italian Space Agency, conducted a flyby of asteroid Didymos to observe the DART spacecraft impact [65][66]. If IZIHAMBO-1 remains operating nominally after its first asteroid encounter, it could have an extended mission encountering other Near Earth Objects (NEOs).

Mission Risks and Mitigation Strategies

The following section outlines the primary technical risks associated with the IZIHAMBO-1 mission and identifies strategies that could be employed to mitigate or accept these risks.

Ion Propulsion

IZIHAMBO-1's only form of propulsion is its pair of BIT-3 ion thrusters. In the event that one of them fails early in flight, it would likely result in an inability to produce the total delta-V required for a Mars encounter. However, this would not necessarily mean the end of the mission. As long as one BIT-3 ion thruster remains operational, it would still be capable of making moderate course adjustments and could be used to desaturate the reaction wheels. IZIHAMBO-1's TLI and lunar gravity assist would still place it into heliocentric orbit, and the mission could be restructured to support multiple NEO rendezvous.

That being said, if both BIT-3 ion thrusters were lost, the mission would effectively be lost, as the spacecraft would no longer have the ability to desaturate its reaction wheels. Reaction wheels are the primary means by which the XACT-50 ADCS controls IZIHAMBO-1's attitude. By changing the rotational speed of the wheels, the spacecraft's attitude can be adjusted. However, this process cannot continue indefinitely, and over time the reaction wheels will become oversaturated.

To remedy this, spacecraft generally use thrusters to desaturate reaction wheels by applying torque in a controlled manner to bleed off unwanted angular momentum. The BIT-3 ion thrusters are capable of performing this function due to their gimbaling capability. Loss of both thrusters would therefore result in reaction wheel saturation, leaving the spacecraft unable to compensate for unwanted angular momentum. As a result, IZIHAMBO-1's attitude control would become unstable, preventing it from accurately pointing its X-band antenna toward Earth. This would effectively eliminate communications with Earth, concluding the IZIHAMBO-1 mission.

To mitigate the risks posed by the loss of both BIT-3 ion thrusters, the inclusion of a cold gas thruster system should be considered. Cold gas thrusters have been the go-to solution for reaction wheel desaturation on interplanetary CubeSats such as MarCO [67][68].

In Low Earth Orbit (LEO), CubeSats generally do not require propulsive systems for reaction wheel desaturation. Instead, they use magnetorquers, which generate torque by inducing a magnetic field that interacts with Earth's magnetic field [69]. However, in interplanetary space there is no magnetic field that a CubeSat can leverage, resulting in the need for propulsion-based desaturation methods.

The incorporation of a cold gas thruster system would allow IZIHAMBO-1 to continue operating in the event of a dual ion thruster failure. That being said, a tradeoff must be considered as to whether this added redundancy justifies the additional mass of a cold gas thruster system.

High Gain X-Band Antenna

IZIHAMBO-1's high gain X-band reflectarray antenna must be successfully deployed in order to support nominal mission communications. A failure to deploy this antenna would result in the loss of the spacecraft's primary high-rate communications system. While this would be catastrophic for mission data return, it would not be mission-ending.

IZIHAMBO-1 is equipped with a passively deployed low-gain X-band patch array antenna, as well as two S-band antennas. These antennas allow the spacecraft to maintain communications with Earth in the event of a high gain antenna failure. However, IZIHAMBO-1's data rate would be severely limited, resulting in the mission needing to be restructured. IZIHAMBO-1 would still be capable of collecting and storing scientific data, but transmitting that data back to Earth would require substantially more time.

This scenario closely mirrors that of NASA's Galileo spacecraft, its primary high gain antenna failed to deploy due to cold welding. As a result, the Galileo spacecraft was forced to operate using solely its low gain antenna. Although mission data return was heavily constrained, the Galileo team adapted operations and successfully achieved a substantial portion of the mission's scientific objectives [70][71].

Unlike Galileo, IZIHAMBO-1 will not be operating in orbit around Jupiter. In the event of a high gain antenna failure, an Earth flyby could be considered as a data dump opportunity. Such a flyby would allow IZIHAMBO-1 to transmit a large volume of stored data while in close proximity to Earth. This maneuver would likely come at the expense of the planned Near-Earth Asteroid rendezvous. However, it could also create the opportunity for an additional lunar flyby.

Following an Earth flyby, and assuming the spacecraft remains operational, an NEA flyby could still be attempted during an extended mission phase, though this would occur beyond the spacecraft's nominal design life. If an Earth data-dump flyby is not performed, overall mission operating costs would increase significantly. The reduced data rate would require substantially more time to transmit the same volume of data, resulting in increased ground-station usage and higher costs for renting Earth-based antennas through providers such as KSAT.

High Resolution Camera

In the event that the CrystalSpace CS-292 Suupistri-EO camera fails, IZIHAMBO-1 would lose its ability to return high-resolution imagery of the Martian surface or a near-Earth asteroid. However, imaging capability would not be completely lost. The spacecraft carries a secondary camera, the CS-101 Kikas, also manufactured by CrystalSpace.

The CS-101 is the Mars Descent Probe deployment camera and provides significantly lower image quality, with a resolution of 5 MP compared to the 67 MP capability of the CS-292. In addition, portions of IZIHAMBO-1's structure are visible within the camera's field of view, obstructing parts of its images. Despite this, the CS-101 could still be used to collect scientifically valuable imagery.

Solar Arrays

In the event one of IZIHAMBO-1's solar arrays fails to deploy, the mission would still likely be able to complete its objectives. That being said, the timeline would change. The reduction in available power could result in only one of the BIT-3 ion thrusters being able to run at a time. This would substantially increase the time required for IZIHAMBO-1 to accumulate the delta-V needed to encounter Mars. Additionally, fewer components would be able to operate simultaneously. There could also be issues relating to the new spacecraft geometry. Primarily, the new asymmetric shape of the spacecraft would result in more frequent reaction wheel saturation, thus requiring more frequent desaturation.

In the event both solar arrays fail to deploy, IZIHAMBO-1 will not be able to complete its primary mission objectives. At that point, it would be limited to its remaining battery power, and once that is depleted, contact with IZIHAMBO-1 would be lost. That being said, in such a scenario it would remain on its TLI trajectory. Because of that, it could be conceivable to place IZIHAMBO-1 into a deep sleep mode, then briefly wake it during the lunar flyby to make observations and transmit what it can back to Earth with the limited power available.

Additionally, in this scenario the Mars Descent Probe could be deployed and used to make observations of the Moon. An attempt could be made to transmit data back from the Mars Descent Probe directly to Earth over S-band.

To reduce the consequences of a dual solar array failure, an additional passive solar array could be considered. Its smaller area would still result in significantly lower power generation when compared to the main arrays. However, it could provide enough power for essential systems. In addition, it could be used to charge IZIHAMBO-1's battery, allowing for brief discharges of higher power. In such a case, the BIT-3 ion thrusters would not be able to operate for long-term propulsion. However, they could be briefly operated to desaturate the reaction wheels onboard IZIHAMBO-1.

The passive solar array could be placed on the same side of the spacecraft as the primary array, adding additional power to the spacecraft's overall power generation during a nominal flight. As with other redundancy solutions, a tradeoff would be made with mass, and the balance between added redundancy and spacecraft mass would need to be examined.

ADCS

In the event of a complete failure of IZIHAMBO-1's ADCS, the spacecraft would lose the ability to orient itself and the mission would be lost. If the failure is only partial and limited to the reaction wheels, and not the mechanisms used to determine IZIHAMBO-1's orientation, it could be conceivable to attempt attitude control using the gimbaling feature of the BIT-3 ion thrusters. That being said, they were not designed with that intention in mind.

If a secondary ADCS were considered, it would likely result in a significant increase in spacecraft mass. As a result, the use of a single ADCS system may be an accepted risk of the mission.

Primary OBC

IZIHAMBO-1 uses the Xiphos Q8S as its primary onboard computer (OBC). In addition to the primary OBC, the spacecraft carries a backup OBC manufactured by EnduroSat. A common question is why two identical primary OBCs were not selected instead.

Using the same OBC as both the primary and backup would appear to simplify IZIHAMBO-1's design, since the hardware interfaces and software environment would be the same. However, with this approach the risk of common-mode failures increases. For example, a fault caused by a design issue, radiation sensitivity, power-handling behavior, or software defect in one OBC would likely affect the second OBC in the same way. For this reason, the backup OBC uses a different architecture to reduce the likelihood that a single failure mechanism disables both computers.

The backup OBC is not intended to perform all of the functions of the primary OBC. Instead, it is designed to support basic spacecraft survival and recovery. At a minimum, the backup OBC maintains a command and telemetry link with Earth and has the ability to control power to the primary OBC in order to reset or power-cycle it if necessary.

In the event that the primary OBC fails and is irrecoverable, data collection from IZIHAMBO-1's science instruments would no longer be possible. However, the backup OBC can keep the spacecraft operational, return engineering telemetry, and provide an opportunity to attempt recovery or diagnose the failure. While a second primary OBC could further increase redundancy, the additional mass, power consumption, and development effort are generally not justified for a CubeSat.

Data Storage

The IZIHAMBO-1 spacecraft uses four DDC 69F256G16 RAD-PAK NAND devices. Each device provides up to 256 Gb of storage and is radiation tolerant to a total ionizing dose exceeding 100 krad. This configuration provides substantial onboard storage for the mission. The devices can be treated as redundant to protect against data loss resulting from single-device failure or data corruption.

Using four storage devices is intentionally conservative. In addition to improving fault tolerance, the added capacity allows IZIHAMBO-1 to retain significantly more science data than a minimal configuration, which is particularly valuable during periods when downlink opportunities are constrained.

Launch Provider and Deployment

IZIHAMBO-1 will be deployed onto its trans-lunar injection (TLI) trajectory by a commercial launch provider. As a result, a complete launch failure would result in the loss of the spacecraft. Similarly, if the deployment mechanism either the separation ring or CubeSat dispenser fails, IZIHAMBO-1 would also be lost.

In the event of a partial launch failure in which IZIHAMBO-1 is placed into a highly elliptical Earth orbit but not onto a TLI trajectory, it may be possible to evaluate whether the spacecraft's remaining delta-V margin is sufficient to place it onto a TLI trajectory or allow it to escape Earth's sphere of influence into heliocentric orbit. While such a scenario would likely leave IZIHAMBO-1 without sufficient delta-V to pursue a Mars encounter, it could still retain enough capability to target a Near-Earth Object (NEO).

If IZIHAMBO-1 is instead placed into a lower Earth orbit, or is otherwise incapable of performing the maneuvers required to reach heliocentric orbit, the mission could be restructured to operate as an Earth observation satellite. In this case, IZIHAMBO-1 could potentially function as a high-resolution Earth imaging platform, as the CS-292 camera was designed with this capability in mind. Additional mission opportunities involving the Mars Descent Probe could also be explored.

The onboard BIT-3 ion thrusters would allow for long-term orbital maintenance if IZIHAMBO-1 were retained in Earth orbit. Because the spacecraft was designed to operate in the higher-radiation environment of interplanetary space, operating within Earth's magnetic field would place it in a significantly lower radiation environment. This would reduce IZIHAMBO-1's radiation exposure possibly enabling the spacecraft to remain operational for longer than originally intended.

Transponder

IZIHAMBO-1 uses the Vulcan Wireless transponder to communicate via X-band back to Earth. In the event of the transponder failing, the spacecraft would lose its primary mode of communication with Earth. However, the spacecraft would not completely be lost, as it could be possible to use its S-band antennas to communicate with the Earth. Its data rate would be severely limited and it would be unable to return the quantity of mission data as initially intended. That being said, as mentioned earlier, other possibilities such as an Earth flyby could be considered to downlink the bulk of its mission data.

Electrical Power System

IZIHAMBO-1 uses the NanoPower P80 as its Electrical Power System (EPS), in the event of a complete failure of the EPS IZIHAMBO-1 the mission would end. As the spacecraft would be inable to direct power from its solar arrays and batteries to its components. If the EPS fails partially, then consequences will vary depending on what is impacted. A partial failure could also include an inability for the EPS to adequately regulate the battery charge. As a result, power could become unstable and largely dependent on the position of the solar arrays. Additionally, voltage spikes originating from the EPS could also pose a risk of component damage. That being said the risk that any of these scenarios occurs with the EPS is low and the mass-redundancy tradeoff would likely not be worth it to add a secondary EPS onboard IZIHAMBO-1. Thus, the risk of EPS failure will likely become an accepted risk of the mission.

Battery

The battery used by IZIHAMBO-1 is the NanoPower BP8, it offers 100 Wh of power storage. Enough for brief periods in which the solar arrays are not facing the sun or are eclipsed. That being said in the event of battery failure, where the battery is incapable of reliably storing power, it could result in an unstable power supply onboard IZIHAMBO-1, as power would be heavily dependent on the solar arrays. The battery output is likely to degrade with time as the mission progresses, but should still be able to meet the demands of the mission.

Mars Descent Probe

As the Mars Descent Probe is an incredibly high risk aspect of the mission, it should not be treated as an integral part of IZIHAMBO-1. Rather, it should be treated as a technology demonstration of an extremely low-cost means of reaching the Martian surface. Informally, the Mars Descent Probe could be viewed as the "thought and prayer" aspect of the mission. It is not something guaranteed to work, but if it did, the payoff would be so significant that it outweighs the risk to build the probe.

Even if the Mars Descent Probe fails, the engineering data relating to its failure would still be extremely valuable. It could directly inform the development of IZIHAMBO-2's Mars Descent Probe. In this sense, any outcome of the Mars Descent Probe would still constitute a success.

The primary risk associated with developing the Mars Descent Probe is the optics of the IZIHAMBO-1 mission as a whole. The mission could return an incredible amount of scientific data, yet still be overshadowed in the public eye by the failure of the Mars Descent Probe. This is a risk worth taking, as success would establish a precedent for one of the most cost-effective methods of reaching the Martian surface.

Why IZIHAMBO-1?

The following section outlines the motivation behind the IZIHAMBO-1 mission, explaining why this mission exists, why its approach was chosen, and what value it is intended to deliver.

The IZIHAMBO-1 mission was designed as a tech demo for delivering instruments to destinations in interplanetary space, and within the atmosphere of Mars, at an incredibly low cost. But why should South Africa care about IZIHAMBO-1?

First, IZIHAMBO-1 is an incredibly cost efficient mission, anticipated to cost in the range of $15 million (ZAR 246,800,000). Previously, one of the lowest cost missions to Mars was India's Mars Orbiter Mission (MOM), which came in at a cost of ₹450 crore ($75 million USD, ZAR 1,224,609,870) [72]. Now, this may raise some eyebrows and a few questions like, "Why is IZIHAMBO-1 so much cheaper?" It may make IZIHAMBO-1 appear to be a mission built on nothing more than idealistic wishful thinking.

But to alleviate those concerns, it should be noted that IZIHAMBO-1 is an entirely different spacecraft than MOM. Its mass is expected to be closer to 14 kg, whereas MOM was 1,337 kg [73]. Additionally, MOM entered orbit around Mars, whereas IZIHAMBO-1 will be on a flyby trajectory. IZIHAMBO-1 is a small standardized satellite, also known as a CubeSat.

A fairer comparison would be NASA's MarCO CubeSats, as previously mentioned. This pair of satellites, MarCO-A and MarCO-B, hitchhiked aboard the launch of NASA's InSight mission to Mars. Notably, the total cost for both spacecraft combined was $18.5 million (ZAR 302,033,700). On a per-spacecraft basis, this places MarCO in a similar cost range to the anticipated cost of IZIHAMBO-1. However, MarCO incurred substantial research and development costs, particularly for custom components such as its high-gain antenna [75]. By contrast, IZIHAMBO-1 is designed to outsource the majority of its components, including its high-gain antenna, to established commercial suppliers such as Anywaves. Additionally, components flown on MarCO, such as the IRIS transponder, could potentially be reused or procured through vendors such as Space Dynamics Laboratory [76][77].

Since MarCO already experienced the same environment as IZIHAMBO-1, it has effectively demonstrated the feasibility and potential for a mission like IZIHAMBO-1. During its development, IZIHAMBO-1 will be able to refer to lessons learned from the MarCO mission.

The most risky aspect of IZIHAMBO-1 is the Mars Descent Probe. It remains the most technologically exciting part of the mission while simultaneously being the greatest engineering pain of the mission. But that is exactly "Why IZIHAMBO-1?" It makes the mission technologically unique, and it tests uncharted waters in low cost deep space exploration. Although many may disregard it as being far fetched, it should be noted that JAXA attempted to land on the surface of the Moon using their OMOTENASHI CubeSat, which got a ride on Artemis I [78]. OMOTENASHI could even be considered more ambitious, since it was designed to fit a lunar lander within its 6U form
(6U approx 10 x 20 x 30cm, IZIHAMBO-1 is a 12U approx 20 x 20 x 30 cm).

The lunar lander on OMOTENASHI was intended to land on the Moon using a rocket and airbag. It should be noted that the entire cost of OMOTENASHI was in an impressive range of $5 to $6 million (ZAR 81,660,136 - 97,992,163) [79]. Surprisingly, it was not OMOTENASHI's ambition that led to its mission failing. Rather, it originated from a cold gas thruster leak that resulted in a rotation greater than the attitude control system was able to compensate for [80]. This made it impossible for OMOTENASHI to orient essential components such as its solar array, resulting in mission failure before it could even attempt its landing on the surface of the Moon.

What we can learn from OMOTENASHI is that it is possible to attempt extremely ambitious CubeSats and build them at an incredibly low cost. It should also be noted that IZIHAMBO-1's design is far simpler in some regards. The Moon has no atmosphere to produce drag to slow a lander down, so a lunar lander requires substantial delta-V to slow down. The Mars Descent Probe, however, is able to leverage the Martian atmosphere for drag during its ballistic descent. The Mars Descent Probe therefore does not require any substantial forms of propulsion to land on the surface of Mars.

It should be noted that the South African government has spent in excess of ZAR 4,400,000,000 ($325 to $330 million, 2018) on the construction and design of the MeerKAT radio telescope and SKA enabling infrastructure [81]. In addition to this, the South African government is expected to spend in excess of ZAR 540,800,000 ($30-40 million) in total on the South African Earth Observation Satellite-1 [82][83]. In comparison, the total cost of IZIHAMBO-1 is anticipated to be in the range of $15 million (ZAR 246,800,000).

For this price, IZIHAMBO-1 would become South Africa's first deep space mission, achieving many firsts, including South Africa's first mission to the Moon, Mars, and an asteroid. Not only would this mission provide the capability to capture incredibly valuable scientific data, it could become a source of pride and respect for South Africa. It would demonstrate the capabilities of South African ingenuity and engineering, and inspire South African youth that South Africa will play a vital role in the frontier of deep space exploration.

Program Plan

This section lays out how IZIHAMBO-1 gets built and flown, including the development phases, operations concept, and the schedule and budget required to execute the mission.

So far this proposal has covered the baseline of the IZIHAMBO-1 mission, including the main architecture behind the spacecraft, its flight plan, and its intended goals. But let's say South Africa wants to move forward with IZIHAMBO-1. What are the next steps? How would it be funded, and what would funding look like?

First, IZIHAMBO-1 would not be funded in whole. Funding would be secured in phases, with ZAR 41,115,000 (~$2.5 million) initially requested for a 12 month Phase B study.

Phase B is typical in mission design and can be viewed as a risk-reduction feasibility study intended to validate the mission cost and schedule, and to produce a Preliminary Design Review (PDR) ready baseline for Phase C.
This does not commit the South African government to funding the IZIHAMBO-1 mission. Rather, it ensures that if the government chooses to fund IZIHAMBO-1, there are no major gaps in the mission design. This increases confidence that IZIHAMBO-1 can be executed within a validated cost and schedule, and reduces the risk of it becoming a mission that overpromises and underdelivers.

To clarify, Phase B is not just "more thinking." It is where the bulk of the mission is designed and where the core team is initially formed. It is different from this Phase A document. The purpose of Phase A is to prove that the mission is feasible. It can be viewed as the outline of the mission, identifying the mission's architecture, objectives, and constraints, and producing a reasonable range for the mission's anticipated cost. Phase B is the step where the detail is added to that outline.

For example, this Phase A document has identified a variety of components that could be used in the baseline architecture of the mission and purchased from vendors. However, these are not set in stone. During Phase B, alternative components could replace these if they are deemed more suitable. Once Phase B has concluded, it is unlikely that these components would change. The purpose of listing components in Phase A is to support a reasonable cost estimate of the mission.

Let's suppose that ZAR 41,115,000 (~$2.5 million) is provided to produce Phase B. How would it be spent?

Initially, it would be used to hire the core team and part-time specialists to advise and contribute to the design of IZIHAMBO-1. The core team would consist of a full-time Project Manager (1.0 FTE), Systems Engineer / Mission Architect (1.0 FTE), Mission Design / GNC (Guidance, Navigation, and Control) Engineer (1.0 FTE), Communications / RF Engineer (1.0 FTE), Power Systems Engineer (1.0 FTE), and Mechanical / Thermal Engineer (1.0 FTE). Part-time roles would consist of a Propulsion Engineer / Electric Propulsion SME (0.2–0.5 FTE), Flight Software Lead (0.2–0.5 FTE), Integration and Test (I&T) / Verification Engineer (0.3–0.7 FTE), Mission Assurance / Quality (0.2–0.5 FTE), Procurement / Supply Chain / Contracts Support (0.2–0.5 FTE), and Ground Segment / Mission Operations Engineer (0.2–0.5 FTE).

To strengthen technical oversight, Phase B will include an independent review element, with external experts contracted as required to review the mission baseline and risk posture prior to PDR. Where necessary, Phase B funding may also be used for limited prototyping and targeted risk-reduction testing, focused on high-risk items such as deployables, separation mechanisms, and communications interfaces.

At the conclusion of the 12 month Phase B effort, a PDR will take place. The resulting design of the IZIHAMBO-1 spacecraft and Phase B findings would be presented to the South African government. From there, it would be the government's discretion whether or not to proceed by funding Phase C/D.

The South African government should expect Phase B to solidify the mission's design and timeline, and to present a budget request for Phases C/D/E. For example, a possible request could be ZAR 165,231,000 (~$10 million) for Phase C/D and ZAR 41,115,000 (~$2.5 million) for Phase E.

Phases C and D should be funded together, not separately. Generally speaking, Phase C is where the Critical Design Review (CDR) takes place and where every detail of the design is finalized and frozen. Phase C could take in the range of 6 to 9 months. Phase D is where the spacecraft is physically built and tested and could last 18 to 24 months.

By the end of Phase B, the main architecture of the spacecraft, such as the Bit-3 ion thrusters, should already be solidified. Many of these components may have lead times approaching 12 months, along with export and licensing paperwork. By ordering components that are not expected to change during Phase C, the IZIHAMBO-1 team can get a head start on lead time. This reduces the chance of the team being idle later and can allow more time for integration and testing.

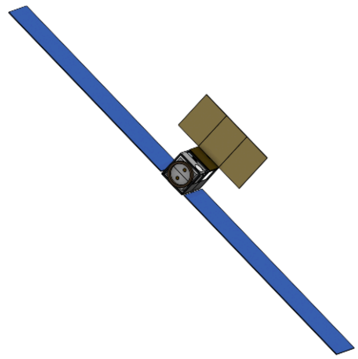
It should be noted that during Phase B, if the Mars Descent Probe is found to substantially increase the mission cost beyond what is reasonably anticipated, it may be removed from the mission baseline. In that event, alternative instruments could be identified as replacements. It should also be noted that the communications mass, power, and data rate will be finalized in Phase B after completing a full link budget and a ground station availability and cost trade.

Following Phase B, roles would migrate into Phase C/D, with some part-time roles transitioning into full-time roles. Additional roles needed for Phase C/D would be identified during Phase B. After Phase C/D, funding can be provided for Phase E, which covers primary mission operations after the launch of IZIHAMBO-1. The operations team would be reduced to roughly 2 to 4 roles, to be identified during Phase B. From time to time, team members from Phase C/D may be contracted to resolve issues that arise during flight.

Phase E is anticipated to last 24 months. If the IZIHAMBO-1 spacecraft continues to operate nominally, funding could be requested for an extended mission period to continue operations. A substantial portion of Phase E funding would be directed toward paying for antenna time through providers such as KSAT.

Following Phase C/D, it could be possible for roles to transition into IZIHAMBO-2, assuming the South African government approves an IZIHAMBO-2 mission. Such a mission could be produced at a lower cost, considering that the majority of the spacecraft's design would originate from IZIHAMBO-1. Design changes could be made to the hosted instruments on IZIHAMBO-2 and the Mars Descent Probe. South Africa could also open the door to international collaboration, potentially allowing international partners to host instruments onboard IZIHAMBO-2.

Possible Mission Timeline



Phase B	Phase C	Phase D	Phase E
12 Months	6 - 9 Months	18 - 24 Months	24 Months

Mission Study and PDR
ZAR 41,115,000 (~$2.5 million)

Mission CDR, Construction, and Launch
ZAR 165,231,000 (~$10 million)

Mission Operations
ZAR 41,115,000 (~$2.5 million)

Possible Mission Total
ZAR 247,461,000 (~$15 million)

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