Workshop on the Technology Requirements to Operate at and utilize the Solar Gravity Lens for Exoplanet Imaging at the Keck Institute for Space Studies (KISS-CALTECH) May 15-18, 2018.

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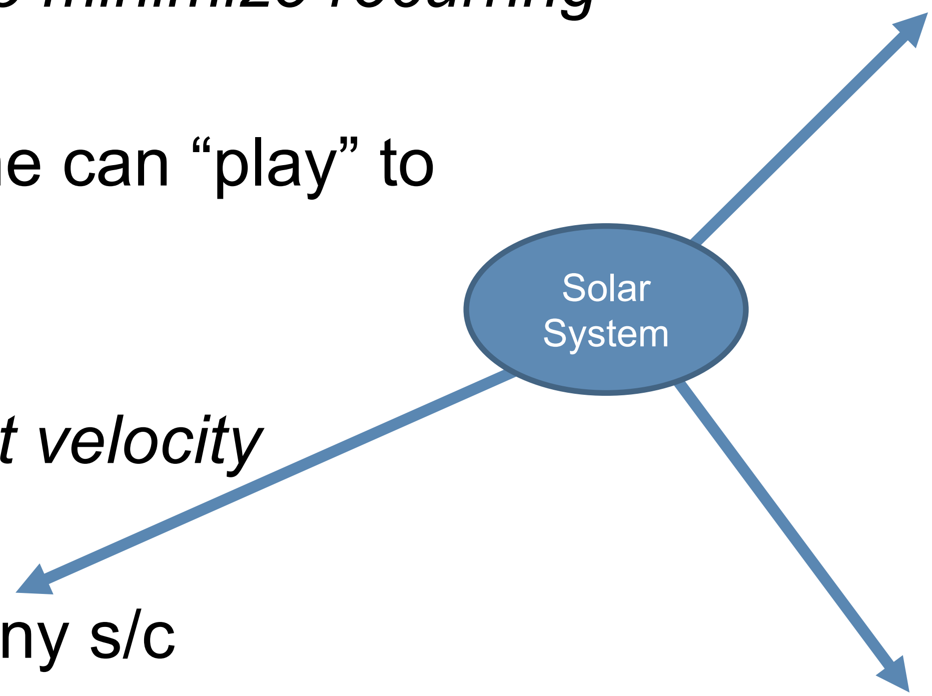
Make SGL Missions Ubiquitous

- 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*



The Value of Incremental Imagery

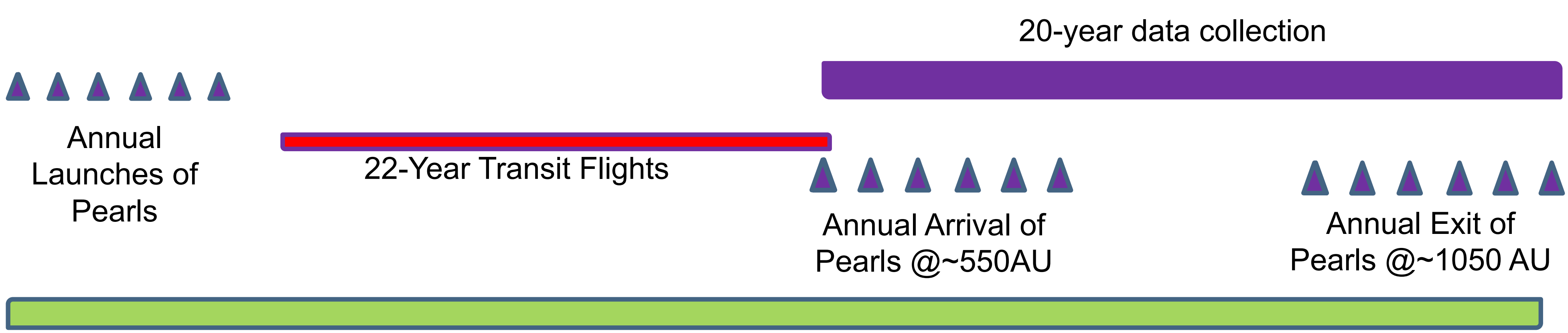
- The ultimate goal is high resolution exoplanet imagery
  - *Many millions of "snapshots" collected over years*
- Breathtaking views occur soon after arrival at the FP
  - *The "pale blue dot" (10s kb)*
  - *Examination of the exo solar system to search for intelligent development (100s Mb)*
  - *1,000 km scale look at exoplanet and moon (100s mb)*
  - *Exo moon details to look for development (1000s mb)*
  - *100 km scale imagery of the exoplanet for cartography (1s gb)*

Conceptual String of Pearls Architecture

- Clusters ("Pearls") of light-weight spacecraft launched at ~1 year intervals
  - *Small, multi-purpose, re-programmable s/c*
  - *Minimal weight to achieve escape velocity, and manage trajectory with minimal fuel.*
    - Baseline – <10 kg spacecraft
    - 8-10 s/c per pearl
    - 6-8 pearls/mission
    - TBD concurrent missions (funding limited)
- System "learns" as it flies into this unknown and complex environment
  - *Reprograming and reallocating functionality to optimize consumables and data collection*
  - *Deal with complexities of varying exoplanet signals vs. spurious photons (corona, etc.)*
  - *Capture targets of opportunity*

Mission Timeline

- Technology based on a first launch in 2030-35 with pearls launched at ~1 year intervals.
  - Flying during 100th anniversary of the Einstein paper
- Pearl launch timing considerations include:
  - Solar system escape trajectory of into a tight path to the FL,
  - Asynchronous collection vis-à-vis exoplanet orbit.



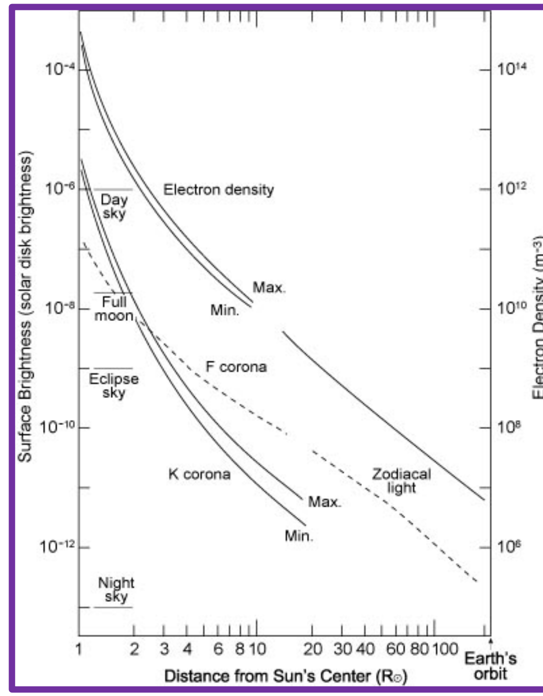
20-Year Mission over 2 solar cycles optimizes collection vs solar activity

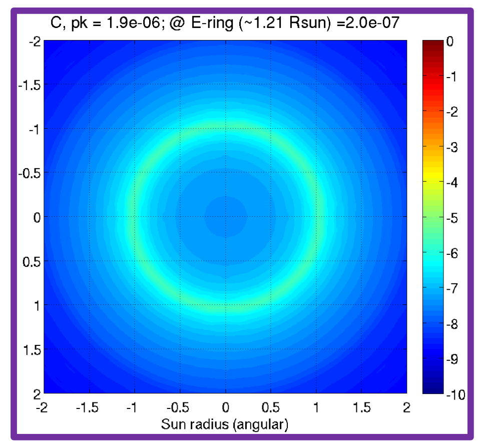
Rationale for String of Pearls Approach

- IF this is THE major international exo solar initiative it should be incremental in time, funding and technology, so anyone can affordably participate over time.
- We launch first pearl when the technology is just good enough to have a chance of success,
  - *Incremental improvements year after year as more space-faring entities participate.*
- Conversely if it were a one-shot deal, it will never be "good enough" to commit to flight – and will be "reviewed to death".
  - *if Apollo or Mars exploration had been planned, promoted and funded for only one launch it would not have happened.*

String of Pearls (SoP) Methodology

- SoP "learning" allows optimizing viewing protocols to adjust for conditions as pearls move outward along the focal line.
  - *At first (when we are looking closest to our sun) the exoplanet signals and solar coronal noise are both strong.*
  - *As the distance increases, both diminish unevenly – so there are optimum places along the line for best viewing.*
- As these optimums will be unknown in advance, we are most likely to succeed by flying multiple pearls that learn as they fly.
- Successive pearls may have evolving enroute science missions:
  - *Dust collection and spectral analysis*
  - *TBD*





SoP Collection CONOPS

- Exoplanet orbit limits viewing seasons to:
  - *When planet image is sufficiently far from its star,*
  - *When planet illumination is best suited for observation.*
- As the exoplanet may be in good view for 20-30% of the time, multiple s/c provide viewing redundancy during "good times".
- When the exoplanet is not positioned for data collection, the sensors can be re-directed to:
  - *Examine other planets in the exo solar system to understand the neighborhood,*
  - *Reconnoiter the exoplanet's moon(s), to look for colonization (>1 km in size),*
  - *Look for intelligent transport of life from the exoplanet to other planets in its solar system.*

S/C Re-use/re-purposing

- Each pearl consists of 8-10 s/c to provide high functional redundancy and reliability.
- Component reconfiguration and reuse is used to re-purpose on-board assets to drive down weight.
- For example – re-use solar sail material:
  - **Communications** – build and re-structure the receiving and transmitting antennas that link the s/c, the pearls and the pearl-Earth link.
  - **Sensor** – make collector 1 – 10 m or larger, change sensor configuration during mission.
  - **Star shade** – consider option to eliminate spurious optical signals.

Flexibly Allocating Mission Tasks to S/c

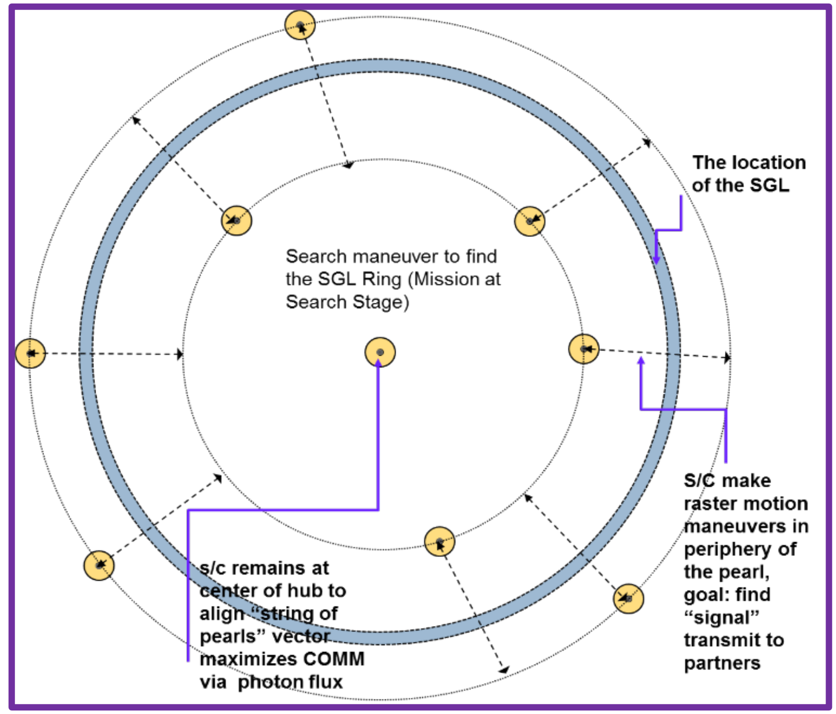
- **Power**: One approach is one or more of the s/c in each pearl providing a centralized power supply, with energy distributed as needed to the other s/c, perhaps by laser links.
- **Navigation and Guidance**: a lead s/c could be the specially-equipped "shepherd" that guides the other s/c into proper trajectories.
- **Data Collection:** s/c could have different telescope designs, perhaps re-configurable, to pool data and optimize collection by "learning" as the mission evolves.
- **Data Storage**: Mission data could be centralized in a s/c processor to eliminate spurious returns and duplicative data, then compress the "good data" to minimize communications bandwidth and power requirements.
- **Communications**: 3 types of communications architectures;
  - **Intra-pearl** -- s/c within a pearl could be in a WAN, (1,000s of km)
  - **Inter-pearl** -- pearls communicate up and down the string through a dedicated communications s/c. (30-50 AU)
  - **String to Earth** -- the "caboose" pearl (last to be launched), would provides Earth-to-String 2-way communications via a dedicated long range s/c. ((up to 800 AU)

Deep Space Optical Communications is Prototype of Comm From Caboose Pearl to Earth

- “DSOC will employ near-infrared lasers.
  - *"The data rates for this demonstration are **200 gigabits per second**," says Brian Robinson, associate group leader at the lab.*
- Key DSOC technologies:
  - *a low-mass spacecraft disturbance isolation and pointing assembly; a high-efficiency flight laser transmitter; and a pair of high-efficiency photon counting detector arrays for the flight optical transceiver and the ground-based receiver.*
- Technologies are integrated into the DSOC Flight Laser Transceiver (FLT) and ground-based receiver
  - *to enable photon-efficient communications with the capability to discern faint laser signals from background "noise" from solar energy scattered by the Earth's atmosphere.*
    - **200 gb/sec at 1 AU corresponds to 800 kb/sec at 500 AU, and 300 kb/sec at 800 AU**
    - **Caboose pearl may have one or more s/c dedicated to this capability.**

Data Management

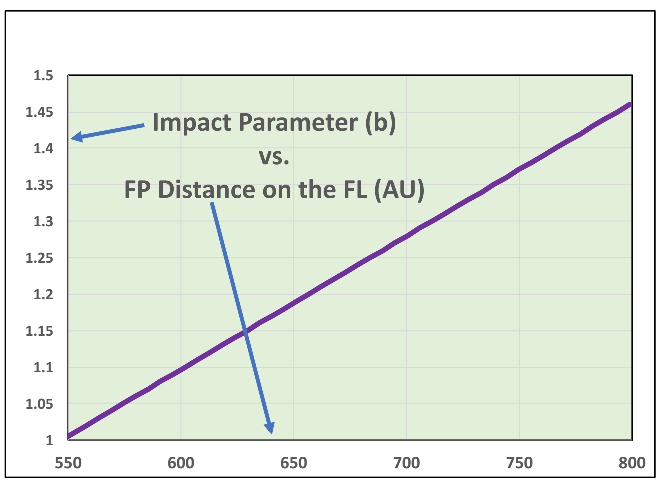
- String-wide data management get the data stream into practical limits.
- How will this be done in an AI/ML environment, with a 1-2 week command loop from Earth?
- We need an analysis of the bits generated by the sensor(s) over time, and the demands on the communications links that this imposes – also, how much data rate smoothing is possible, as the duty cycle of the sensors is likely to be small?



Cluster formation in a single "pearl" within the string-of-pearls configuration as observed in the trajectory path in the SGL's focal area

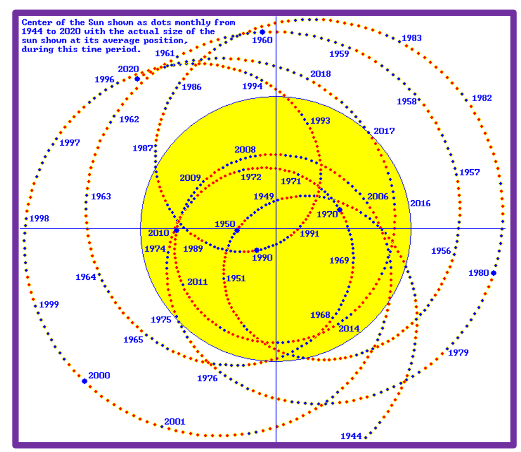
Navigation Considerations

- Navigation requires resolution of two challenges:
  - The 6-dinensionsal state vector of each s/c
    - What accuracy is needed over time?
    - How do we obtain it?
  - The 3-dimensional location of the FL
    - Where is it, given the uncertainties and variability of the environment?
    - How do we find it?
- How to create a minimum-fuel protocol over the mission lifetime?
- Once in the FL, the nav feedback loop should use the sensor data.
- This is a major area for modelling to establish the timeline for data collection.
  - With many s/c in many pearls acting concurrently, how do they work together to optimize time on target?



Navigation must incorporate changes in viewing geometry

Solar motion, one of the FL-perturbing factors that will move the FL up to 0.5 *10^6 km/year (~16 m/sec)



Appendix 1

Using the Exostar FL to Acquire the Exoplanet FL

The Approach Path to the FL

- We want the simplest, lowest cost approach to acquiring the exoplanet's FL.
- DSN tracks each string-of-pearls out to ~250 AU (or further?? TBD)
  - *We need JPL data to estimate residual cross-track error (in-track does not matter)*
  - *Each 1 cm/sec of cross track error produces 10,000 km error at the FP*
  - *Can we "dead reckon" out to ~550 AU?*
- When we arrive, can we use the exostar FL as the beacon to guide us to the exoplanet's FL?
  - *S/C in each pearl conduct search pattern to find exostar FL*
  - *This puts us into a FL-centered coordinate system*
  - *From there it is easy to find the exoplanet's FL*

Using the Exostar to Find the FL at 550 AU+

- Looking for the thin and dim exoplanet FL is hard, finding the exostar's FL first, then moving to the exoplanet's FL is easier:
  - *Sun at 547 AU = 23 km disk at -15.5 Mag*
  - *Mag 6 exostar is 230 km disk at (6 + -27.5) = -21.5 Mag*
  - *Exoplanet is 1.3 km thick disk outside the 23 km solar disk at -4.9 Mag*
- A simple photometer would see our sun, until the s/c enters the exostar's FL – with an illumination increase of 6 Mag
- Strategies for moving from exostar FL to exoplanet FL are illustrated in the following charts
  - *Varying the geometry of the planet's orbital plane with respect to the s/c line of sight*

Star-Planet FL Geometries

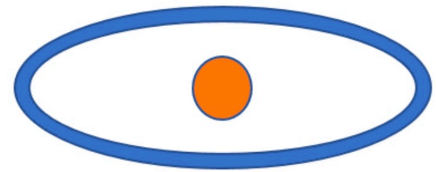
Planet's Orbit Inclined 45° Vertically

Orbit Plane Data Entry		Planetary Orbit Data Entry		
dec-v (degrees)	dec-h (degrees)	Plaetary Orbit Radius (km)	Y (Year in Days)	Plate Scale
45	0	1.50E+08	360	0.0001

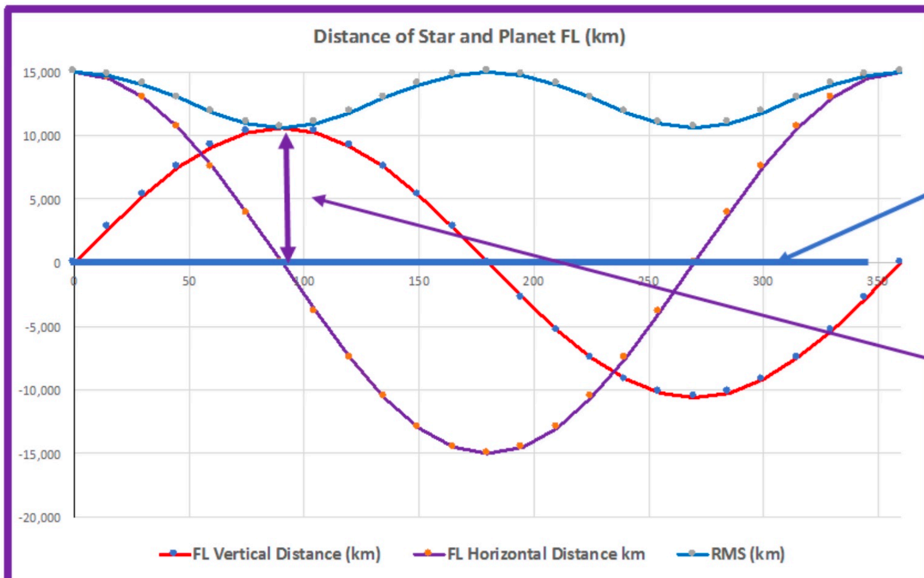
D(t)	FL Vertical Distance (km)	FL Horizontal Distance km	RMS (km)
0	0	15,000	15,000
15	2,745	14,489	14,747
30	5,303	12,990	14,031
45	7,500	10,607	12,990
60	9,186	7,500	11,859
75	10,245	3,882	10,956
90	10,607	0	10,607
105	10,245	-3,882	10,956
120	9,186	-7,500	11,859
135	7,500	-10,607	12,990
150	5,303	-12,990	14,031
165	2,745	-14,489	14,747
180	0	-15,000	15,000
195	-2,745	-14,489	14,747
210	-5,303	-12,990	14,031
225	-7,500	-10,607	12,990
240	-9,186	-7,500	11,859
255	-10,245	-3,882	10,956
270	-10,607	0	10,607
285	-10,245	3,882	10,956
300	-9,186	7,500	11,859
315	-7,500	10,607	12,990
330	-5,303	12,990	14,031
345	-2,745	14,489	14,747
360	0	15,000	15,000

Horizontal Distance	(R)*cos (PA) * cos(dec-h)
Vertical Distance	(R)*sin (PA) *sin(dec-v)

dec-v (degrees)	45	dec-h (degrees)	0



Planet Orbit Inclined 45° vertically



Star Focal Line

Moving 10,000 km in 1 month, to move from the star FL to the planet FL, requires 4 m/sec

Star-Planet FL Geometries

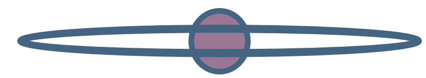
Planet Orbit Inclined 0^{o} Vertically and Horizontally

Orbit Plane Data Entry		Planetary Orbit Data Entry		
dec-v (degrees)	dec-h (degrees)	Plaetary Orbit Radius (km)	Y (Year in Days)	Plate Scale
0	0	1.50E+08	360	0.0001

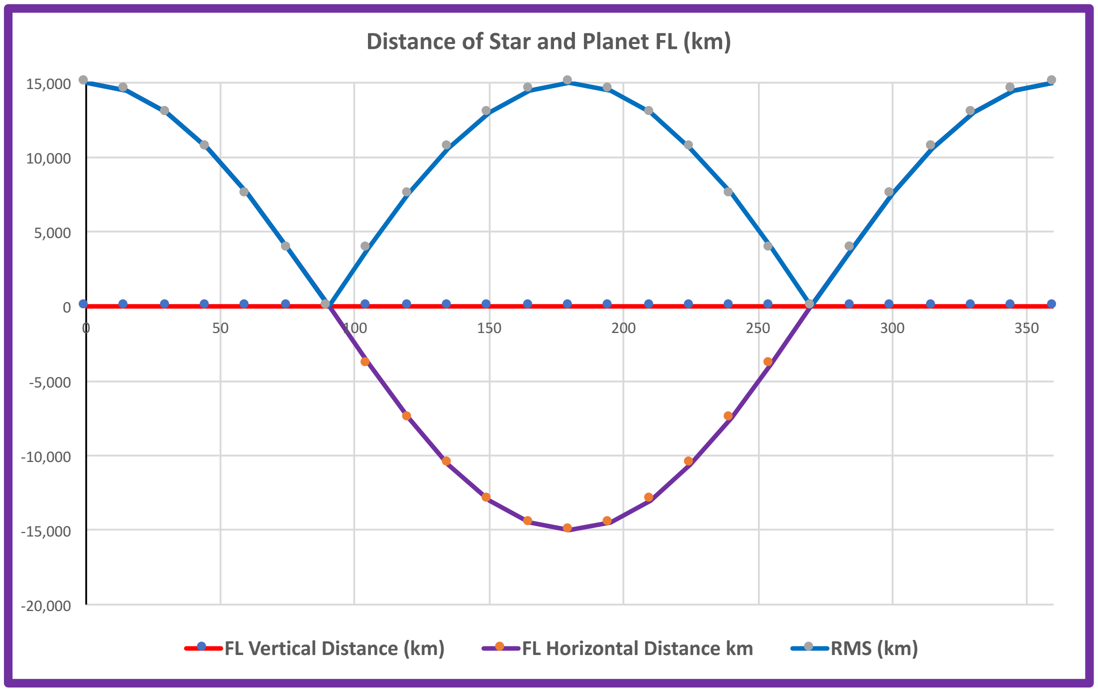
D(t)	FL Vertical Distance (km)	FL Horizontal Distance km	RMS (km)
0	0	15,000	15,000
15	0	14,489	14,489
30	0	12,990	12,990
45	0	10,607	10,607
60	0	7,500	7,500
75	0	3,882	3,882
90	0	0	0
105	0	-3,882	3,882
120	0	-7,500	7,500
135	0	-10,607	10,607
150	0	-12,990	12,990
165	0	-14,489	14,489
180	0	-15,000	15,000
195	0	-14,489	14,489
210	0	-12,990	12,990
225	0	-10,607	10,607
240	0	-7,500	7,500
255	0	-3,882	3,882
270	0	0	0
285	0	3,882	3,882
300	0	7,500	7,500
315	0	10,607	10,607
330	0	12,990	12,990
345	0	14,489	14,489
360	0	15,000	15,000

Horizontal Distance	(R)*cos (PA) * cos(dec-h)
Vertical Distance	(R)*sin (PA) *sin(dec-v)

dec-v (degrees)	0	dec-h (degrees)	0



Planet Orbit Inclined 0^{o} vertically and horizontally



Once on the exostar FL, wait for the exoplanet FL to semiannually coincide with the Star FL, then stay on it

Star-Planet FL Geometry

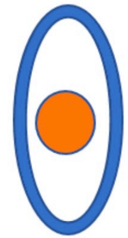
Planet Orbit Inclined 0º Vertically and 45º Horizontally

Orbit Plane Data Entry		Planetary Orbit Data Entry		
dec-v (degrees)	dec-h (degrees)	Plaetary Orbit Radius (km)	Y (Year in Days)	Plate Scale
0	45	1.50E+08	360	0.0001

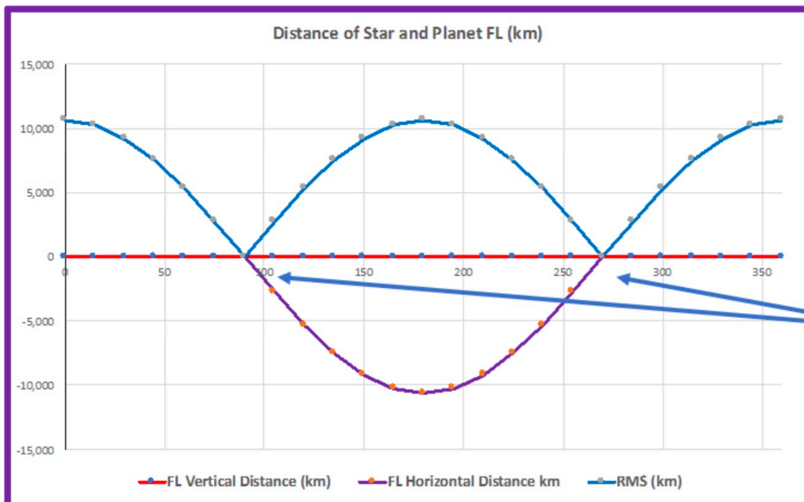
D(t)	FL Vertical Distance (km)	FL Horizontal Distance km	RMS (km)
0	0	10,607	10,607
15	0	10,245	10,245
30	0	9,186	9,186
45	0	7,500	7,500
60	0	5,303	5,303
75	0	2,745	2,745
90	0	0	0
105	0	-2,745	2,745
120	0	-5,303	5,303
135	0	-7,500	7,500
150	0	-9,186	9,186
165	0	-10,245	10,245
180	0	-10,607	10,607
195	0	-10,245	10,245
210	0	-9,186	9,186
225	0	-7,500	7,500
240	0	-5,303	5,303
255	0	-2,745	2,745
270	0	0	0
285	0	2,745	2,745
300	0	5,303	5,303
315	0	7,500	7,500
330	0	9,186	9,186
345	0	10,245	10,245
360	0	10,607	10,607

Horizontal Distance	(R)*cos (PA) * cos(dec-h)
Vertical Distance	(R)*sin (PA) *sin(dec-v)

dec-v (degrees)	0	dec-h (degrees)	45



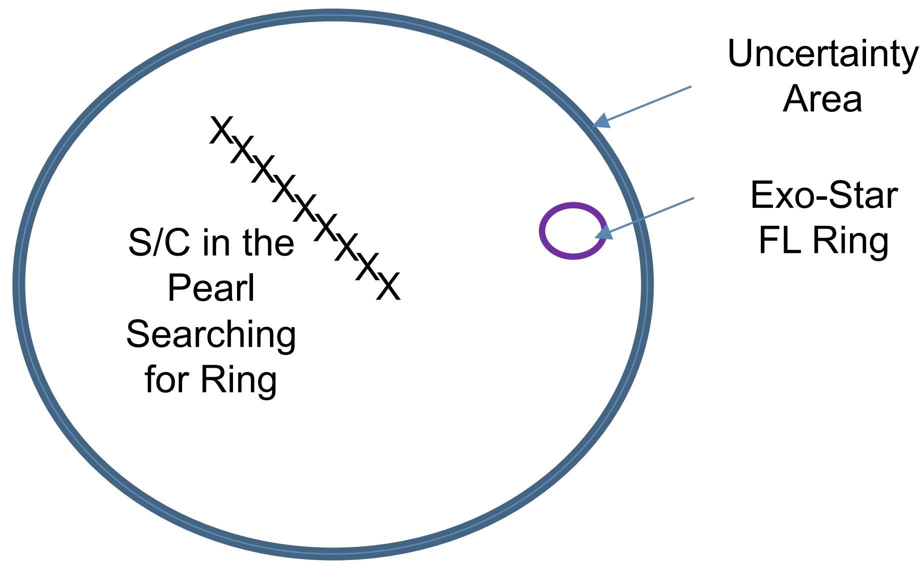
Planet Orbit Inclined 0º vertically and 45º horizontally



Once on the star FL, wait for the planet FL to semiannually coincide with the Star FL, then stay on it

Mechanisms for Finding the Exoplanet FL Option 1

- Equip all s/c in a pearl with a simple photometer looking back
- Develop optimum maneuver CONOPS to find the exostar FL
- Once a s/c finds the exostar FL, move the constellation as required to acquire the exoplanet FL
- This is only done for the first pearl – subsequent pearls just home in on the exoplanet’s FL



Mechanisms for Finding the Exoplanet FL Option 2

- Create a special purpose s/c as the first pearl pearl leader
- Equip it with ~10,000 1 gram femtosats (FS)
  - *Photometer*
  - *Time-tagged radio*
  - *Clock*
  - *Battery*
- Deploy them in a conical array ahead of the pearl – each FS is identified by its unique time of transmission
- Once an FS finds the exostar FL, it send a time-tagged radio chirp to the lead s/c
- Lead s/c guides the pearl to the target
- This is only done for the first pearl – subsequent pearls just home in on the exoplanet's FL