Orbiting Artificial Star for High-Resolution Coronal Imaging from the Ground

Eliad Peretz[a], John Mather[a], Doug Rabin[a], Thomas Rimmele[a], Jeff Kuhn[a], Dirk Schmidt[a], Andrew Lewis[a], Kayla Carmical[a], and Luis Leon[a]

[a]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

ABSTRACT

This paper establishes the scientific motivation of the Orbiting Artificial Star for High-resolution Coronal Imaging from the Ground (ORCAS-Helio), and presents the Preliminary Science Traceability Matrix (STM), defining the scientific objectives, the expected significance, and the impact of the mission. Furthermore, the paper describes the payload, mission configuration, and spacecraft architecture and shows it could meet its scientific and engineering requirements. By doing so, a viable mission configuration for the ORCAS-Helio mission is established.

Keywords: ORCAS, corona, traceability matrix, magnetic topology, k-corona, heliophysics

1. INTRODUCTION

The Orbiting Artificial Star for High-Resolution Coronal Imaging from the Ground mission is a project taking an essential step in our understanding of the way the Sun works. The Sun has a thin outer atmosphere, the corona, that is 100–1000 times hotter than the visible surface of the star. Many other stars have a corona; many do not. The Sun's corona is scientifically important because we can't definitively explain why it is present, despite more than half a century of close study. The corona is also important because it is the source of "space weather" that can harm satellites, astronauts, and, in extreme cases, power grids on Earth.

Because we lack knowledge regarding the magnetic structure of the corona, our understanding of its heating, inextricably linked to the magnetic structure, is very limited. It is clear that understanding the manner in which the corona is heated is dependent on our knowledge of its magnetic structure; therefore, it must be made a priority to study this in order to better understand the other. Unfortunately, the current accessible technology is not capable of capturing data regarding the corona at a high resolution.

The Orbiting Artificial Star for High-Resolution Coronal Imaging from the Ground project aims to change that – by placing into orbit an artificial star, ground-based telescopes will have the ability to capture high resolution data from the Sun's corona. This data will allow us to both determine the scale at which coronal heating occurs, as well as determine the role of magnetic topology on the release of energy from certain areas. In addition, past work on the ORCAS Astrophysics mission[1,2] and starshade-based missions[3,4] have created a starting point for the this heliophysics mission.

In this paper, we describe the scientific principles pushing the project's development in section 2, share the scientific significance of successful completion of this project in section 2.3, discuss the engineering requirements needed to implement the scientific objectives in section 3, and present the mission operations in section 4.

2. SCIENCE

2.1 Science Motivation and Background

Today's leading theories of coronal heating share a key ingredient: the interaction of matter with magnetic fields on spatial scales smaller than we have ever resolved. The expectation that coronal magnetic fields will develop small-scale structure was introduced by Parker[5] in the 1980s (Figure 1). Today's understanding of the development of magnetic structure in the corona is more refined but still leads to the conclusion that the coronal field will be structured on all scales from the solar diameter to less than 1 km.

Further author information: E-mail: eliad.peretz@nasa.gov

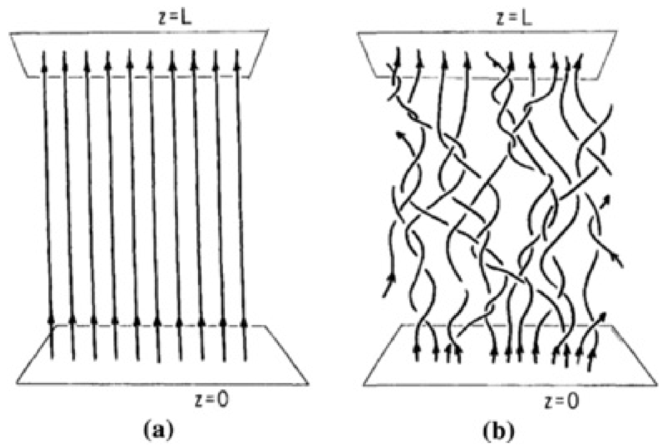

Figure 1. (a) Initial "straightened" uniform magnetic arch rooted in the photosphere. (b) At a later time, mixed and interlaced field driven by photospheric motions (Parker 1994).[5]

Theories are tested by comparing them with observations, but we don't have the observations we need to carry out definitive tests. Perhaps we will never resolve the smallest scales of coronal heating from outside the corona itself. However, we can get much closer to those scales and much closer to understanding and prediction. The heating process is best observed at extreme ultraviolet (EUV) and soft x-ray (SXR) wavelengths because coronal plasma (1–30 MK) radiates mostly in that spectral region. Direct measurements of the coronal magnetic field are challenging, particularly with high ($\lesssim 1$ arcsec) resolution. Nevertheless, the structure of the coronal electron density (the so-called K- or white-light corona), which traces magnetic field lines, can in concept be observed with very high angular resolution (see Fig. 2).

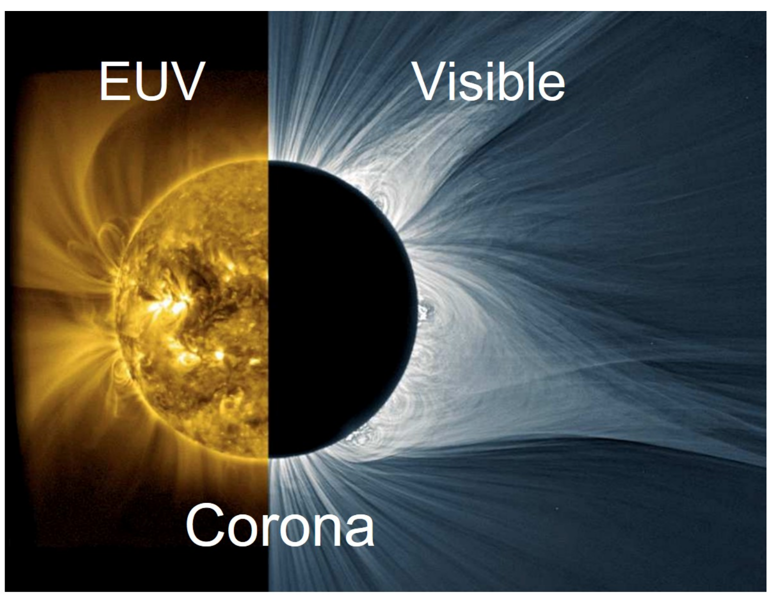

Figure 2. S.R. Cranmer and A.R. Winebarger / AR Astronomy and Astrophysics 2019[6]

The complex structure of the K-corona reveals complex magnetic structure. Historically, the K-corona is best observed during a total solar eclipse, but the angular resolution of Figure 3—among the best extant—is only about 1700 km (2.3 arcsec). The highest resolution image of the white-light corona known to exist was obtained during the total of eclipse of 11 July 1991 with the 3.6-m Canada-France-Hawaii telescope (November & Koutchmy 1996, Figure 4).

Figure 3. Total Solar Eclipse Corona in HDR, from Nicolas Lefaudeux 2017.[7]

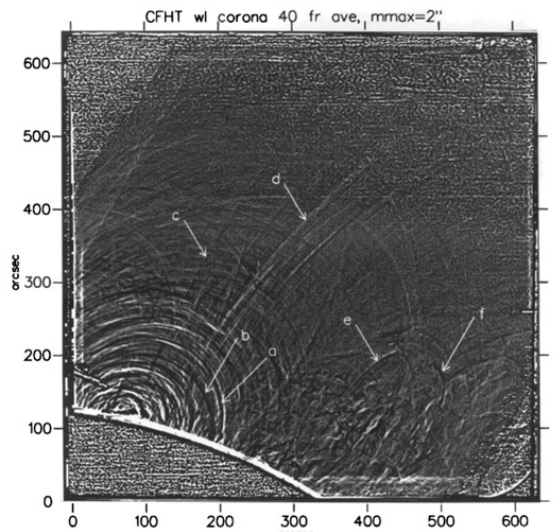

Figure 4. Spatially filtered image from November & Koutchmy 1996.[8]

However, adaptive optics were not available and the resolution of this image is about 1000 km (1.4 arcsec). The 4-m Daniel J. Inouye Solar Telescope (DKIST) is an all-reflecting, unobstructed coronagraphic telescope equipped with adaptive optics. Using a space-based artificial guide star (laser beacon),[9–11] DKIST will be able to obtain high-resolution (0.05 arcsec or 40 km) images of the white-light corona outside of eclipse.

The temperature of coronal plasma can also be measured from the ground using forbidden emission lines, although the diagnostics are limited to T $\lesssim$ 3 MK. The scientific return from artificial guide star observations can therefore be increased by extending it to narrow-band photometry and spectroscopy (Figure 5). The approach is not specific to DKIST and could be used by other telescopes.

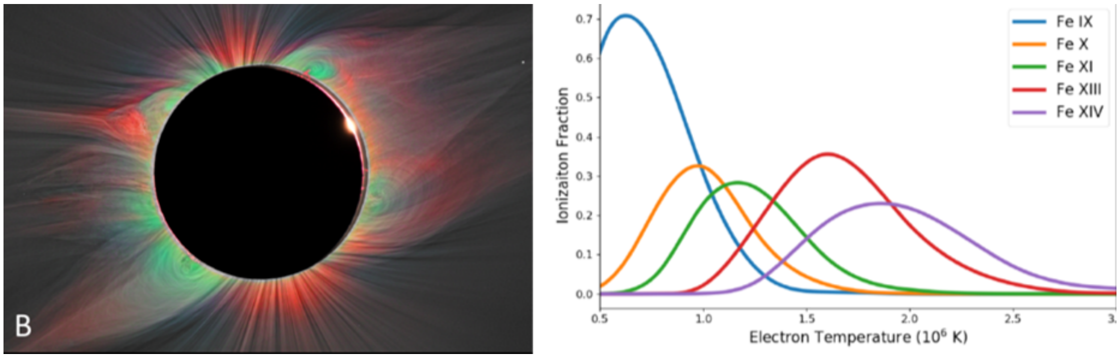

Figure 5. *Left*: Composite image in [Fe XI] (red), [Fe XIV] (green) and white light (grey) from 1 August 2008 total solar eclipse (Habbal, 2020).[12] *Right*: Ionization fraction of iron ions as a function of temperature.[12]

2.2 Objectives

The three main scientific objectives behind this mission are to determine the spatial scales on which heating occurs, determine the role of magnetic topology on the properties of primary energy-release regions, and measure the physical conditions in impulsively heated regions to test alternative theories. See Table 1 to see how these objectives have determined the requirements for the mission.

Table 1. The preliminary science traceability matrix (STM) for the mission.

Preliminary Science Traceability Matrix (STM)				
Science Goal	Science Objectives	Measurement Req.	Instrument Req.	Mission Req.
Where and how is the solar corona heated?	Determine the spatial scales on which heating occurs	Observe coronal structures on small physical scales predicted by theory and simulation	Spatial resolution <50km (<0.07 arcsec)	Mag 0 Laser Beacon at 532 [nm]
	Determine the role of magnetic topology on the properties of primary energy-release regions	Observe a large enough field of view to connect with context images (space- and ground-based)	Field of view $\geq$30x30 arcsec^2	Rate of Motion – to accommodate a series of observations
	Measure the evolving physical conditions in impulsively heated regions to test alternative theories	Characterize the evolving temperature and density in small-scale heated regions	Observe K-corona in visible light (magnetic structure and electron density), observe visible-light emission lines (temperature), time resolution <1 min	Time on target (exposure time) from 40 min to 3 hours

2.3 Significance and Impact

Visible-light imaging of the corona complements EUV/SXR imaging because it is a sensitive and ubiquitous tracer of magnetic fields and total electron density. However, for the foreseeable future, only a large, nearly diffraction-limited ground-based telescope can resolve the physical scales accessible to EUV/SXR observations. One or more orbiting artificial guide stars can enable Visible/Near-IR observations of unprecedented spatial resolution in conjunction with existing adaptive optics systems. In addition, one significant aspect of this mission is that the cost will be much lower than a fully space-based mission with similar capabilities.

3. ENGINEERING REQUIREMENTS AND MISSION TRACEABILITY

In this section, we establish major engineering mission requirements for the three individual science cases for the mission. Four major subsystems are defined with individual requirements for each. Table 2 provides a high-level traceability matrix of all engineering requirements. Requirements are indexed by science case, source of requirement, and subsystem. The table and indexing system will allow us to trace all mission requirements and ensure they are met.

The mission engineering requirements have been defined by the science teams to ensure ORCAS is able to meet the goals for each science case. These requirements are outlined in Table 2. Each requirement is labeled for traceability. The first number in the prefix corresponds to the science case, where the science cases are **1)** Determining the spatial scales on which heating occurs, **2)** Determining the role of magnetic topology on the properties of primary energy-release regions, and **3)** Measuring the evolving physical conditions in impulsively heated regions to test alternative theories. The letter corresponds to the requirement component, where the components are **M)** Mission operations, **L)** Payload system, **D)** Daniel K. Inouye Solar Telescope, and **S)** Spacecraft. Finally, the last number indicates the identifying number of the requirement. For example, requirement 1.L.1 identifies itself as a requirement for Determining the spatial scales science case defined by the Mission Level, and it is the first such requirement.

Table 2. Engineering Requirement Traceability Matrix. Each bold numeral in the prefix corresponds to its respective ORCAS-Helio Science Case. If multiple science cases have an identical requirement, a single row will be filled. The letter corresponds to the mission component. Note that the guide star laser power need not be continuous; it can be the time average of a pulsed laser, if the pulse rate is enough larger than the few KHz adaptive optics sample rate.

Requirement Traceability Matrix			
Prefix	Parameter	Requirement	Expected Performance
1.L.1	Spatial resolution	<50km (<0.07 arcsec)	
2.D.1	Field of view	$\geq$30x30 arcsec^2	
3.M.1	Time resolution	<1 min	
3.M.2	Time on target	40 Minutes - 3 Hours	
3.M.3	Observation targets	K-corona in visible light	
3.M.4		Visible light emission lines (temperature)	
1-3.M.1	Observations	100 observations	300 observations
1-3.M.2	Mission Lifetime	3 Years	3-5 Years
1-3.D.1	Laser Reference Beam	100 fW/cm^2	850 pW/cm^2
1-3.D.2	Reference Laser Divergence	$\leq$ 1'	14"
1-3.D.3	Reference Laser Pointing Accuracy	7"	2"
1-3.D.4	Reference Laser Power	0.5 - 15 W	0.5 - 15 W
1-3.D.5	Instrument	Near diffraction limited imaging	
1-3.D.6	Time to Acquire ORCAS Laser	$\leq$ 3 Hours	15 Minutes
1-3.D.7	Wavefront Error Input (Zenith Angle $\leq$ [30°, 50°])	$\leq$ [150nm, 160nm]	
1-3.D.8	Tip-Tilt Error (Zenith Angle $\leq$ [30°, 50°])	$\leq$ [5mas, 7mas]	
1.L.2	AO Source Brightness	5 Magnitude	0-5 Magnitude
2.L.1			1 Magnitude
1-3.L.1	Payload Used	Laser 532 nm or 1064 nm	532 / 1064 nm
1-3.L.2	Laser FOV	4' x 4'	8' x 16'
1-3.L.3	Laser Volume	$\leq$ 6U	4U
1-3.L.4	Laser Mass	$\leq$ 6kg	4kg
1-3.L.5	Laser Power	$\leq$ 150W	75 - 130W
1-3.L.6	Laser Pointing	$\leq$2"	0.2"
1-3.S.1	Absolute Position Knowledge (GPS)	$\leq$ 100 mas	50 mas at 3σ
1-3.S.2	Trajectory Knowledge (GPS)	$\leq$ 5 mas	3 mas at 3σ
1-3.S.3	Spacecraft Body Pointing	3'	7"
1-3.S.4	Delta-V (m/s)	$\geq$ 4000	4200-4700
1-3.S.5	Thrust	$\geq$ 60 mN	100 mN
1-3.S.6	Projected Thrust Lifetime	$\geq$ 1000 kN-s	1200 kN-s
1-3.S.7	Power	$\geq$ 1600W	2300W

4. MISSION OPERATIONS

4.1 Mission Lifetime

A sample mission sequence which outlines the proposed mission timeline is given in Table 3. The mission starts out with release from the Artemis spacecraft at about 36,000 km. The spacecraft then goes through a series of maneuvers to get it into the proposed orbit, which was detailed in Section 3. The spacecraft will be in position about 6.5 months after launch. At that point, observations can begin. Orbit determination will take 2.5 days, and the AO observation preparation will take an additional 40 hours. Then, the observation will begin, taking about one day to complete. Once observations are completed, the spacecraft will make corrections to its orbit, which depending on the necessary movements will take one to five days. The total observation sequence therefore is on average about 5 days, and this sequence will be repeated about 120 times to allow for observations of as many target stars as possible. Once the mission is finished, de-orbit will take 120 days.

Table 3. Mission Timeline

Sample Mission Sequence		
Commissioning	Release spacecraft Maneuver to science orbit	6.5 Months
Science (Single Observation Orbit)	Orbit Determination, Verify target schedule at DKIST Adaptive Optics Observation Prep	2.5 Days 3 Hours
	Observation - Imaging	1 Day
	Correction to orbit to allow repeat observations	1-5 Days
	Total time for 1 observation sequence	5 Days
Total Science Lifetime	Repeat 5-day observation sequence (1 AO observation each) up to 120 times[13]	3 years
End-of-Life	De-Orbit and Disposal	120 Days

4.2 Observation Sequence

This operations sequence is detailed in Table 4. Potential orbits are illustrated in Fig. 6 and Fig. 7.[14,15] Three hours before the observation is scheduled, the spacecraft makes final fine orbital maneuvers to ensure it will be positioned correctly for the observation. At the same time, DKIST will be configured for using adaptive optics with the spacecraft, and the spacecraft establishes a connection with the Mission Operations Center (MOC) to ensure the spacecraft is scheduled for the same operations as DKIST.

Two hours before the start of the mission, the MOC updates DKIST with the location of ORCAS-Helio, and the telescope is adjusted to point toward the spacecraft. Following this alignment, the spacecraft's laser is pointed toward DKIST, and verifies that it is targeting the correct location of the telescope. At this point, the spacecraft has completed its tasks in the observation sequennce, and DKIST must complete additional tasks in order to complete the observation.

Firstly, DKIST locks onto the laser from the spacecraft approximately 72 minutes before the start time of the observation. A safety gap period of approximately 42 minutes is provided, allowing a second attempt to lock onto the spacecraft's laser if required. $\frac{1}{2}$ hour before the observation, DKIST is further configured with the power and wavelength of the ORCAS-Helio light source. Finally, at 15 minutes before the scheduled start time, the telescope is provided updated updated trajectory information of the satellite. The observation is then conducted, and the sequence is repeated.

Table 4. Time stamped adaptive optics operations sequence. Red items are for the spacecraft and blue items are for the observatory. For a more detailed description of the contents of this table, see Section 4.2.

AO Observation Sequence	Time
Projected vs. Measured Trajectory comparison (MOC/SOC) ground	T-3 Hours
DKIST System Configuration (AO, instrument)	T-3 Hours
Fine Maneuver corrections (1 Hour window)	T-3 Hours
ORCAS establishes communication with MOC to sync ops with DKIST	T-3 Hours
MOC/SOC provide location to DKIST update	T-2 Hours
DKIST acquires science field location and centers (point telescope to ORCAS-Helio)	T-1.8 Hours
ORCAS body points laser payload FOV to DKIST	T-1.6 Hours
ORCAS Laser Payload Acquire DKIST (Point to target, search pattern if not seen)	T-1.3 Hours
ORCAS Laser Payload locks and provides to required beam (based upon EOC)	T-1.2 Hours
Safety Gap (Second attempt to acquire if req.)	T-1.2-0.5 Hours
DKIST AO system sets predetermined ORCAS power and wavelength, closes DKIST AO loops and tracks ORCAS Source	T-0.5 Hours
Flight Dynamics provides DKIST, MOC/SOC an updated ORCAS trajectory estimate (GPS + Optimetrics)	T-0.25 Hours
Begin Adaptive Optics Observation	T
End Adaptive Optics Observation	T + Δ T (minutes - hours)
Total Time	2-3 Hours

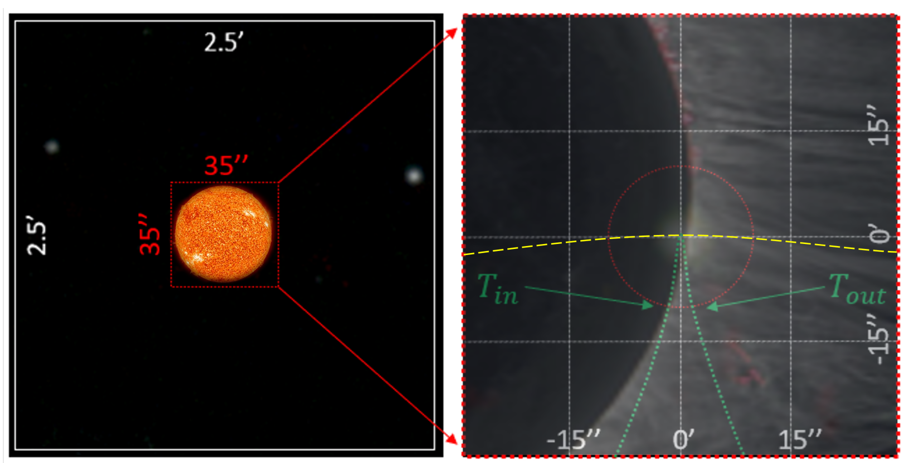

Figure 6. Spacecraft trajectory in the isoplanatic frame for a non-optimal orbit, during a one-hour observation of the Sun, as viewed from DKIST. *Left*: The white frame indicates 2.5 arcminutes field of view, while the red frame indicates 1 arcminute field of view. *Right*: An enlarged image of the red zone marked, red dashed circle indicated the FOI size, green dashed line indicates the natural spacecraft trajectory as seen from DKIST, total time on target (within the FOI) is 3300 sec without using thrusters.

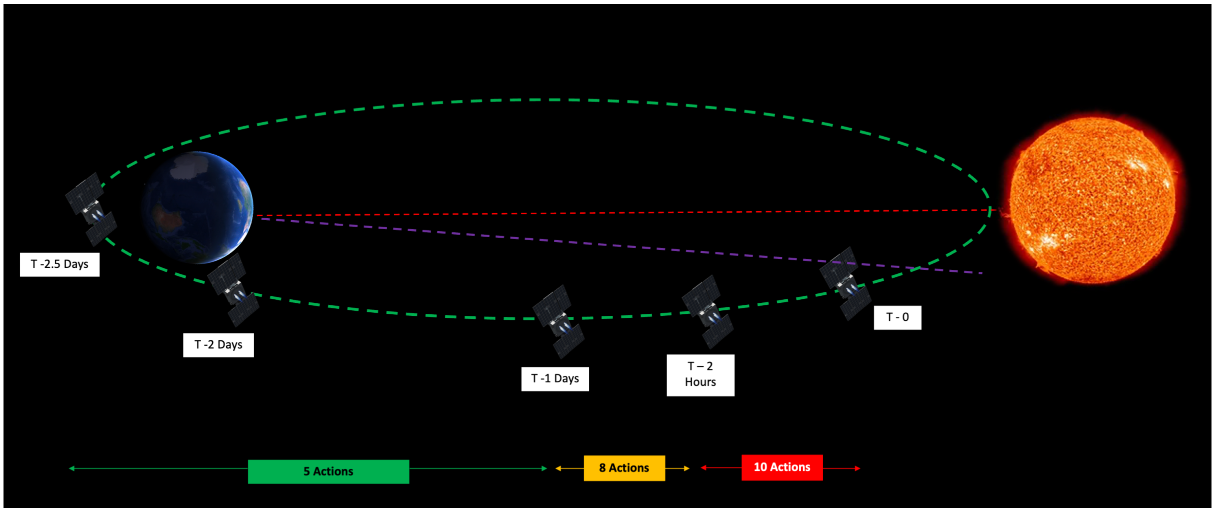

Figure 7. An illustration of the AO observation sequence. Once the spacecraft has been released and maneuvered into a helio-orbit, where the apogee is on the same line as the Earth and Sun, operations begin 2-3 hours before AO Observation. This consists of observatory system configuration, establishing communication between DKIST and ORCAS, and the ORCAS-Helio body pointing the laser payload FOV to the beam. For more details about this sequence, see Table 4.

4.3 Cost Estimate

During the ORCAS Concept Study, cost estimates were gathered for each component of the mission: ground systems, spacecraft, payload, and mission operations. A Request For Information (RFI) cost estimate (in the fiscal year 2021 dollars (FY21$)) was requested for all effort to implement the proposed approach for the hardware unit quantities. The cost estimates were broken down into design and development, including all effort to design, develop, build, and test, including development units and ground test sets.

The team conducted grassroots cost estimates to accurately determine the total cost of the mission. The collaborative effort of many organizations results in cost estimations specific to each. In February 2021, ORCAS produced a RFI for the ORCAS laser, spacecraft, partnership, and advice:

- Concepts and designs for the development of the Adaptive Optics (AO) laser source
- Concepts and designs for the spacecraft bus
- Scientific advice for the adaptive optics systems
- US and international partnerships, capable of providing access to other observatories and instrument systems

For this RFI, a quantity of one full source payload complement was assumed when developing plans and cost estimates. To enable assessment of cost estimates and trades involving other quantities of systems, the cost estimate to develop the first unit, four units, and each additional unit was requested. After reviewing the responses received, ORCAS selected those which most favorably met the mission requirements and formulated a baseline mission cost (Table 5).

Costs include full system integration, test, launch, and commissioning activities, including all effort to integrate the hardware, perform full system performance and environmental test, launch site activities, and commissioning as requested per the **RFI**. Each system utilizes a different portion of the budget as the project progresses to each phase. The cost breakdown per scheduled project phase.

Table 5. Mission cost estimate.

Mission Cost Estimation		
WBS	**System**	**Mission Expenses (FY21$)**
1	DKIST Adaptive Optics Instrument and System DKIST Visible Science Instrument	$12,000,000
2	Spacecraft Bus Design and Development	$20,050,000
3	Payload - Laser Source	$6,400,000
4	Operation (GSFC)	$4,250,000
	Ground-Based Contingency (15%)	$3,009,225
	Space-Based Contingency (30%)	$10,635,000
	Total	**$56,344,225**

5. CONCLUSIONS

In this paper, we explore the difficulty in studying the heating and magnetic structure of the Sun's corona, primarily caused by low observational resolution. This drives the mission's operational and engineering requirements to increase resolution and scientific return.

We find that utilizing an artificial star to aid in the implementation of adaptive optics technology would greatly improve our knowledge of the Sun's corona. We discuss the deployment of the artificial star, including the orbit and the mission timeline. Additionally, we provide details regarding the specific timeline for an observation utilizing the artificial star, as well as prove that up to 120 observation sequences will be able to be conducted with the spacecraft. Finally, we develop a preliminary plan for the budgeting, which demonstrates the low budget required for the usage of the spacecraft. Through the development of this paper, we learn that an orbiting artificial star is essential in our continued comprehension of the Sun and its corona.

REFERENCES

[1] Patat, F., Ugolnikov, O. S., and Postylyakov, O. V., "Orbiting configurable artificial star (orcas) for visible adaptive optics from the ground," *Astronomy & Astrophysics* **51**, 385–393 (Aug. 2006).

[2] Peretz, E., Mather, J., Slonaker, R., O'Meara, J., Seager, S., Campbell, R., Hoerbelt, T., and Kain, I., "Orbiting configurable artificial star (orcas) for visible adaptive optics from the ground," in [*Bulletin of the American Astronomical Society*], *APC White Papers, no. 284* **51**(7), Astro2020: Decadal Survey on Astronomy and Astrophysics (2019).

[3] Peretz, E., Hall, K., Mather, J. C., Shaklan, S., and Hildebrandt, S., "Exoplanet imaging performance envelopes for starshade based missions," *Journal of Astronomical Telescopes, Instruments, and Systems* **7** (2020).

[4] Peretz, E., Mather, J., Parbarcius, L., and *et al.*, "Mapping the observable sky for a remote occulter working with ground-based telescopes," *Journal of Astronomical Telescopes, Instruments, and Systems* **7**(1) (2021).

[5] Parker, E. N., "Spontaneous current sheets in magnetic fields : with applications to stellar x-rays," *Spontaneous current sheets in magnetic fields : with applications to stellar x-rays. International Series in Astronomy and Astrophysics* **1** (Jan. 1994).

[6] Cranmer, S. R. and Winebarger, A. R., "The Properties of the Solar Corona and Its Connection to the Solar Wind," **57**, 157–187 (Aug. 2019).

[7] Nicolas Lefaudeux, HDR astrophotography by Nicolas Lefaudeux, "Total solar eclipse corona in hdr," (2017). [Online; accessed June 29, 2022].

[8] November, L. and Koutchmy, S., "White-light coronal dark threads and density fine structure," *The Astrophysical Journal* **466**, 512 (06 1996).

[9] Peretz, E., McCormick, K., Moehring, E., Hamilton, C., Mather, J., Hall, K., Hyland, D., Freeman, A., Russin, T., Nash, J., and Robie, D., "Orbiting configurable artificial star multi-wavelength laser payload," *Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems III* **11820** (2021).

[10] Peretz, E., Hamilton, C., Mather, J., Pabarcius, L., Hall, K., Michaels, A., Pritchett, R., Yu, W., Wizinowich, P., and Golliher, E., "Orcas–orbiting configurable artificial star mission architecture," *UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts X*. **11819** (2021).

[11] "Orcasat." https://www.orcasat.ca/.

[12] Habbal, S. R., "Total solar eclipse observations: A treasure trove from the source and acceleration regions of the solar wind," in [*Journal of Physics: Conference Series*], **1620**(1), IOP Publishing (2020).

[13] Peretz, E., Mather, J. C., Hall, K., Canzoniero, C. M., Pabarciusa, L., Gilchrist, K., Lieber-Kotza, M., Slonaker, R., Yu, W. H., Hughes, S., Hur-Diaza, S., Koenigb, A., and D'Amico, S., "Exoplanet imaging scheduling optimization for an orbiting starshade working with extremely large telescopes," *Journal of Astronomical Telescopes, Instruments, and Systems* **7**(1) (2020).

[14] Peretz, E., Hamilton, C., Mather, J., D'Amico, S., Michaels, A., Pritchett, R., Yu, W., and Wizinowich, P., "Astrostationary orbits for hybrid space and ground-based observatories," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**(1) (2022).

[15] Koenig, A. W., D'Amico, S., Peretz, E., Yu, W., Hur-Diaz, S., and Mather, J., "Optimal spacecraft orbit design for inertial alignment with ground telescope," IEEE Aerospace Conference (March 2021).