Government Reference Design of the Vertical Solar Array Technology Demonstrator

Scott Belbin[*], Carl Mills* and Ryan Chan*

Abstract

NASA Langley Research Center (LaRC) is developing and constructing a Government Reference Design (GRD) version of the Vertical Solar Array Technology (VSAT) Demonstrator for lunar surface applications. This paper provides an overview of the conceptual design effort and discusses the planned demonstrations of its associated mechanisms.

Introduction

With the upcoming robotic and human lunar surface exploration efforts, NASA seeks to provide a means of powering and recharging various assets on the lunar surface at the southern polar region. The VSAT Program is developing a system by which an array of photovoltaic cells can be elevated above shadowing caused by boulders, hills, mountains, and crater walls to provide near-continuous electrical power to those assets. The Program has awarded initial development contracts to three awardees to develop their concepts to at least TRL-6. Langley is simultaneously designing and building a GRD Concept Demonstrator to assist in mechanical deployment and stowing issue mitigations and to inform the various reviewers of the awardees' efforts in the upcoming down-selection of awardees for the next phase of the Program.

VSAT GRD Overview

Original Concept

VSAT Program advisor and AIAA Fellow Martin Mikulas provided the original concept of a deployable array system on a deployable mast to elevate the arrays (originally named Retractable Surface Array). Parameters included a minimum power capability of 10 kW and a minimum elevation of 10 m from the lunar surface to the bottom of the arrays. This yielded an estimated array size of 6 m x 6 m divided into two separate arrays on either side of a mast.

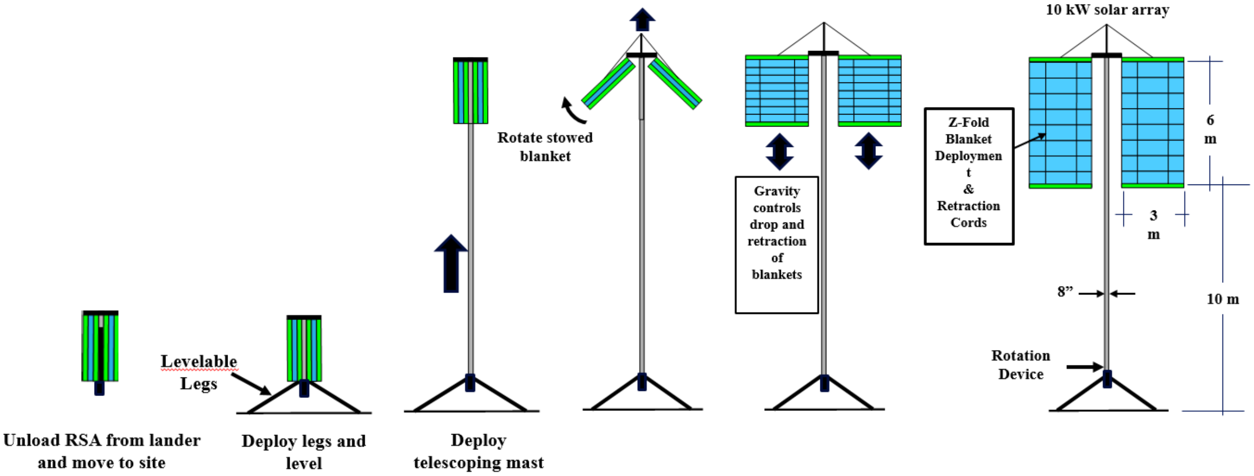


Figure 1. Original concept from Stowed State to Fully Deployed State

---

[*] NASA Langley Research Center

GDR Design

From this, preliminary designs of the various subsystems were developed, eventually evolving to a four-array package system to optimize volumetric packaging when stowed. Subsystems included a tripod base structure, gimbal for rotating the mast and making it plumb, deployable array housings, and deployable mock-arrays. This paper will discuss the decisions made in reaching this configuration along with the sizing of materials, mechanisms, and drivetrains, as well as lessons learned during the design and analysis phase, such as sizing gearmotors well in advance of final design and purchasing those gearmotors due to long lead times.

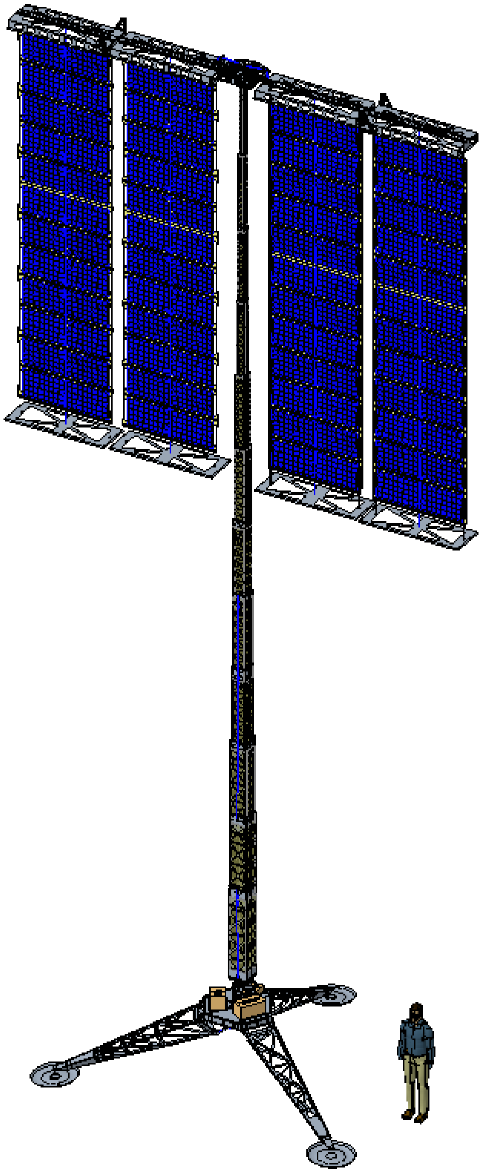


Figure 2. 4-Array Package GRD

Concept and Requirements

As originally presented by Martin Mikulas, a tall mast with two arrays on either side of the mast were shown with a series of images depicting deployment. To clear the shadowing of the local rims of craters and other lunar surface features, the arrays need to be elevated to a minimum of 10 m at their lowest extreme. The sizes of the arrays were determined by setting the goal of reaching 10 kilowatts of power available to end users.

Lunar Mission Requirements included:

- 36 m^2 solar array area
- 10 m from the lunar surface to the bottom of the arrays
- The ability to be off-loaded from the landing vehicle
- Accommodate local slope of no more than 15° at initial placement (pre-deployment)
- Autonomous mast verticality (plumbness)
- Autonomous deployment and retraction of the mast and arrays
- Transportability for relocation to other sites
- Survivability during the lunar night

This design of the GRD was to be flight-like, with all the features required to proceed to TRL-6 in parallel with the awardees. However, due to cost constraints COTS item were used whenever possible and the decision was made to focus on the deployment and stowage of the arrays, and not pursue actual solar panels or the surface interaction components. A truncated set of requirements was generated:

- 36 m^2 mock solar array area
- Minimal necessary clearance from the bottom of the arrays to the test cell floor (test cell ceiling height limits mast height)
- Accommodate local slope of no more than 15° at initial placement (pre-deployment)
- Autonomous mast verticality (plumbness)
- Autonomous deployment and retraction

Preliminary Design Iteration (Flight-like)

Referring to Mikulas' concept, major subassemblies were identified and include:

- Three axis gimbal
- Extendable/retractable mast with and array support structure and lifting point.
- Two array packages
- Base with deployable legs and launch constraint features.

From the original concept, the estimated sizes of the array packages drove the retracted (stowed) mast height. With an array net width of 6 m, two 3 m width arrays would need to be housed with drives, with the housing needing to be slightly larger than 3 m.

Gimbal Design

The requirement of accommodating up to 15° of local terrain slope dictated the need for some means of making the mast plumb, that is, making the mast parallel to the gravity vector. Given the overall scale of the demonstrator, compactness of the gimbal was not a primary concern. Instead, control authority and stability of the demonstrator once fully deployed was of utmost importance. A concept for a 2-axis gimbal for use on a conceptual lunar crane had been initiated and was used as the basis for a larger version sized for the VSAT concept. As this early concept used high-force self-braking linear actuators to provide the needed stability for a tall structure in a gravity environment, larger COTS linear actuators of the same type were sized and selected. This larger version used ball screw linear actuators with worm drives and recirculating ball nuts driven via worm and worm gears using DC brushed motors, with the two linear actuators providing independent X axis and Y axis motion. To that, a rotating feature for Z axis motion was incorporated.

The gimbal consisted of three subassemblies; the base which had the X axis and the end pivot point for the X axis linear actuator, a cruciform middle subassembly which had the location for the trunnion for the ball-nut for the X axis linear actuator as well as the location for the trunnion for the ball-nut for the Y axis linear actuator. The third subassembly mounts to the Y axis of the cruciform subassembly and the location for the end pivot point of the Y axis linear actuator.

The new rotator feature for z-axis motion consisted of a central high-strength steel axle, two tapered roller bearings in a spool-shaped hub, and a lower and upper plate to which the mast is attached. It is driven by a right-angle drive work and worm gear driven by a COTS gearmotor. The drive has a helical pinion gear driving a ring gear attached to the bottom of the rotator. This right-angle drive is attached to the upper subassembly of the gimbal. A slip ring assembly at the top of the gimbal below the rotator facilitates motor power and signal conductors such that continuous rotation would be allowable. This is in lieu of using a service loop, or an Omega shaped flat cable and rotating the mast +180° through zero to -180°. The slip ring has decks with each deck comprised of a rotor and stator. The rotor has concentric copper traces that align with spring loaded pins on the stator. The rotor is driven by the bottom of the rotating portion of the gimbal, with conductors passing through the rotator's bottom and top plates and out to the mast's side wall.

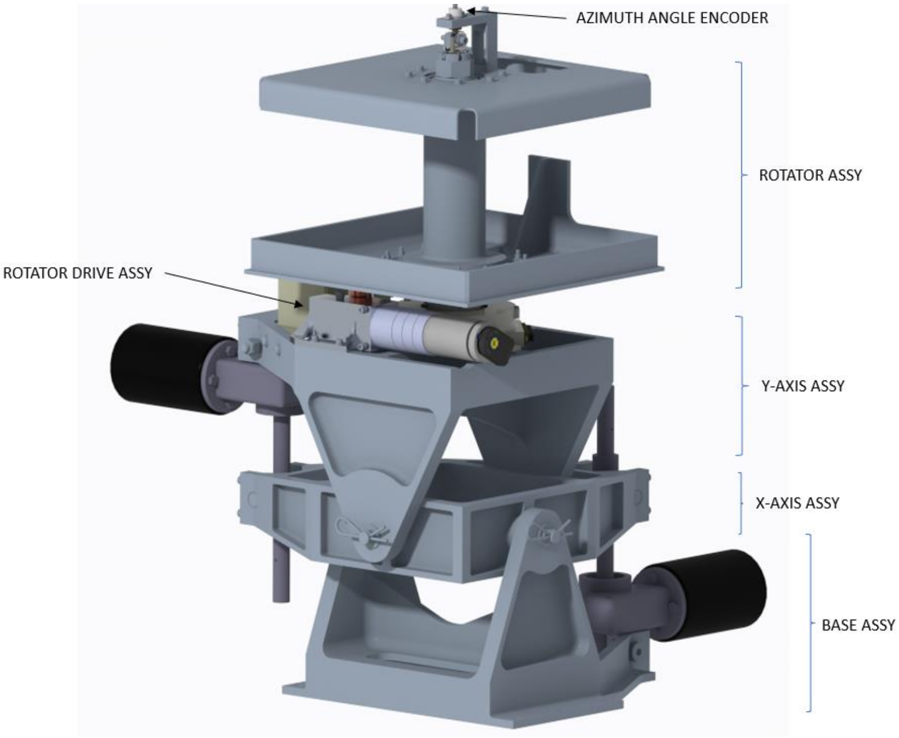


Figure 3. Gimbal Features, Rear

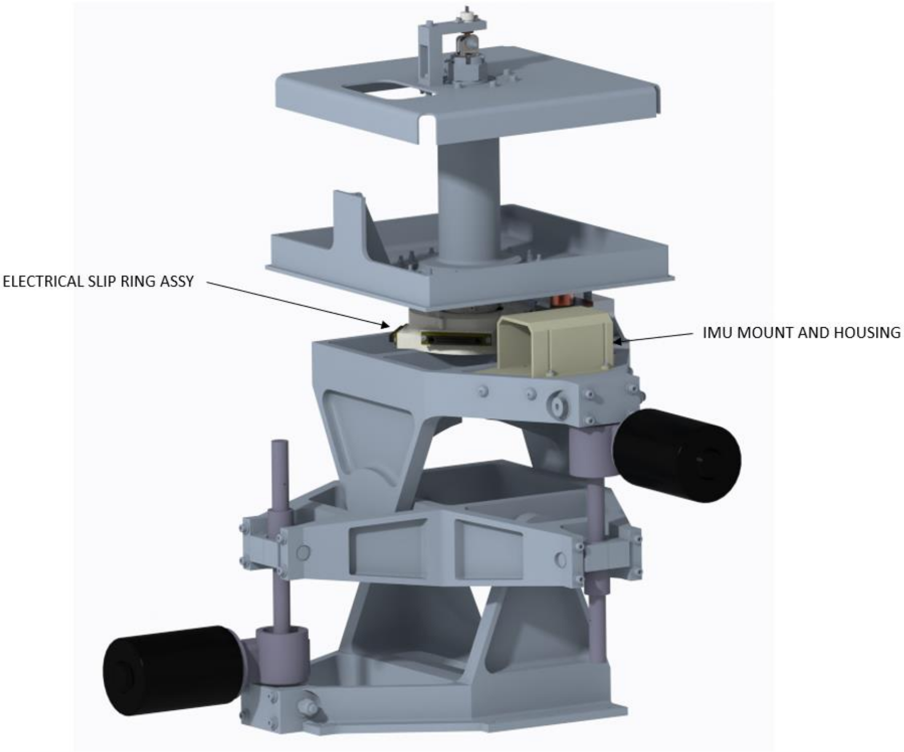


Figure 4. Gimbal Features, Front

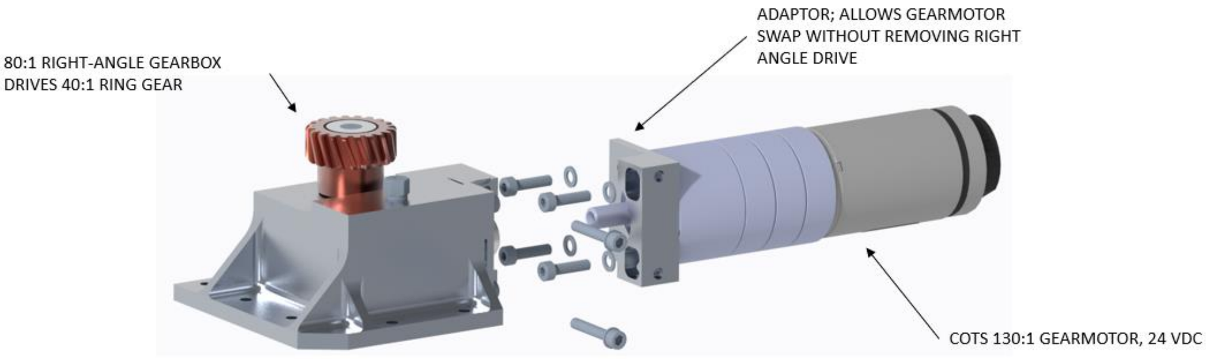


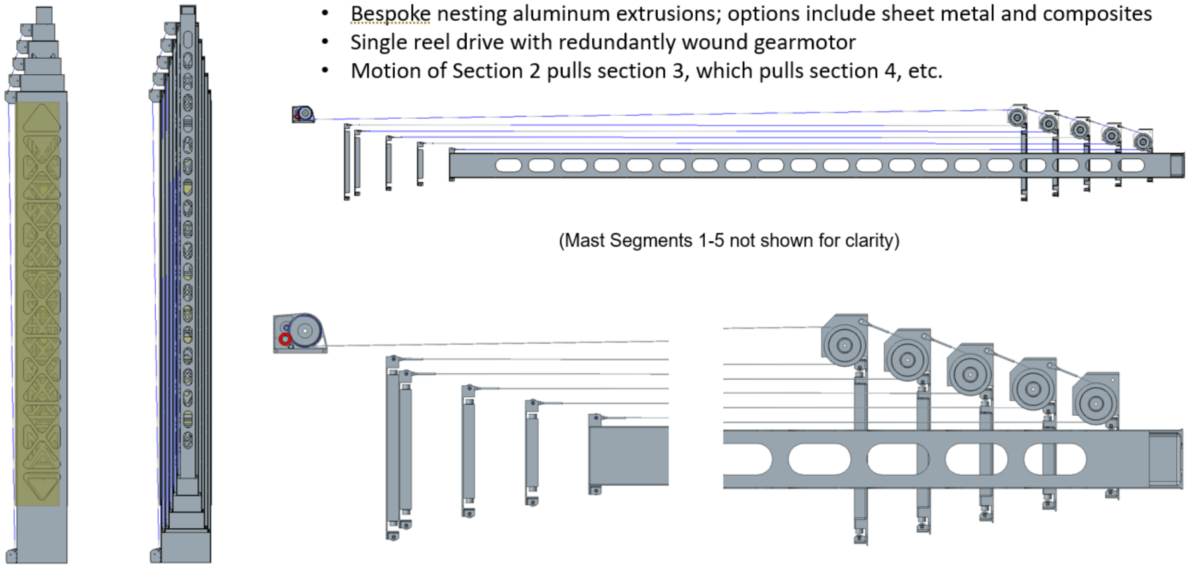
Figure 5. ROTATOR DRIVE ASSEMBLY

Mast Design

Being in a gravity environment, the mast requirements deviated from the typical booms used for spacecraft for their solar arrays. In addition to being stiff enough to prevent buckling in gravity, it must be retractable, which is a feature that few spaceborne booms have. It could also use gravity to retract instead of relying on a driving mechanism. The inspiration for the design came from terrestrial telescoping masts for light-towers and other portable industrial equipment. Those masts are driven by a winch mounted on the lowest segment (segment 1) which pulls segment 2 up. Segment 3 and the subsequent segments are each attached to the previous one via wire rope over a pulley at the top of each segment, bootstrapping all the segments up simultaneously.

For the telescopic mast segments, bespoke nesting box section extrusions were implemented in the CAD model, with the intent of procuring aluminum extrusions with the cross-sectional dimensions needed. These extrusions would receive lightening features and wall-thinning to minimize mass. With two 3-meter arrays astride the mast and the gimbal at the bottom of the mast, initial sizing determined that the mast segments were limited to about 3 m in height. With a net deployed height of 16 m (6 m array height and 10 m clearance to the surface), it was determined that 6 segments would be needed.

The mast drive was designed using a worm and worm gear arrangement driven by a gearmotor, driving a wire rope drum. The mast drive is attached through the bottom of the first mast segment to the gimbal’s rotator structure at the rotator assembly’s base and upper plates.



- Bespoke nesting aluminum extrusions; options include sheet metal and composites
- Single reel drive with redundantly wound gearmotor
- Motion of Section 2 pulls section 3, which pulls section 4, etc.

Figure 6. Six Segment Mast Details

A support structure was added to incorporate hinge points at the top of the mast for mounting array housings. This structure carried the two pulleys for the wire ropes that become taught when the mast is fully deployed, causing the array housings to fold upward to their deployed positions. It also incorporated the lifting point for the VSAT for off-loading from the landing vehicle and for relocating to alternate locations.

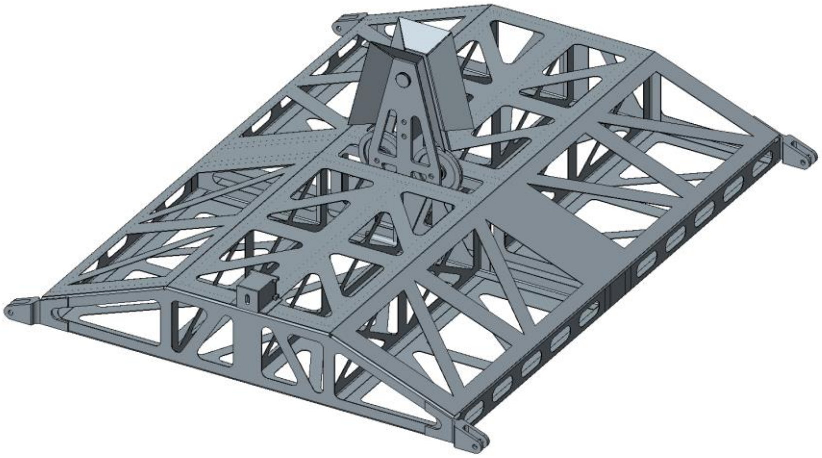


Figure 7. Array Support Assembly

Array and Array Housing Design

Array panels were sized at 3 m wide by .75 m high, with 8 panels per package. Being flat panels, they were arranged in a folding pattern with links at the top and bottom to attach to the housing and the housing closing panel, respectively.

Sheet metal housings were designed to keep regolith off the panels during landing and transport. Lightening cutouts were added to reduce mass, and Mylar film was to be used to cover the lightening cutouts. Hinged at their inboard ends and attached to the Array Support Assembly, the housing motion came from a single wire rope up through the mast that wyes into two ropes and becomes taught, pulling the housings to their positions normal to the mast. Relying on gravity, the array panels would then deploy via a dual drum winch atop the housings. The closing panels add weight to the arrays to assist deployment in lunar gravity.

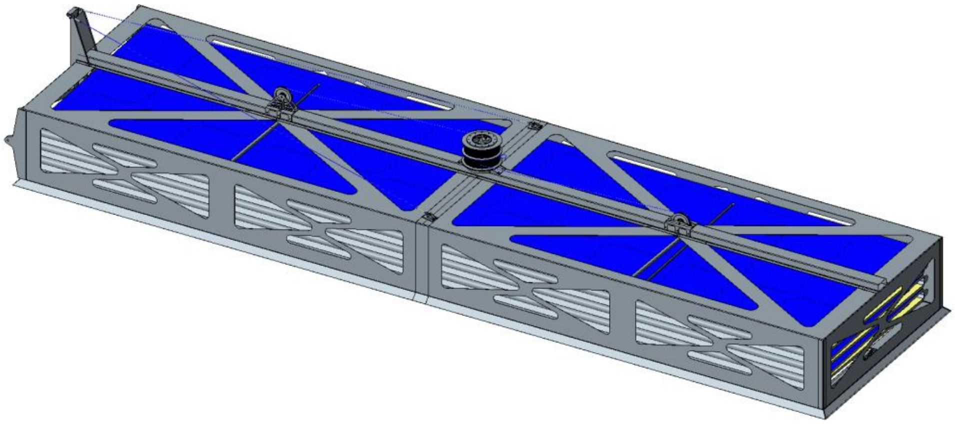


Figure 8. 3 m Array Package with Double Drum Rope Drive

The array panels are deployed via a drive with a double-wound drum for wire ropes that pass through the folded panels to the closing panels. The weight of the array panels and the closing panel cause the panels to descend as the ropes pay out. Unlike the CAD images, the panels do not unfold simultaneously, but rather, they stay folded near the bottom of the set with the uppermost panels unfolding first. Once the ropes deploy fully, the last of the panels move into their desired positions. The wire ropes are woven through in a manner that the panels cannot fold in the incorrect direction when retracting.

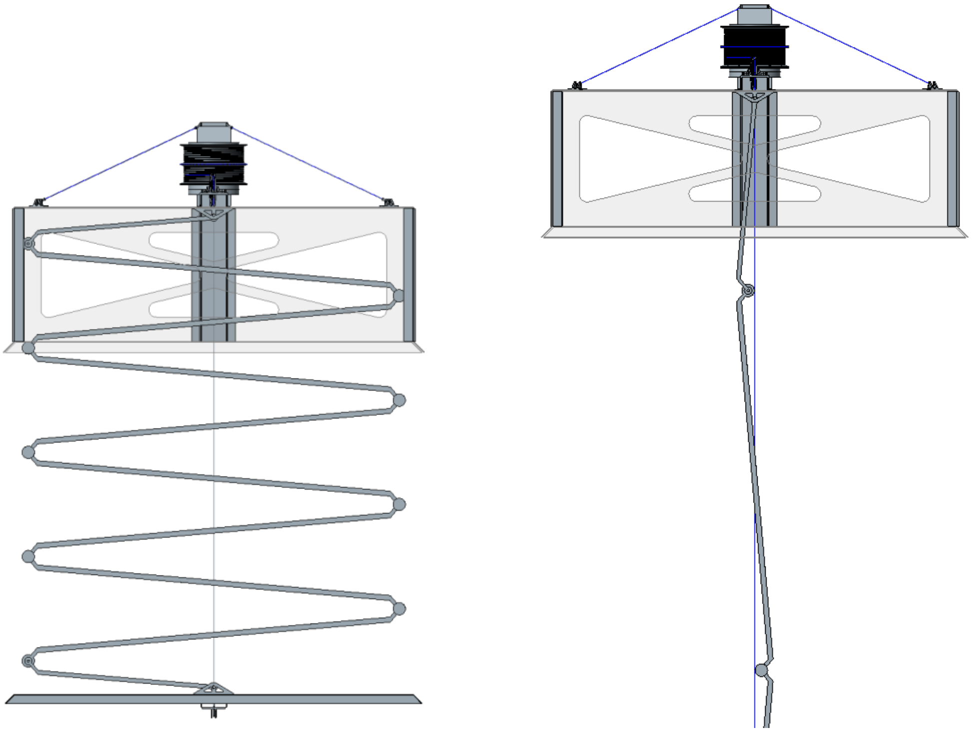


Figure 9. Array Panels Folding

<u>Base Design</u>

The base consists of a triangular platform with mounting points for the three legs with the gimbal mounted in the center. The legs retract upward and are stowed parallel to the mast. They are driven commonly via a single motor driving a triangular pivot with connecting rods to each leg.

Launch constraint components were designed and incorporated. These included a central pin with a ball-end that would be captured by an over-center hook latching mechanism and three cup-cones for constraining the VSAT. These same components could be incorporated into a transport vehicle for relocating the VSAT.

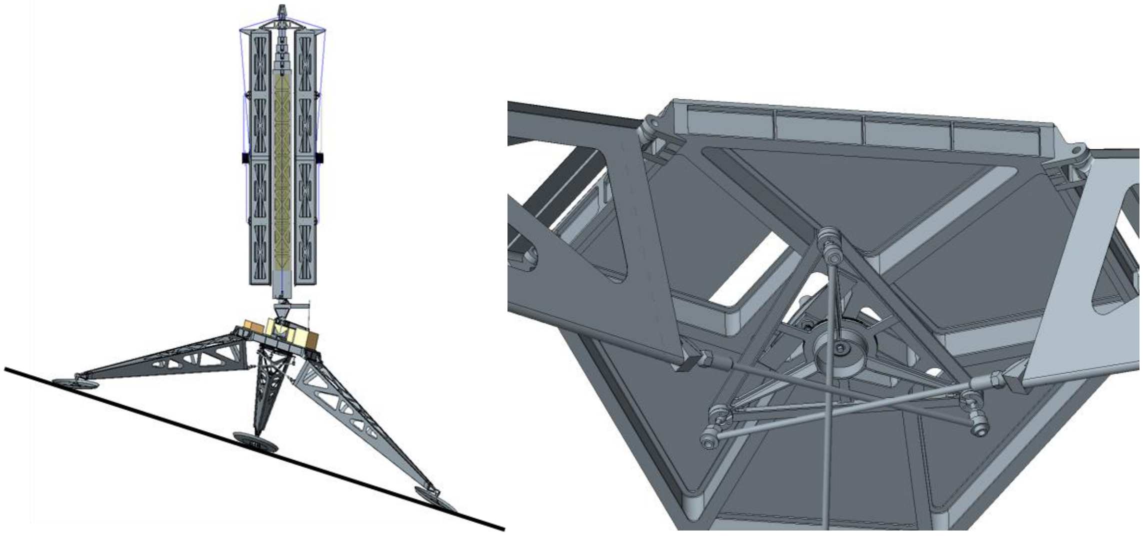


Figure 10. VSAT Base with 3 Leg Drive

<u>Second Design Iteration</u>
For the second pass at the overall design, it was decided to not proceed with the base and leg design since project management decided to not build a demonstrator of it. This allowed increased focus on the mast and array packages and their various drive mechanisms.

To reduce the overall volume and improve packaging of the stowed VSAT, the arrays were divided into two array sets per side yielding four 1.5 m wide arrays. With the array housing sizes reduced in stowed height, the mast's stowed height needed to be shortened as well, so the mast went from having six segments to twelve segments. While the added housings increased the stowed width of the stowed VSAT package, the net width did not exceed the base footprint and overall formed a better package volumetrically.

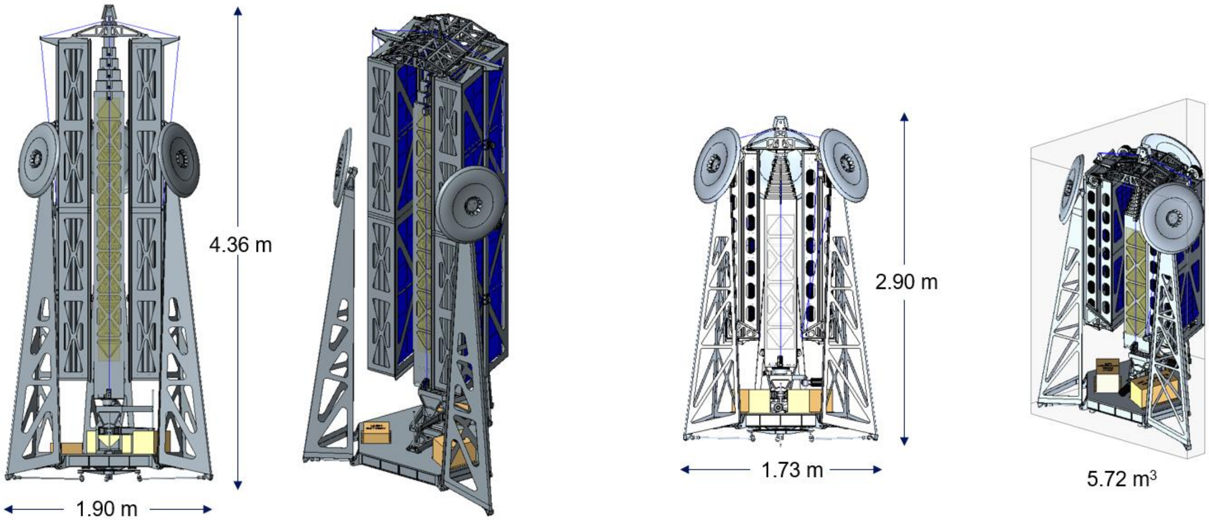


Figure 11. VSAT Iterations, Stowed Dimensions

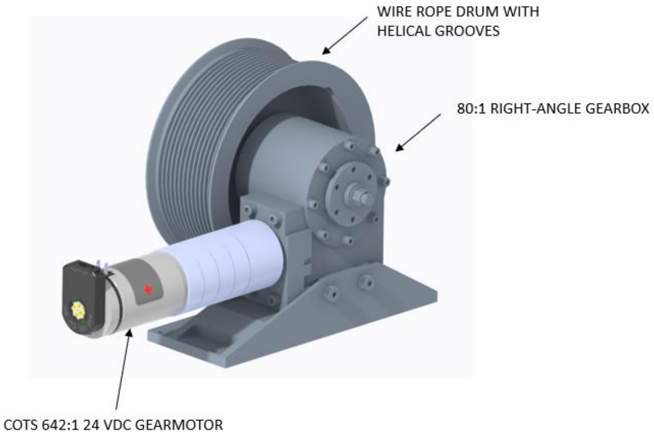
Mast Second Iteration

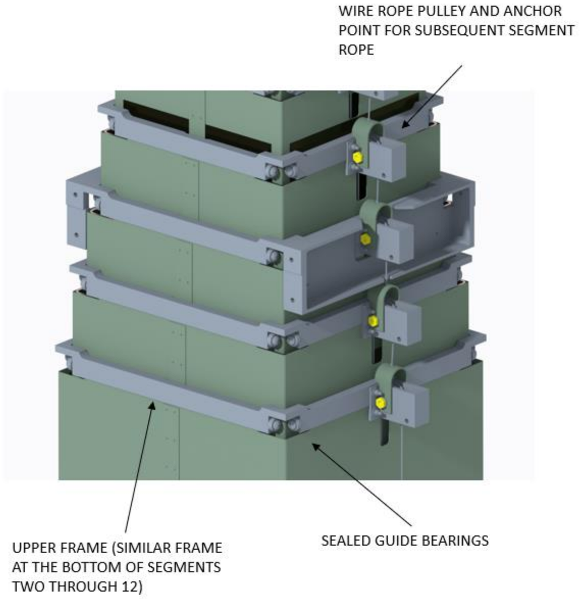
Going from six to twelve mast segments wasn't necessarily difficult as the added segments were shorter versions of the original segments, with six additional smaller cross-section segments added. Efforts to purchase bespoke square telescopic extrusions proved to be excessively expensive for a concept demonstrator, so the design switched to formed sheet metal components riveted together to form the individual segments. Sealed bearings at the corners of each segment controlled the nesting of the segments and would provide smooth motion during extension and retraction. These bearings were placed in the corner of frames on each end of the nesting segments, with eight bearings per frame. These frames also provided locations for the wire rope pulleys at the segment tops and the rope anchor points at the segment bottoms. The thin walls of the segment sections were reinforced in the corners with doublers.

For the GRD build, a shorter seven segment version of the mast was built due to the constraints of the test chamber.

Figure 12. Revised 7 Segment Mast (GRD Build Version)

Wire ropes, drums, pulleys, and their terminations were designed and chosen per MIL-DTL-83420P, General Specification for Flexible Wire Rope for Aircraft Control. This document dictates safety factors, minimum radii, and breaking strengths of mil-spec wire rope. Drum winding management was handled via helical grooves in the drums, and the drums were designed for single wrap in their diameter and width. This eliminated the need for an active rope guiding fairlead.





The Array Support assembly was redesigned in conjunction with the array packages to provide anchor points for new array housing drive ropes instead of the original taught rope pulleys. The estimate to build the sheet metal structure with machined fittings was deemed high, so a brief design study was performed exploring the use of bonded sandwich panels with machined fittings. The cost analysis was comparable to the sheet metal design, so the sheet metal design continued forward.

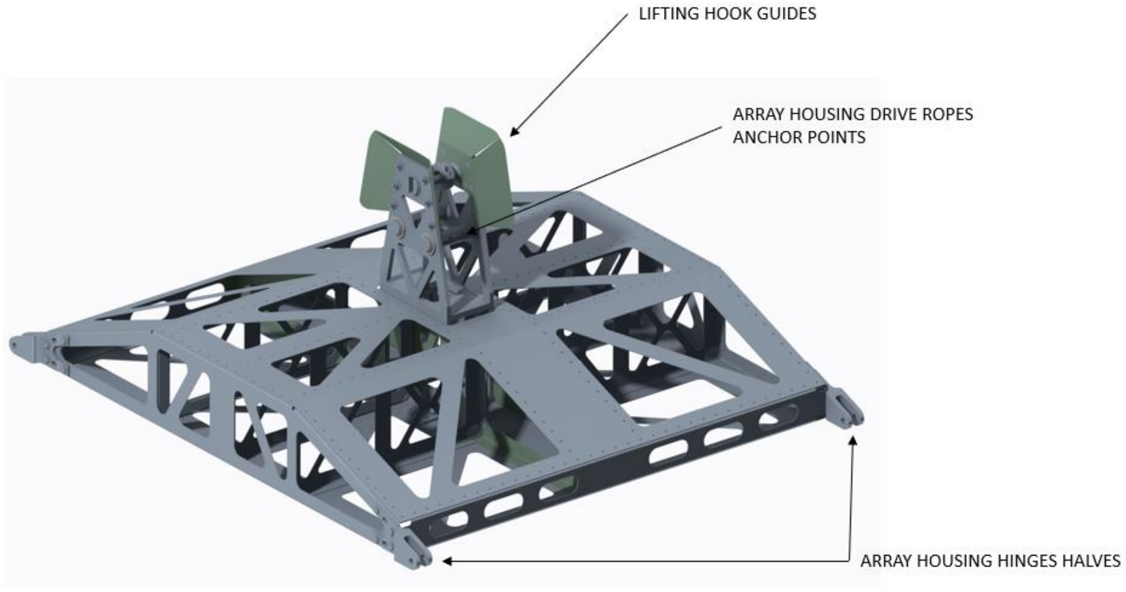


Figure 13. Revised Array Support Assembly

Array Packages Design, Second Iteration

Going from two array packages to four proved to be challenging. While the means of deploying the inboard housings via the single rope through the mast's core would work, unfolding the new outboard housing out and having them return to their stowed positions would require a separate method. Instead, a common drivetrain for the inboard and outboard housings was developed that incorporated a drum for the inboard housing and two drums for the outboard housing. The driveline is operated via a right-angle worm drive powered by a COTS gearmotor, with the outboard housing drums attached to it. It in turn drives the inboard array housing through a planetary gear set with a ratio of 5:1. That reduction, along with the two different drum diameters, provide the 2:1 folding motion of the outboard array housing vs. the inboard array housing. That is, the inboard array must fold upward 90 degrees, and the outboard array housing must fold downward 180 degrees relative to the inboard array housing.

The inboard wire ropes are anchored to the Array Support Assembly and the outboard wire ropes are anchored at the outboard array housings distal ends. To prevent the wire rope crossing the inboard/outboard hinge-line, two "kickers" were added to the outboard housing to prevent a zero-angle-crossing rope geometry case. The heights of the kickers were set such that the wire rope tension did not exceed its working load capability.

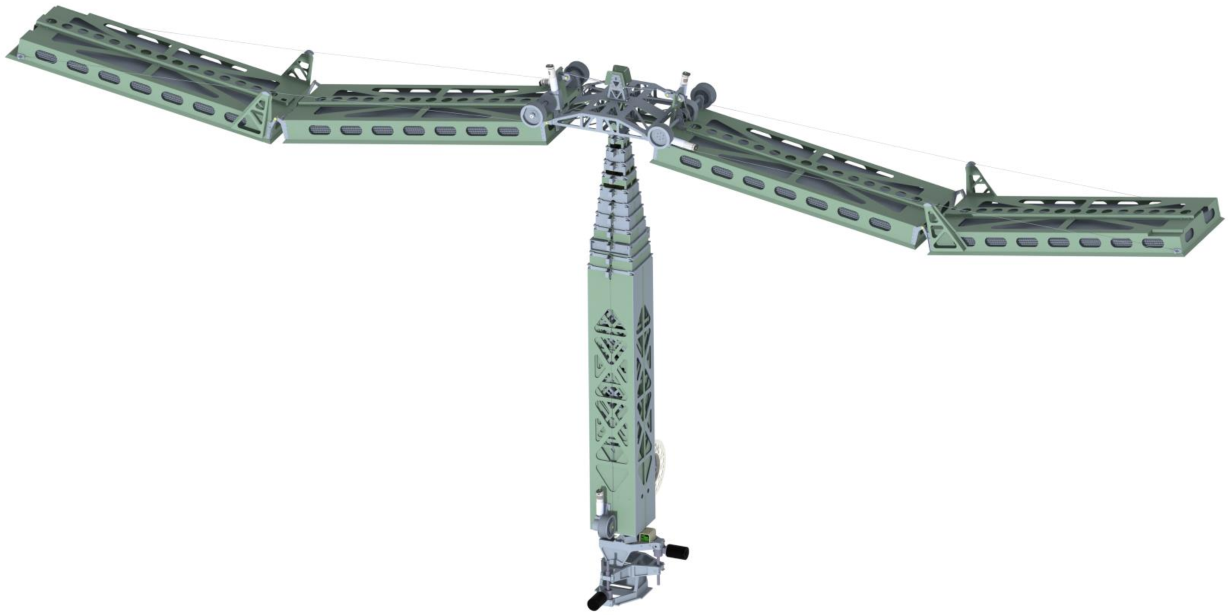


Figure 14. Four Array Configuration at "Kicker" Contact Deployment Stage

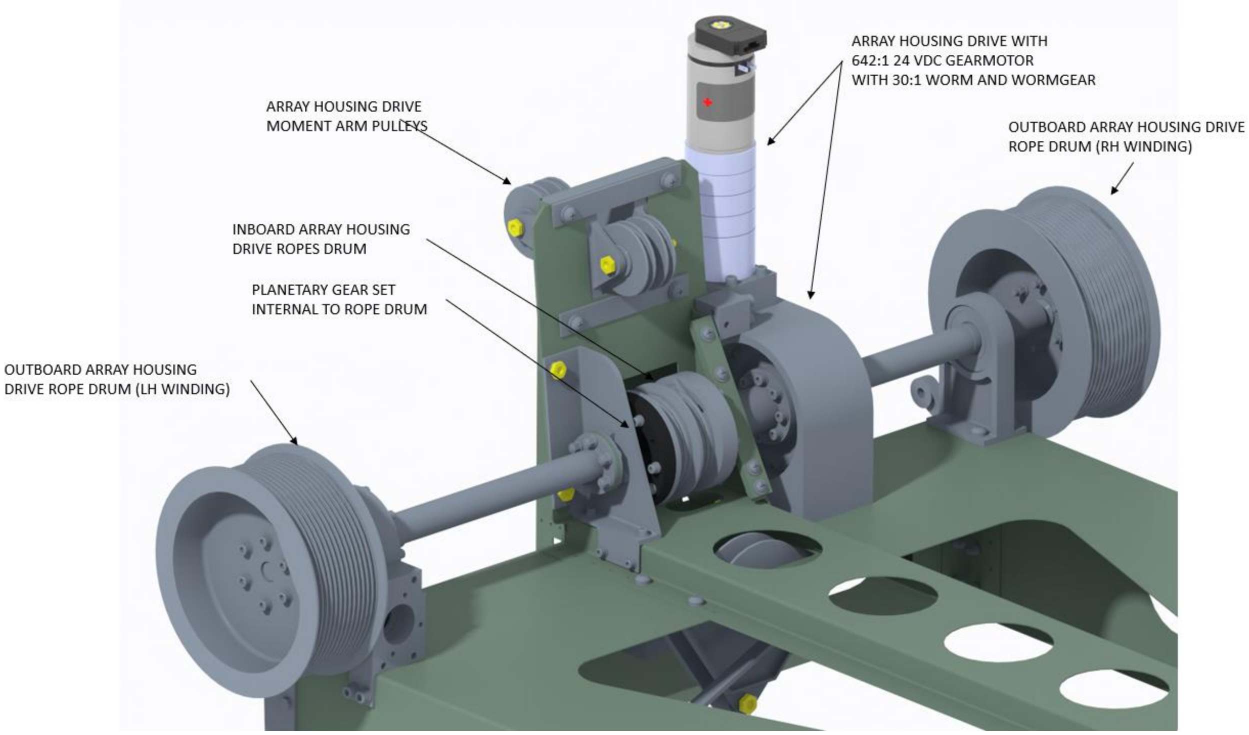


Figure 15. Array Housing Drivetrain

The array panel deployment method was changed to individual drivelines per package. This consisted of two array strap reels that unwind and wind nylon straps that lower and raise the arrays. These reels are on a common driveshaft driven by a right-angle gearbox and gearmotor. An adjustable clutch was added between the drive and the driveshaft to prevent stalling of the drive when the arrays are retracted. Strap length adjustment is provided by adjustable anchors on the bottom housing panels.

The mock array panel material was changed from thin aluminum to corrugated plastic panels to reduce mass, and instead of piano hinges, flexible tape was used for hinges. Only the first and last panels have bent aluminum sheet stiffeners to which the linkage pivot points are added.

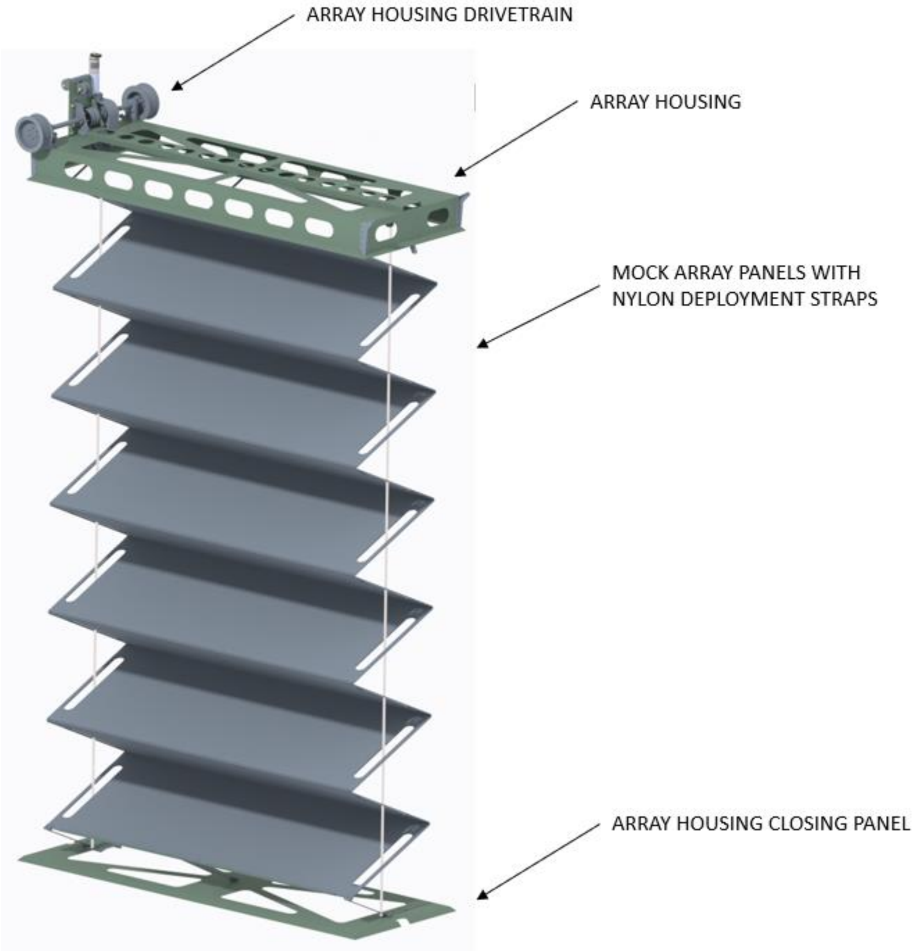


Figure 16. Inboard Array Package with Housing Drive

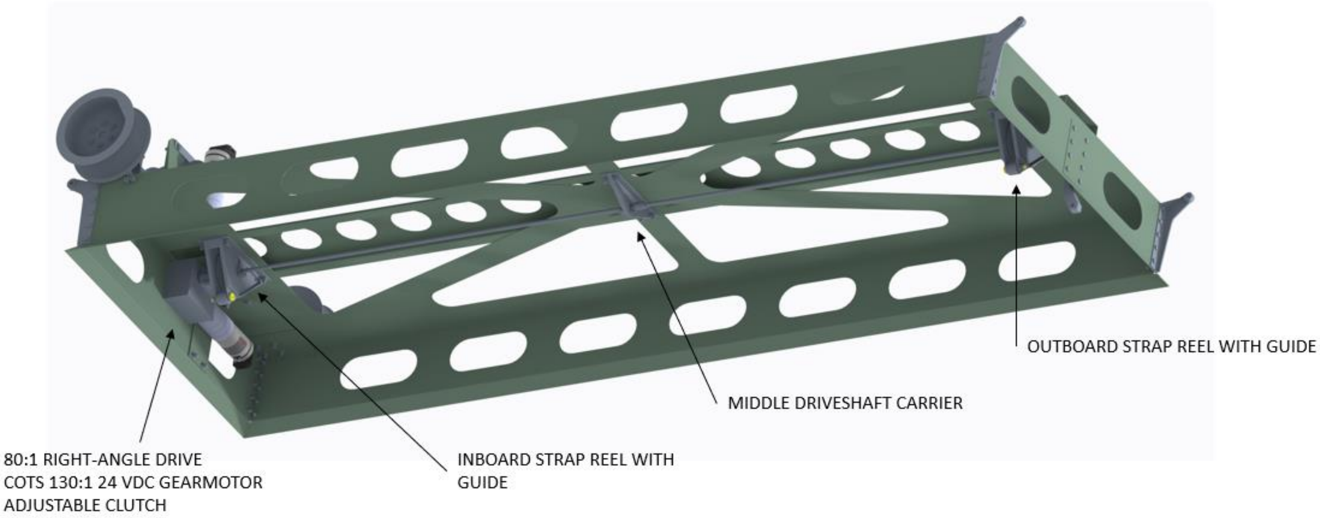


Figure 17. Array Panel Drivetrain

Control System

A SpeedGoat target machine serves as the main controller, taking both user and sensor input and generating analog control signals from this input. A motor driver takes these control signals and generates 24-volt PWM signals for the motors.

For the gimbal control, the SpeedGoat reads pitch and roll angle values from an inertial measurement unit (IMU) on the gimbal and feeds these angles into a proportional-integral-derivative (PID) loop. It then generates the control signals for the gimbal motors that will drive the mast to a desired angle. For the mast deployment control, the SpeedGoat reads sensor data from potentiometers and limit switches located at key points throughout the structure and uses this data to determine when to stop the mast, array housing and array panel deployment motors.

The user interacts with the control system by using a graphical user interface (GUI) running on a host machine connected to the SpeedGoat via an Ethernet connection. The user can set the desired gimbal angles and can start or stop the mast deployment. The user can also manually control each motor individually.

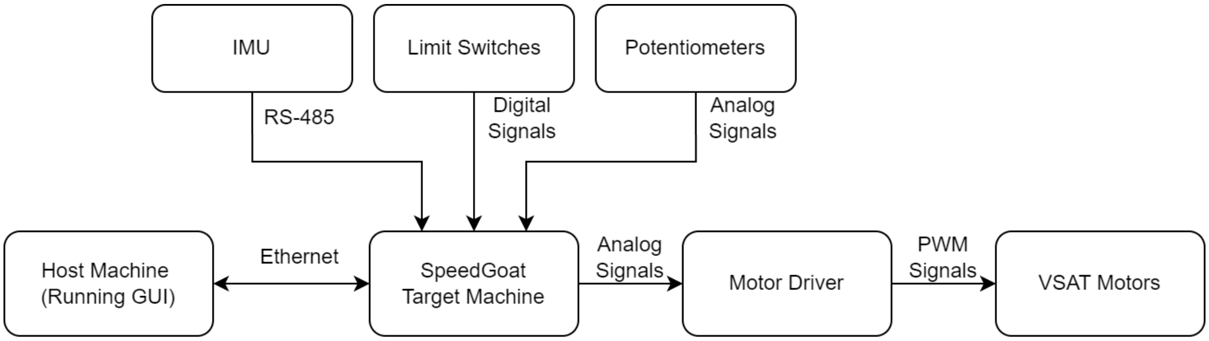
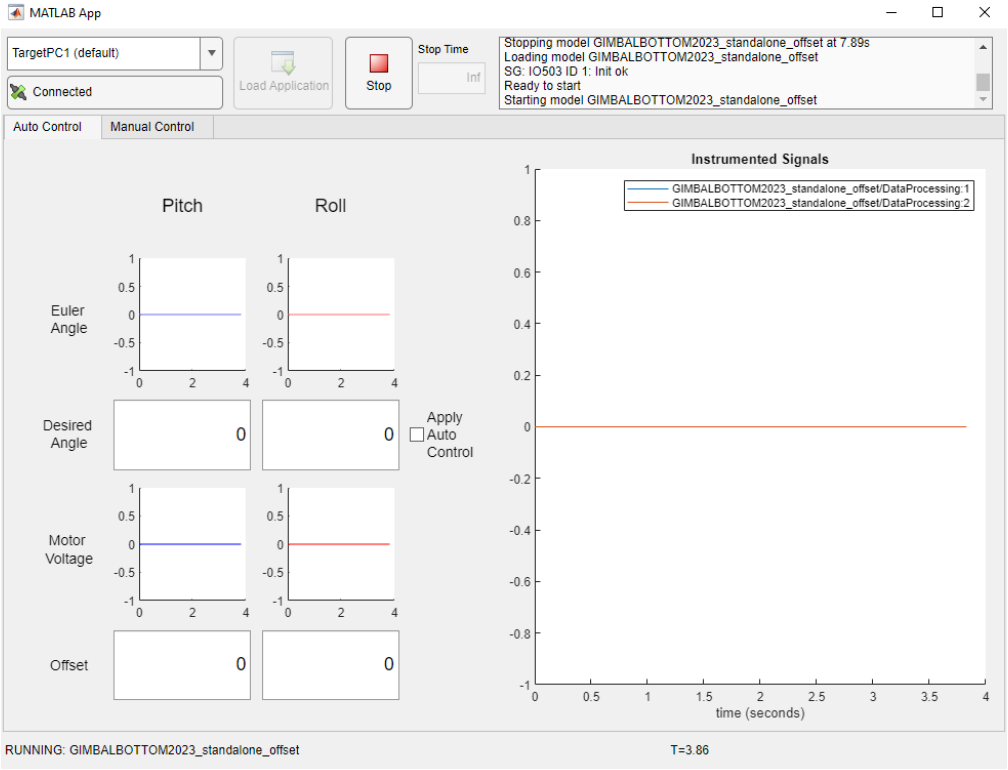


Figure 18. Diagram of the VSAT Control Setup



```
Stopping model GIMBALBOTTOM2023_standalone_offset at 7.89s
Loading model GIMBALBOTTOM2023_standalone_offset
SG: IO503 ID 1: Init ok
Ready to start
Starting model GIMBALBOTTOM2023_standalone_offset
```

Desired Angle: Pitch 0, Roll 0

☐ Apply Auto Control

Offset: Pitch 0, Roll 0

RUNNING: GIMBALBOTTOM2023_standalone_offset

T=3.86

Figure 19. VSAT GUI

Conclusion

At the time of this writing, the VSAT GRD is undergoing assembly in a test cell in B1293B at Langley Research Center. All major components are complete or are near complete with revisions being made as assembly progresses. Wiring for the control system is partially complete and testing of the gimbal has been conducted successfully using a dummy mast with deadweight at the top to simulate the inertial properties of the VSAT in the stowed condition. The completed mast has been installed and the off-loader system is being installed.

Assembly and operational testing will be incremental with the assembly progress. As major components are installed, their operation will be tested. These steps include the following:

- IMU zeroing ensuring the mast is plumb
- Gimbal operation with the mast stowed to simulate mast up-righting
- Mast deployment and retraction/stowing
- Inboard array housings installations; deployment with the mast stowed (lower risk and allows for easier observation)
- Mast deployment with inboard arrays stowed
- Inboard array deployment and stowing
- Inboard array panel deployment and stowing
- Installation of the outboard arrays; deployment of inboard and outboard arrays with mast stowed
- Deployment of the mast with array housing deployment and stowing
- Deployment of outboard array panels

References

1. Mikulas, Martin M., et al., “Telescoping Solar Array Concept for Achieving High Packaging Efficiency.” AIAA SciTech Forum, January 2015, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150006022.pdf
2. Pappa, Richard, et al., " Relocatable 10 kW Solar Array for Lunar South Pole Missions." *NASA/TM-20210011743*, March 2021.