Astro2020 White Paper - APC

Orbiting Configurable Artificial Star (ORCAS) for Visible Adaptive Optics from the Ground

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation

☒Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics

☒Stars and Stellar Evolution ☒ Resolved Stellar Populations and their Environments

☒Galaxy Evolution ☒Multi-Messenger Astronomy and Astrophysics

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Abstract:
Enabling Adaptive Optics (AO) for a variety of targets across the sky at visible wavelengths for a range of telescopes on the ground could transform many key areas in astronomy. As a result, a 30th magnitude star could be imaged within minutes, the structures of distant galaxies could be resolved, and the surfaces of planets, satellites, and asteroids could be mapped without visiting. Cameras and spectrographs would have pixel areas reduced by factors of 10^4 to 10^5, and the isoplanatic patch could be resolved into ~100 megapixels for a Nyquist-sampled camera. The Keck telescopes, Giant Magellan Telescope (GMT), Thirty Meter Telescope (TMT), and European Extremely Large Telescope (E-ELT) could reach nearly diffraction limited angular resolution, achieving up to an order of magnitude better performance than the Hubble Space Telescope. We propose a small-scale mission composed of four wavelength-configurable artificial star small satellites propelled by ion engines and controlled from a ground station. ORCAS require only minor adaptations to existing technologies, which reduces risk and maximizes technology readiness levels. Such a system would overcome some major challenges facing current development in order to enable visible band AO: 1) insufficient brightness; 2) the cone effect; and 3) Tip-Tilt correction limitation. The necessary ground-based technologies are developed but would require some modification because the ORCAS laser source will be at variable distances and is not stationary during observations. **We recommend a new collaboration between the ground-based telescope community and the space science community to establish through a pre-formulation study how such advances could be achieved and accommodated by astrophysics science communities.**

Introduction:

Extending AO technology from the near-IR to visible wavelengths within the coming decade would open new phenomena to investigation, ranging from high-redshift galaxies to cosmology to stellar populations to planetary systems. Challenges facing current solutions include the scarcity of Natural Guide Stars (NGS) that provide sufficient brightness and their spatial availability throughout the sky. Current Laser Guide Star (LGS) systems on the ground are limited by the cone effect and are difficult to use when higher order, tip/tilt and focus corrections are made simultaneously.

Extraordinary performance is required to obtain the necessary contrast and Strehl ratio to enable visible observations of exoplanets from the ground. Achieving diffraction limited performance maximizes ground-based telescopes' capabilities. Current AO systems include MagAO (*1*) on the Magellan telescope (*2*), the K-band PALM-3000 (*3*) on the 5-m Palomar telescope, and the Very Large Telescope (VLT) Zurich Imaging Polarimeter (ZIMPOL) with the extreme adaptive optics Spectro Polarimeter high-contrast Exoplanet Research (SPHERE) (*4*), working at 500-900 nm. As an example the MagAO-X project (*5*), funded in 2016, is underway for the Magellan Telescope, and is projected to produce a Strehl ratio of up to 0.7 at the Hα wavelength (~0.656 μm). But performance relies on an available NGS with sufficient brightness. For stars as faint as mag 10, the Strehl ratio will drop to 0.3.

Utilizing lasers from space to work with a variety of ground-based telescopes is a highly developed concept. Lasers have been used to successfully demonstrate laser communications from as far as the moon with the Lunar Atmosphere and Dust Environment Explorer (LADEE), and to map Earth features with Ice, Cloud and Land Elevation Satellite-2 (ICESat-2). Space-based guide stars have been seriously studied for the purpose of detection and characterization of other satellites at low-Earth/geosynchronous orbits as well as astrophysical purposes [6-8].

This mission will enable transformational science to be conducted by ground-based telescopes, potentially prior to the emergence of extremely large telescopes (ELT). It will also be beneficial for future endeavors from expanding ELT's abilities to minimizing stability challenges facing future large space observatories. It could assist in better understanding the underlying science as a preparation and support for future space missions ranging from the solar system to planetary systems to galaxy formation and evolution.

In this paper we discuss how a small-scale mission of four orbiting configurable artificial stars (ORCAS) could potentially address this challenge within the coming decade.

A. Key Science Goals and Objectives:

A.1. Placing the mission study in broad context

We identified decadal science white papers which would benefit from increased AO performance and that could enhance or enable their scientific investigation. These papers touched on *every single science theme* identified for the decadal survey (identified in Figure A.2.1). ORCAS would most robustly support three science themes: i) Stars and Stellar Evolution, ii) Planetary Systems and Star and Planet Formation, and iii) Galaxy Evolution, which together account for half of the white papers. The full list of relevant papers is available upon request. The potential impact of ORCAS on the astrophysics community is uniquely broad. Here we enumerate examples of applicability for these three focused science areas.

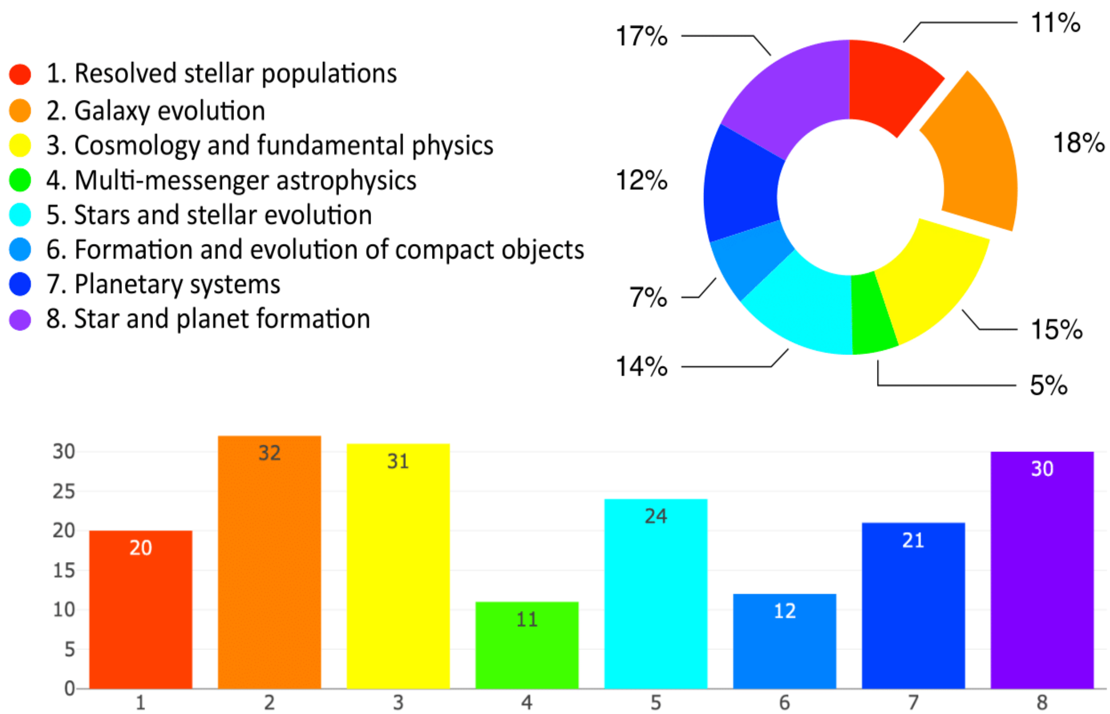

Figure A.2.1: Top right) Breakdown for each science theme of percentage of white papers with requirements that would be supported by this mission (ORCAS supported white papers constitutes 26% of all submitted white papers. **Bottom)** Number of white papers supported by ORCAS by theme. Galaxy evolution is the most commonly occurring category, closely followed by star and planet formation. Number of papers served by the ORCAS mission is displayed in the lower chart.

In the following section (A.2) we indicate for each scientific theme: 1) typical scientific targets 2) observation type 3) observational requirements 4) submitted scientific white paper that will benefit from such advancement. We summarize that information and present an initial science traceability matrix that serves as the basis for this mission concept

A.2. Scientific Goals and Objectives

Science Traceability Matrix (STM)

Science Theme/Topic	Example Target	Observation Type	Observation Requirement	Example Paper
Theme 1. Stellar initial mass function	Young massive clusters	Optical/near/mid-IR and mm spectroscopy	Angular resolution ~10 mas arcmin scale FoV	Calzetti et al.
Theme 2. Cosmic dawn	High-redshift galaxies	Direct imaging, spectroscopy	Resolve faint (<25 mag) targets Wide FoV, 10 deg^2 For faintest targets, ~10 hour ET	Cuby et al.
Theme 3. Measuring Hubble Constant	Type Ia SNe	Wide-field multi-object spectroscopy (R>25,000)	10-20 mas angular resolution Resolve faint >29 mag at <100 Mpc	Beaton et al.
Theme 4. Gravitational wave sources	Black hole mergers	Optical, IR moderate-precision spectroscopy	10-100 Mpc resolution Resolution of faint > 25 mag events	Chornock et al.
Theme 5. Stellar photospheres, chromospheres	Cool evolved stars	High-resolution spectroscopy	High spatial resolution Angular resolution ~3 mas	Rau et al.
Theme 6. GR effects of SMBH	Stars in galactic center	Stellar astrometry, radial velocity	Resolution of objects as faint as 23 Mag Astrometric precision < 30 mas	Do et al.
Theme 7.	Earth twins in binary star	Direct imaging	• FoV ~1 arcsec	Belikov

Earth-like exoplanets	systems		• 10^{-9} contrast • Resolution of objects as faint as ~25 Mag	et al.
Theme 8. Planet formation	Protoplanetary disks	High-contrast imaging, high-resolution spectroscopy	• Angular resolution ~7 mas	Jang-Condell et al.

ORCAS will support the fully developed ground based astrophysical key science programs already formulated by the wide scientific community, as well as observation programs identified across Astro 2020 whitepapers to be relevant. This mission aims to achieve these scientific goals through a small satellite program within the coming decade.

A.3. Critical Science Enabling capabilities.

The following section discusses how basic observation parameters like sensitivity, angular resolution and spectroscopy will benefit from ORCAS achieving its goals for improved AO performance.

Superior AO using ORCAS. Wavefront measurement for adaptive-optics equipped ground telescopes is currently done in one of two ways: with an NGS, or with an LGS in the upper atmosphere, generated by a ground-based laser. The use of an NGS is limited to targets with an appropriately bright guide star, in close proximity, and within the isoplanatic patch. Ground-based LGS systems are limited by the cone effect (or focus anisoplanatism), where the spherical wavefront of the light from the upper atmosphere traverses a different path from the light from target stars. This can be overcome with multiple laser beams and elaborate computation, but becomes increasingly difficult as telescopes grow in size. A space-based ORCAS avoids the availability problem of NGS, circumvents the cone effect, and can be as bright as needed. The laser can be at any desired wavelength (650, 1550 [nm] etc.), which is helpful in dealing with the chromatic dispersion of the atmosphere. Additionally, it avoids the entangled tip-tilt error of ground-based LGS, since it passes through the atmospheric layer only once. Typical LGS systems are calibrated for ~ 80 km, and NGS at infinity, and ORCAS could be approximately 200,000 km away.

Sensitivity. With most of the light from a point source concentrated into a spot a few milliarcseconds across, instead of an arcsecond, sky background light would be suppressed by factors of 10^4 to 10^5. Taking advantage of the relatively low background at visible wavelengths compared with near IR, it would be possible to image a 30th magnitude star in only few minutes of exposure, and sensitivity could be limited by source photon fluctuation noise. Sensitivity is also governed by the quality of the adaptive optics.

Angular Resolution. With AO working, we can expect an angular resolution close to the diffraction limit. With the diameter of telescopes expected to increase by a factor of 3 to 4 over current observatories, and the possibility of reducing λ by a factor of 3 relative to near IR AO, we should expect for an order of magnitude improvement of angular resolution, and two orders of magnitude in the numbers of pixels per square arcsecond. With λ = 0.5 µm, d = 30 m, we would have Nyquist-criterion pixels of λ/2d= 1.7 milliarcseconds. A 100-megapixel camera would cover a 17 arcsec square, enough to include the isoplanatic patch around a guide star with radius ~ 7 arcsec. A Hubble Space Telescope pixel would be resolved into at least 100 pixels.

Spectroscopy. Reducing the image size from seeing-limited to diffraction-limited reduces the necessary volume of a spectrometer by orders of magnitude as well. Concepts already implemented at near IR wavelengths could be scaled to the visible band. Integral field spectrometers would be essential for exploratory work on newly resolved objects. Fiber-fed spectrometers would be ideal for high resolution spectroscopy of bright-enough point sources. Sky background interference would be reduced by orders of magnitude.

B. Technical Overview:
Technical Requirements – Space Segment.

B.1 Major Mission Considerations:

We open by discussing the core elements necessary for ORCAS: 1) Laser Beacon; 2) Orbit; 3) Propulsion; and 4) Number of ORCAS spacecrafts. A full discussion of each system parameter is in section B.2.

Laser Beacon. The main function is to provide a laser beam focused toward the observatory. The beacon will be gimbaled for precise pointing, reducing the need for high precision on-board attitude control. A choice of laser wavelengths should be provided, to deal with the chromatic dispersion of the atmosphere. A beacon on the ground station will be provided to facilitate ORCAS laser beacon pointing.

Orbit. The concept is to find a long elliptical orbit in which the guide star velocity perpendicular to the line of sight matches the ground-observatory velocity. The distance and radial velocity are not constrained by this requirement. The smallest orbit that does this has an apogee of about ~175,000 km and a period of 3 days, but this orbit is not stable. Higher orbits can be used, and there is no requirement to observe at apogee, allowing for two observing opportunities per orbit. Each target-observatory-time combination will require a different orbit. Maneuvers might be needed to take place when observing different targets. We require positioning accuracy within a few arcseconds of the desired sky location, possibly determined by the ground instrument. The orbit precesses enough that active orbit management will be required before every observation.

Propulsion. Electric propulsion can be used for maneuvering between targets and potentially during observations if needed. Electric propulsion implies large solar arrays, but each ORCAS spacecraft only requires a small amount of thrust due to its low mass (~80Kg) reducing this challenge. Solar electric propulsion provides high specific impulse and therefore enable large total delta-velocity and a concomitant expansive array of targets.

Number of ORCAS. Each ORCAS spacecraft can stay near a desired target for a limited time and is in a specific location in the night sky, so for overall availability a large number of ORCAS spacecraft is preferred. We propose to start with four spacecraft to enable repeating observations in different sky positions and for minimizing delta-velocity costs if targets are to be observed all over the sky. A larger fleet with with reduced unit cost could be employed once the mission concept is proven.

Lifetime. A 5-year mission life is proposed.
B.2. Mission Architecture:

The ORCAS mission requires launch, delivery to Earth orbit, deployment and a minimum of 5 years of operations. Development and operation of a ground station is required in addition to the ORCAS spacecraft themselves. Finally, ORCAS is required to allow access to at least 75% of the night sky.

Laser Beacon.

The laser beacon is required to provide an adjustable 5 – 10th magnitude artificial star light within the telescope field of view with an orbit accuracy that ensures it is within the isoplanatic patch, during an observation to enable enhanced performances of ground-based AO systems. We calculated flux levels and spot size for a 10 cm aperture diameter with a 1W laser for a variety of ranges are shown in Table B.2.1 for two different HEO, Moon trailing and L2 orbits. **Existing lasers can provide the required power levels**, **photon flux**, and ground **spot sizes**. **Existing gimbal systems can position the laser to within the required tolerances**. This in turn allows us to estimate initial volume, mass and power requirements for the LGS system

Range [1000 Km]	173	200	385	1500
Flux [10^10 Photon/m^2/sec]	622	465	126	8.27
Spot Diameter [km]	0.94	1.08	2.08	8.12

Table B.2.1 – Flux and spot diameter for a tunable power laser guide star provided by ORCAS for a 1-Watt maximal laser power and a 10 cm aperture lens for selected ranges at a wavelength of 850 nm. [The baseline flux for a Mag 8th star is 3.15x10^10photons/m^2/s]

Establishing observable sky regions:

We open with a calculation of integration times and night sky regions available for observations from Mauna Kea for the night of Dec 3rd, 2025 available to the ground-based telescopes. Figure B.2.2. indicates the maximal available observing window (before taking to consideration how much time ORCAS can stay within the isoplanatic patch) assuming the observation is no more than 60° from zenith (maintain low air-mass) and that zenith sun angle is at least 110° (sky is dark enough). Based on this analysis if both northern and southern hemispheres are considered, throughout the year most of the night sky is observable (>90%). ORCAS should be positioned such that both sites can be supported (north and south), as well as spread across the sky to allow for smaller maneuvering costs and faster reaction times between targets. ORCAS is required to maintain field of view positioning of <3 arcseconds. The required time for each target will be established based on the observational parameters, scientific importance and fuel limitations.

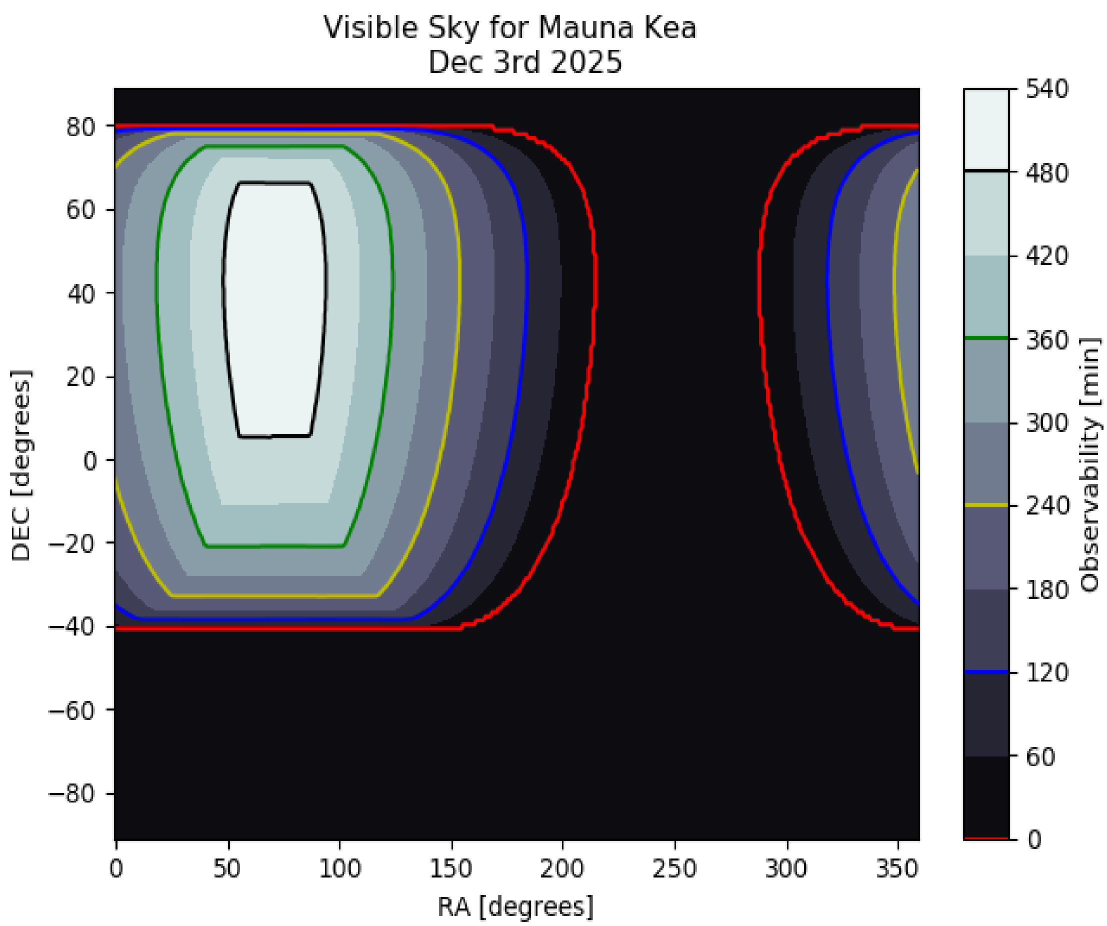

Fig B.2.2. Heatmap for the ORCAS-enabled sky availability for a single night, Dec 3rd, 2025 for Mauna Kea. (Further analysis for the exposure time availability offered by ORCAS is presented in the following sections)

Establishing an Orbit for each observation:

As an example, a group of four ORCAS spacecrafts will be deployed to support four different observations taking place at different locations on the night sky at different times. Specifically, ORCAS 1 & 2 will be positioned to support the Mauna Kea observatories when observing targets located at declination and right ascension of: (10,40) (30,110), ORCAS 3 & 4 are positioned to support Las Campanas observations observing targets located at targets located at declination and right ascension of: (-40,60) (-20,60). General Mission Analysis Tool (GMAT) was used to determine the position of the satellite with 60 seconds intervals, a calculation of the maximal distance (vector) from apogee was made for each one of these time intervals, this information in turn was used to calculate (for the worst case where the entire distance is projected perpendicular to the field of view) and the resultant angular distance.

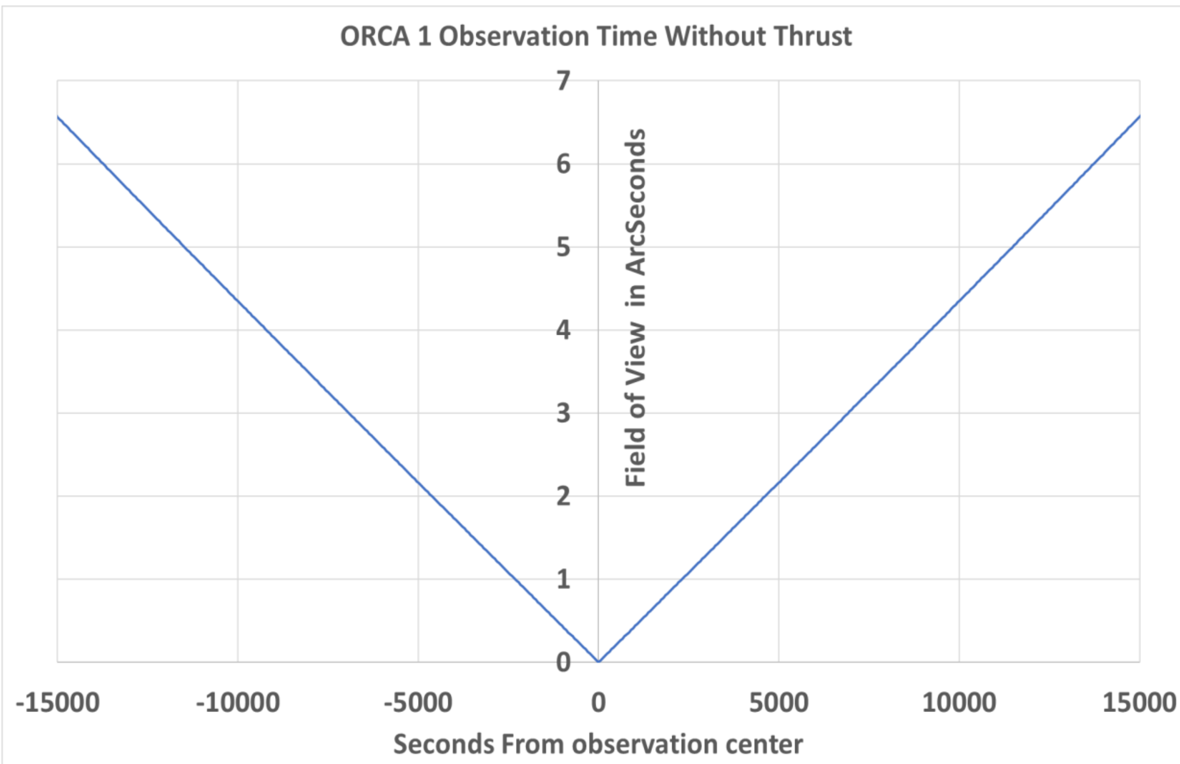

Figure B.2.1. Maximal observation time available without thrusting while in orbit for ORCAS when it is in a range of 200,000 Km.

B.3 Spacecraft Technical resources:
Technical Implementation Concept – Space Segment.

While this section is not a design for ORCAS spacecrafts, it provides details on some of its core subsystems that help us with composing initial mass, volume and power estimations. These details are provided in the following Table B.3.1.

Mission Duration	*5-Year prime mission*
Wet Mass	80 [Kg]
Dry mass	35 [Kg]
Outer Diameter	0.32 [m]
Length	0.9 [m]
Volume	0.0635 [m^3]
Total Power	900 [w], (Provided by a 1 [m] radius Ultraflex solar array)
Electric Propulsion	Thrust - 40 [mN], ISP - 1500 [sec], Peak Power - 600 [W], 2.5 [Kg]
EP Power Unit	300 [V], 650 [W], 3 [Kg]
Laser Guide Star	Peak Power – 50 [W], 5 [kg] (+Gimbal)
Reaction Wheels	Peak Power – 3 [W], 1 [Kg]
Ultraflex Array	Produces - 900 [W]. 6 [Kg]
Star Trackers [x2]	6 [W], 1 [Kg]
Backup Battery	2.7 [Kg]
Xenon Fuel	45 [Kg]
Xenon Tank + subsystems	5 [Kg]
30% allocation for additional systems	~ 9 [Kg]

Table B.3.1 – initial mass, power and volume estimation for a single spacecraft. (as can be seen, our mass, volume and power estimates are well within our range)

Table B.3.1 illustrate an initial architecture potentially suitable for the ORCAS mission study, it is also in agreement with ORCAS being a small-scale mission.

B.3 Proposed Schedule:

Space segment:

2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Phase A		Phase B		Phase C		Phase D		Phase E	
CSR start – CSR End	Mission Selection SRR PDR	PDR	CDR PSR	Ship					
	ATP			Launch	Begin Science Operations				End of Baseline mission

B.4 Technical Requirements – Ground segment.

Adaptive optics. Although the basic technology development is well underway for exoplanet observations with natural guide stars, this new concept requires modifications. First, the ORCAS spacecraft is not at infinite distance, and the distance is not fixed. Second, the separation of the laser wavelength would be done with dichroic filter. Third, ORCAS spacecraft move slowly across the field of view (for the case where no fuel is used to stabilize the ORCAS), and software or hardware will be required to hold the sky image steady on the instruments. The guide star ephemeris can be known accurately enough to correct for this drift, but probably not well enough for astrometry.

Cameras. The necessary cameras to record diffraction limited images will need many megapixels to cover the isoplanatic patch, low dark current and low read noise, to take advantage of the extremely dark high-resolution sky at visible wavelengths.

Spectrometers. Both integral field and fiber fed spectrometers are likely to be used. Diffraction-limited spectrometers are very different in concept and size from seeing-limited spectrometers.

Laser Beacon. The orbiting laser beacon needs to point precisely toward the observatory. An upgoing laser would provide a target for it, but this target laser beacon can be very weak compared with the sodium wavelength lasers used for near-IR AO.
Implementation Strategy: Existing adaptive optics programs already have the capability to analyze, design, simulate, and test the needed configurations, using small bench-level optical systems and computer models. Progress towards the visible band AO depends on the availability of new hardware technology, such as large and fast deformable mirror arrays, fast low noise detectors, and fast software running on fast computer hardware.

B.5 Cost Estimates:

This mission fits into the small mission category as stated by this call (< 500$ mill). This estimate is based on the low total mission dry mass of ~120 Kg and wet mass of ~320 Kg.

Main Technology Drivers:

Visible AO systems are already under development for ground-based telescopes; however, they will need to be adapted for this specific mission. The proposed schedule indicates instruments developed for this purpose should be adapted within five years of mission initiation.

The laser beacon to be developed requires simplification of existing systems and will need to be finalized within three years.

Organization, Partnerships, and Current Status:

This work was initiated at NASA Goddard Space Flight Center by John Mather and Eliad Peretz and supported by Goddard internal funds. Contributors to the discussion include Richard Slonaker, representatives of Keck, GMT, TMT, and ELT observatories. Laser beacon performance was calculated by Eliad Peretz (GSFC) and Isabel Kaine (GSFC/Northeastern University). Observable night sky maps were prepared by Eliad Peretz (GSFC). Orbit calculations at GSFC were made by Eliad Peretz and Tiffany Hoerbelt(GSFC). We thank Kerri Cahoy (MIT), R. Campbell, M. Cirasuolo, Matt Greenhouse, John O'Meara , David Leisawitz, Jay Pittman, Jonathan Gardner, and Peter Hughes, for fruitful discussions and advice.

The current technical objective is to complete a mission concept study, mission design lab and proceed to competing for a small satellite announcement of opportunity or directed funding.

Institutions

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