The Search for Habitable Planets via the Solar Gravity Lens
Shaping the Future - A “Big Idea” for Space Exploration and Technology Development

Been There – Done That

Exploit Einstein’s Rings to Explore Distant Solar Systems
Solar Gravity Lens (SGL) is being funded by NASA.

We have just completed the mid-term review NASA Innovative Advanced Concepts (NIAC) phase II Effort. “This is three NIAC projects worth of work, very impressive, mission design fantastic.”
Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Focus (SGLF) Mission

An imaging mission to SGLF appears to be feasible, but needs further study

Concept
- SGLF provides a major gain (~10^{11} at 1µm), resolution of 10^{-9} arcsec in a narrow FOV;
- A 1-m telescope at ~750AU has a collecting area equivalent ~80 km aperture in space;
- A mission to the SGLF could image Earth 2.0 up to 30pc away with resolution to ~10km to see surface features;
- A small s/c with electric propulsion (or solar sails) can reach the SGLF in <35-40 yrs.

Proposed Study and Approach
- Define baseline design, sub-syst components;
- Define mission science goals & requirements;
- Develop system and subsystem requirements;
- Study mission architecture and con-ops;
- Assessment of feasibility (cluster) small-sats;
- Identify technology development needs;
- Study instruments & systems: power, comm, pointing, s/c, autonomy, coronagraph, nav, propulsion, raster scan in the image plane, etc.

Benefits
- A breakthrough mission concept to resolve a habitable exoplanet at modest cost/time;
- Could find seasonal changes, oceans, continents, life signatures on an exo-Earth;
- Small-sat & fast exit from the solar system;
- Electric propulsion for raster-scanning the image using tethered s/c (or cluster);
- SLGF is valuable for other astrophysics and cosmology targets.

Earth with resolution of (1000 × 1000) pixels.
The Power of $10^4$ – SGL Shrinks the Exo-Solar System by the Ratio of Star to Focal Point (FP) Distances

This distance compression means that a mission can be designed to survey an entire exo-solar system.
Multiple Spacecraft Architecture to the Einstein Ring Solar Gravity Lens (SGL) Mission
Where We Want to Go

THE SOLAR GRAVITATIONAL LENS

The Solar Gravitational Lens (KISS study, 2015)

The Interstellar Medium

Heliosphere

Asteroid Belt

Termination Objects

Solar Gravity Lens

Interaction Zone

The Local Interstellar Cloud

Oort Cloud

100,000 AU = 1.58 Light Years

10,000 AU = 16 Light Years

1,000 AU = 13.4 Light Hours

100 AU = 13.5 Light Hours

10 AU = 1.39 Light Hours

Solar System

Nebula Belt

Interstellar Medium
A candidate-rich cluster lies some 70 degrees north of the ecliptic plane.

Trappist is a likely candidate.

What we might want to look at:

http://phl.upr.edu/projects/habitable-exoplanets-catalog/
Why investigate this mission?

• It is challenging and delivers a tool to future generations that could possibly answer the age-old question, “are we alone”.

• It explores the development of satellite architectures that are
  • “self-reliant”,
  • adaptable,
  • and long lived.

• Attributes that will be expected in future space systems
The first problem is exiting the solar system at >25 AU/year with extreme precision. This drives the weight of each s/c to < 10 kg.
• Architecture is ~10 “pearls” each composed of 10-20 small “sailcraft” (payload + solar sail) launched by cost-effective shared or dedicated launches.

• The pearls “learn as the fly”, to optimize science return.
  • Designs based on concurrent developments in spacecraft miniaturization, AI flight management, swarm CONOPS, and long-term reliability.
  • Successive pearls benefit from technology advancements to improve cost-effectiveness.
• Navigation uses existing and planned resources
  • DSN support during flight to solar perihelion and then outward to \( \sim 200\text{AU} \).
  • From 200 AU to 900 AU, optical imaging—parallax using planets and occultation astrometry.
• Multi-vane solar sails control flight trajectories to perihelion and to self-assembly point.
  • E-propulsion used for midcourse corrections and flight along the SGL
• Flying many s/c on the mission ensures reliability and science return.

*Spread the risk, spread the cost, minimize launch costs to maximize science return.*
Propulsion Uses Solar Sails and e-Propulsion

**Solar Sail Phases of the Flight**
- Group each swarm of s/c into a “pearl” having interactive links and nodes.
- Spiral down to the perihelion while setting the orbital inclination.
- Accelerate at perihelion to \( \sim 160 \text{ km/sec} \) for escape velocity of 20 AU/year.
- Adjust trajectory from hyperbolic to linear to align with SGL with precise aim at SGL.
- Use DSN and solar sails to minimize residual trajectory error.

**E-Propulsion Phases of the Flight**
- Multiple sailcraft, drop sails and re-assemble to form the mission capable spacecraft. Transition to e-propulsion to acquire and fly along the SGL.

**Solar sail propulsion does large delta v in our solar system, then there is a transition to e-propulsion for small delta v for the cruise and SGL mission**
Each spacecraft passes perihelion to achieve >100 km/sec escape velocity

Solar sail propulsion accelerates the s/c without need for propulsive fuel
**Navigation Phases Timeline**

- **Distance from Sun (AU)**
  - 1000
  - 550
  - 5
  - 1
  - 0.05

- **Navigation Method**
  - DSN (+ others when near Earth)
  - Solar Sail
  - DSN
  - Optical NAV

- **Control Method**
  - EP

- **Phases**
  - **Phase 1:** Launch to Perihelion Point
  - **Phase 2:** Perihelion to Injection Point
  - **Phase 3:** Injection Point to SFL Acquisition

- **Targets**
  - **Target 1:** Perihelion
  - **Target 2:** Sail Injection Point ~5 AU
  - **Target 3:** SFL Acquisition

- **SFL Operations**
Navigation from Injection Point to SFL Acquisition

• From self-assembly orbit outward toward the SFL, precise tracking and monitoring will continue on a weekly basis to maintain the low position uncertainty limits.

• Autonomous navigation will be employed for the pearl cluster of satellites
  • Navigation status sent back with health and safety report schedules.
  • EP system is available for small maneuver adjustments if needed

• SFL acquisition is NOT similar to a New Horizons’s Pluto/Charon approach
  • We won’t be able see the SFL upon approach and will have to detect it when we are within exo-star SFL.
  • Use the exo-star SGL line (which will be orders of magnitude brighter) as guide.

• Once SFL acquisition is confirmed, a hand over to intra-cluster ranging relative to the exo-star focal line will be used to determine relative positioning of spacecraft (establish a local coordinate system based on the exo-star SGL focal line).
Focal Region CONOPS
An acquisition strategy that looks for the thin and dim exo-planet focal line (FL) is difficult, but a strategy that acquires the exo-star’s FL first, and then moves to the planet’s FL is much easier.

Electric Propulsion (EP) will be required to maintain the path along the exo-star line as our Sun wobbles and also to maneuver to other planet FLs.

The science environment between ~500 – 1000 AU expected to be benign with no significant perturbations to flight in terms of satellite performance.

Strategies for moving from Star FL to Planet FL are illustrated in the right-hand figure below

- Factor in the geometry of the planet’s orbital plane with respect to the s/c line of sight
**ΔV Estimates for Focal Line Maneuvering**

- Using a rectilinear model to estimate the delta-v as a first order approximation
  - Not accounting for station keeping due to Solar wobble
- Assuming the following EP engine:
  - Electrospray thruster: Isp (s)/ Thrust (mN) = 1200/0.1
- Model assumptions:
  - Constant gravity from Sun at 550 AU
  - Constant thrust from engine at 0.1 mN
  - Started at zero initial velocity
  - Burn in direction against Sun for a time, then immediately turn around and burn in the opposite direction such that vehicle is at zero velocity again at desired distance

### ΔV Estimates for Focal Line Maneuvering

<table>
<thead>
<tr>
<th>Time-of-flight [days]</th>
<th>Target Distances</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>10,000 km</td>
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<tr>
<td></td>
<td>20,000 km</td>
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<td>30,000 km</td>
</tr>
<tr>
<td></td>
<td>40,000 km</td>
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<td></td>
<td>50,000 km</td>
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### Fuel Estimate vs ΔV for 50000 km transfer from SFL

<table>
<thead>
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<th>Estimated ΔV [m/s]</th>
<th>Estimated Propellant Cost [kg]</th>
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<tr>
<td>4</td>
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<td>8</td>
<td>0.03</td>
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<td>9</td>
<td>0.035</td>
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</table>
Technology Hardware and Software
## Timing & Synchronization with Earth Clocks

How to maintain synchronization of on-board clocks given length of SGL mission

**Microsemi Spec sheet: 900-00744-007. A. 4/19**
- <120 mW, 35 g, < 17cm³
- Rad Tolerant 20krad,
- SEL, SEU tested to 64 MeV*cm²/mg
  (LET_{th} for Cosmic Ray 10-100 MeV*cm²/mg)

### Design to maintain on-board clocks to < 1 ppm for duration of mission

<table>
<thead>
<tr>
<th></th>
<th>Current TRL</th>
<th>Approach</th>
<th>Synchronization period</th>
<th>Improvement in 10 years (aggressive)</th>
<th>Key technology barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>7-8</td>
<td>10 MHz CSAC (Microsemi) on s/c, Laser in Earth orbit. (100W, 10 MHz, 1 micron wavelength, 5 m output beam telescope)</td>
<td>CSAC clock every 4 months (Allan Deviation ~ 1E-11 @ 1000s),</td>
<td>100X, so 33 years synchronization period (10MHz clock)</td>
<td>Controlling thermal drift</td>
</tr>
<tr>
<td><strong>Eventual</strong></td>
<td>2-3</td>
<td>Optical frequency comb on s/c</td>
<td>~ 1300 years for 10 MHz clock, 32 years for 500 MHz clock (Allan Deviation 2E-15, Y. Hisai et al. Optics Exp. 27(5) 2019, pg 6404.)</td>
<td>10X, so 53 years, for (3 GHz clock).</td>
<td>Support equipment very large (tabletop)</td>
</tr>
</tbody>
</table>

NIST physicists Scott Diddams (left) and Scott Papp with a prototype atomic clock based on a chip-scale frequency comb. Diddams is holding the silicon chip, which fits into the clock apparatus on the table.
**Length of Mission and Sensor Contamination**
Self-produced outgassing contaminating sensors and reflectors during the SGL journey

<table>
<thead>
<tr>
<th></th>
<th>Contamination requirements (End of life – Beginning of life)</th>
<th>Contaminant particle density around spacecraft m⁻³</th>
<th>Expected number of contaminant monolayers forming from “self outgassing” during SGL mission (40 years)</th>
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</thead>
<tbody>
<tr>
<td><strong>Rosetta Mission</strong></td>
<td>6E11 (measured 6.9 yrs)</td>
<td>16500 (~9µm)</td>
<td></td>
</tr>
<tr>
<td><strong>NASA LADEE Mission</strong></td>
<td>~ 20 Angstroms (160 days)</td>
<td>495 (~0.3µm)</td>
<td></td>
</tr>
</tbody>
</table>

- **Baseline solution** (TRL 8-9):
  - Heating sensors, proper spacecraft venting design.
  - Open spacecraft structure.

- **Possible eventual solution** (TRL 2):
  - Ultrasonic excitation for enhanced diffusion on critical surfaces.
  - Enhancement of surface diffusion of atomic/molecular adsorbates by ultrasonic surface excitation.
    - A 4500-fold enhancement in surface diffusion corresponds to an equivalent temperature increase of 1000 K.

![Data from Rosetta Mission](image)

**Gas kinetic estimation of contamination level**
- Spacecraft temp. ~ 80K, sticking coefficient ~ 1.
- Average mass of contaminant (carbon: 12 amu).
- Mission length ~ 40 years.
- Did not include UV/VUV photochemistry

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Henry.Helvajian@aero.org
Crosslink COMM

- Assumptions into analysis
  - Establish a Local Area Network,
  - SGL spacecraft flying in formation,
  - Low gain or omni directional antenna on each of the SGL sat,
  - Low pointing accuracy required,
  - Frequency division among the cross links to avoid interference,
- Link budgets worked for Intra Pearl or Cluster
  - UHF, Ka, and V-band
  - Really should use V-band

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Intra Pearl (UHF)</th>
<th>Intra Pearl (Ka-band)</th>
<th>Intra Pearl (V-band)</th>
<th>Intra Pearl (V-band)</th>
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<tr>
<td>Data Rate</td>
<td>kbps</td>
<td>0.1</td>
<td>10</td>
<td>8000</td>
<td>80000</td>
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<tr>
<td>Frequency</td>
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<td>401</td>
<td>2800</td>
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<td>Distance</td>
<td>km</td>
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<td>0.20</td>
<td>0.20</td>
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<td>Antenna efficiency</td>
<td>%</td>
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<td>65%</td>
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<td>65%</td>
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<tr>
<td>Wave length</td>
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<td>Antenna Gain</td>
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<td>1</td>
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<tr>
<td>Line Loss</td>
<td>dB</td>
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<td>-1</td>
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<td>-1</td>
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<td>Transmit EIRP</td>
<td>dBW</td>
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<td>32.49</td>
<td>41.61</td>
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<td>Free Space Loss</td>
<td>dB</td>
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<td>-215.4</td>
<td>-216.5</td>
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<td>Atmospheric Loss</td>
<td>dB</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Polarization Loss</td>
<td>dB</td>
<td>-0.4</td>
<td>-0.4</td>
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<tr>
<td>Tx Pointing Loss</td>
<td>dB</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Isotripic Signal Level</td>
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<td>-177.88</td>
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<td>Antenna Diameter</td>
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<tr>
<td>Antenna efficiency</td>
<td>%</td>
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<td>65%</td>
<td>65%</td>
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<tr>
<td>System Noise Temperature</td>
<td>K</td>
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<td>140</td>
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<td>Noise Figure</td>
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<td>Receiver Loss</td>
<td>dB</td>
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<td>-1</td>
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<td>Receiver G/T</td>
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<td>Rx Pointing Loss</td>
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<td>-3</td>
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<td>Boltzman constant</td>
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<td>Received C/No</td>
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<td>dB</td>
<td></td>
<td></td>
<td></td>
<td>83.3</td>
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<td>Received Es/No</td>
<td>dB</td>
<td>7.5</td>
<td>9.6</td>
<td>7.9</td>
<td>8.3</td>
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<td>Received Eb/No</td>
<td>dB</td>
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<td>12.6</td>
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<td>Implementation Loss</td>
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<td>-2</td>
<td>-2</td>
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<td>Required Eb/No at BER=10^-7</td>
<td>dB</td>
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<td>10.6</td>
<td>5.1</td>
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<td>Margin</td>
<td>dB</td>
<td>0.3</td>
<td>2.6</td>
<td>3.1</td>
<td>3.5</td>
</tr>
</tbody>
</table>

50,000 km max distance

One Cluster Shown

SGL sat SGL sat SGL sat SGL sat SGL sat SGL sat

Intra-Pearl Distance (km) Data Rate (Mbps) Frequency (MHz) (V-Band) ~ 3dB link margin

- 2000 100 8000
- 6000 10 8000
- 20000 1 8000

Parameter Units Intra Pearl (UHF) Intra Pearl (Ka-band) Intra Pearl (V-band) Intra Pearl (V-band) Intra Pearl (V-band)
Downlink COMM: Pearl-to-Pearl

### Parameter Units
- **Data Rate** kbps 0.1
- **Frequency** MHz 80000
- **Distance** km 2992000000

#### Transmit Station Parameters
- **Antenna Diameter** m 4.00
- **Antenna efficiency** % 65%
- **Wave length** m 0.004
- **Antenna Gain** dBi 68.63
- **Transmit Power** W 10
- **Line Loss** dB -1
- **Transmit EIRP** dBW 77.63

#### Propagation Parameters
- **Free Space Loss** dB -320.0
- **Atmospheric Loss** dB 0
- **Polarization Loss** dB -0.4
- **Tx Pointing Loss** dB 0
- **Isotropic Signal Level at Rx Station** dB -242.79

#### Receiver Parameters
- **Antenna Diameter** m 4.00
- **Antenna efficiency** % 65%
- **Antenna Gain** dBi 68.6
- **System Noise Temperature** K 140
- **Noise Figure** dB 5
- **Receiver Loss** dB -1
- **Receiver G/T** dB/K 42.8
- **Boltzman constant** dBW/Hz/K -228.6
- **Received C/No** dB-Hz 25.63

### Carrier Parameters
- **Modulation order** 2
- **Symbol Rate** ksps 0.2500
- **Noise Bandwidth** dB-Hz 23.0
- **Required Eb/No at BER=10^-7** dB 1.5
- **Margin** dB 2.1

### Range Link
- **System Range (AU)**
  - **20 AU** (4m antenna) 5W (1.55 µm) laser, 40 cm Tx telescope, 2.5 m Rx dish,
  - **200 AU** 80 bps (~ 6 hrs to transmit S&HS data for a 3U CubeSat ca 2019)
  - **500 AU** 12.5 bps

### Suggestions
- Could get 10-15X increase in Tx rate: Increasing laser power 3X, Tx telescope to 1m dia.
- The caboose should be a sequence of 3 s/c with higher power lasers (@ 200, 400 and 600 AU).
Overview of current COMM architecture
Laser Comm While “Staring at the Sun”

- NASA to install Deep space optical Comm
  - Data rates of 200 Gbs at 1 AU have been claimed
    - then at 500AU and 800AU 800 kbs and 300 kbs can be expected.
- For SGL, constraints of emission from sun limit S/N
  - Situation critical for receiving s/c sensor
  - For Comm to 550AU need ~100W laser in LEO
  - Or ∼10W repeater” s/c at 200 AU distances.
- Advantages of formation flying a cluster of s/c and laser COMM.
  - Not every s/c needs laser downlink capability.

The range of laser linewidth of current commercial high power fiber lasers

<table>
<thead>
<tr>
<th>Uplink Laser Wavelength (µm) with 60 KHz linewidth (FWHM) filter at Rx</th>
<th>S/N @ 200 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.06</td>
<td>6</td>
</tr>
<tr>
<td>1.55</td>
<td>8</td>
</tr>
</tbody>
</table>

Uplink Laser Wavelength (µm) with 60 KHz linewidth (FWHM) filter at Rx

S/N: # photons in Sensor “bucket” from a 10W laser at 200AU separation vs photons from the Sun at 500AU

- At 1.06 micron wavelength
- At 1.55 micron wavelength

S/N @ 200 AU

- 1.06: 6
- 1.55: 8

- 1.06: 1.55

S/N ~ 1.2

Linewidth (FWHM) of Necessary Optical Filter on S/C Sensor (Hz)

5.0E+03 6.0E+03 7.0E+03 8.0E+03 9.0E+03 1.0E+04 1.1E+04 1.2E+04 1.3E+04 1.4E+04 1.5E+04 1.6E+04 1.7E+04 1.8E+04 1.9E+04 2.0E+04 2.1E+04 2.2E+04 2.3E+04 2.4E+04 2.5E+04 2.6E+04 2.7E+04 2.8E+04 2.9E+04 3.0E+04 3.1E+04 3.2E+04 3.3E+04 3.4E+04 3.5E+04 3.6E+04 3.7E+04 3.8E+04 3.9E+04 4.0E+04 4.1E+04 4.2E+04 4.3E+04 4.4E+04 4.5E+04 4.6E+04 4.7E+04 4.8E+04 4.9E+04 5.0E+04
SGL spacecraft design
Current Space Craft Design

- Parse mission functions into functional *units* trying to reduce each unit to ~10 kg mass.
- Give each *unit* the capabilities of a 6U Cubesat (avionics, ACS, batteries, EP, ...), operates alone for limited time.
- Each unit can “take care of itself”, self powered but also carries a critical function or capability for the SGL mission (e.g.; primary telescope mirror, RTG, extra batteries, coronagraph, optical COMM, ...)
- Fly each *unit* on a solar sail to high velocities.
- Deploy the *units* between Earth and Mars orbits.
- Conduct in-orbit self-assembly using 6U CubeSat propulsion and ACS
- The assembled vehicle then conducts the SGL mission.
<table>
<thead>
<tr>
<th>Component</th>
<th>pMC-1</th>
<th>pMC-2</th>
<th>pMC-3</th>
<th>pMC-4</th>
<th>pMC-5</th>
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<td>Coronagraph</td>
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<td>High Res Star Tracker</td>
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<td>Robotic Arm (boom) + Secondary Mirror</td>
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<td>Larger RW (100 kg mass)</td>
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Intelligent Autonomy Drivers

• Months-long period of blackout, where comms link will be blocked by the sun
• Perihelion passage for the gravity assist, when the AI will need to manage GNC
• 4+ light day distance to the SGLF, where optimal operations will require intelligent autonomy
• Optimize power usage on smallsats, given limited power for extensive mission requirements
AI Algorithm Design

• AI Executive functionality with Intelligent Autonomous Agents (AI Subsystem concept)

• Deep Convolutional Neural Networks (CNNs) for pattern recognition

• Recurrent Neural Networks (RNNs) for Anomalous Signal Processing

• Reinforcement Learning to learn from new data then find and drive optimal solutions

• General Adversarial Network (GANs) and/or Hierarchical Temporal Memory (HTM) to find "imaginative" optimal solutions to unknown data coming available throughout the mission

USE Case understudy: Integrated Vehicle Health Management (IVHM) system
The Concept of Operations (CONOPS) in overview

Rendezvous orbit

A Pearl leaves Rendezvous orbit

Pearl s/c (10-20) released and solar sail deploy

@ 650AU find and track Exo-planet SGL, then form “cooperative cluster” of Science s/c to collect data, analyze, communicate results to Earth. Take data to 900 AU

Containerized s/c, secondary payloads

RIDE SHARE

Solar sail s/c undergo near circular trajectory to solar perihelion (possibly doing solar mission: corona warning)

On perihelion exit dispose extra thermal shielding

Near Earth, Self-Assembly starts, forming the mission capable satellite

~28-year cruise phase

@ 550 AU find, track the bright Exo-Sun SGL focal line

MISSION TIME
The Keys to Mission Executability

• To make the SGL mission attractive we need to:
  – Drive down and spread non-recurring costs – lots of players
  – Gain economies of scale to minimize recurring costs – lots of spacecraft

• Open architecture so everyone can “play” to spread costs
  – Small s/c (<10 kg)
  – Affordable methods for exit velocity
  – Lean ground-based TT&C

• Then we can build and fly many s/c
  – To a single exo solar system, or
  – To multiple exo solar systems
Come Join Us

https://aerospace.org/article/solar-gravity-lens-looks-exoplanets