Earth-to-orbit Beamed Energy eXperiment (EBEX)

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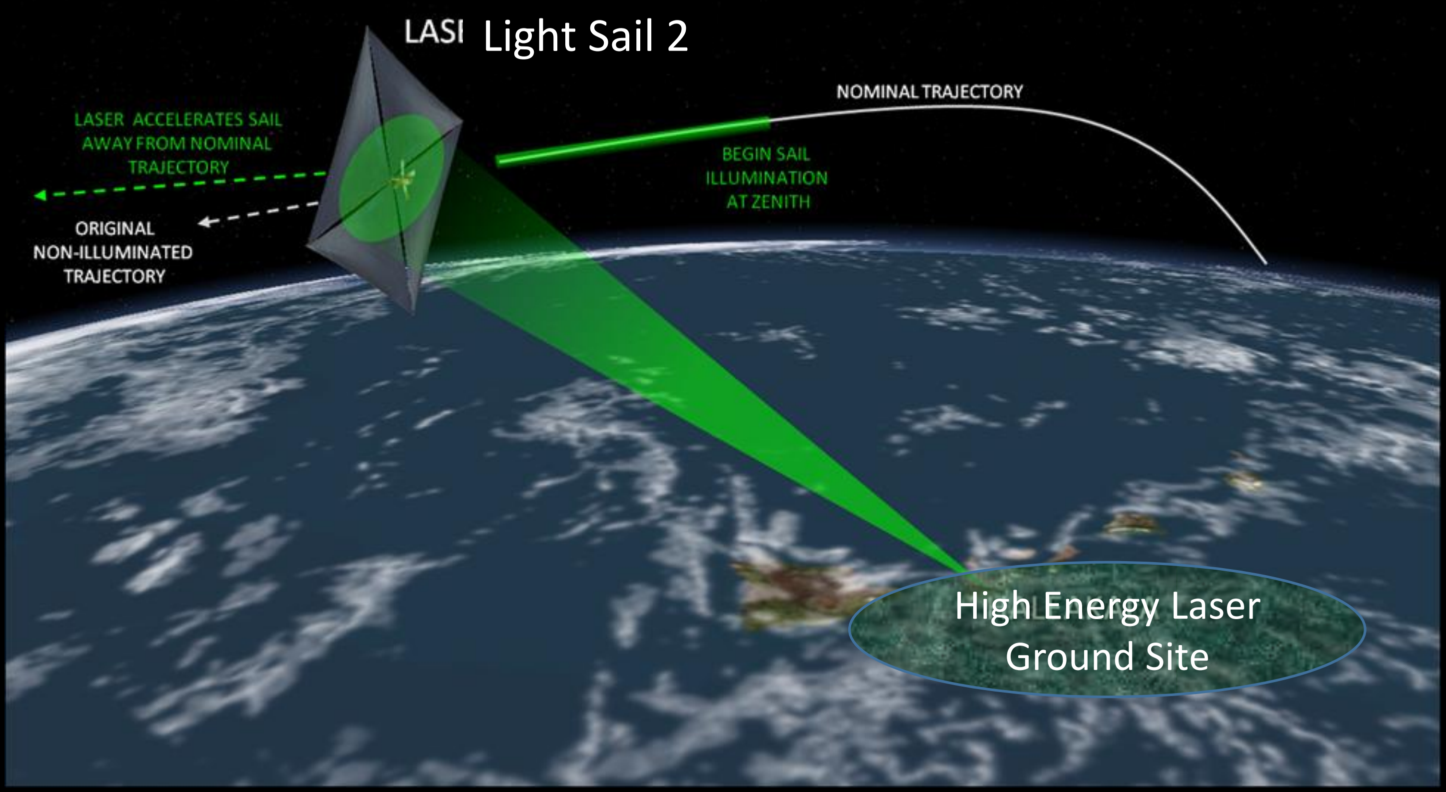
What is EBEX?

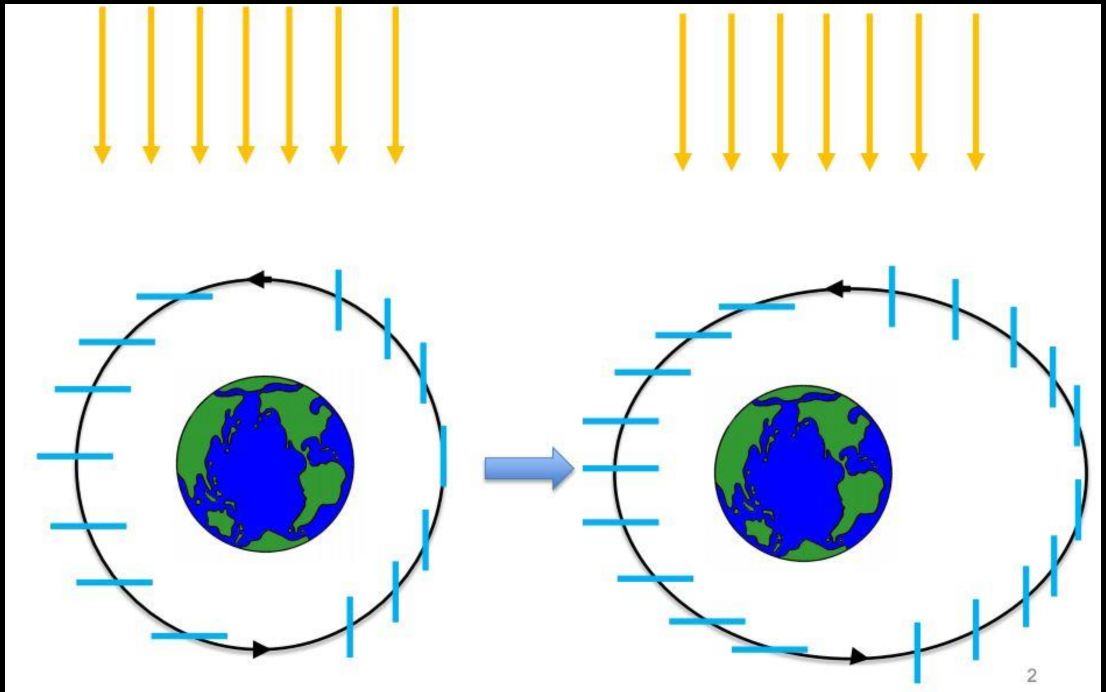
- Ground to space laser illumination of a solar sail to impart measurable ΔV (= 0.1 mm/sec)

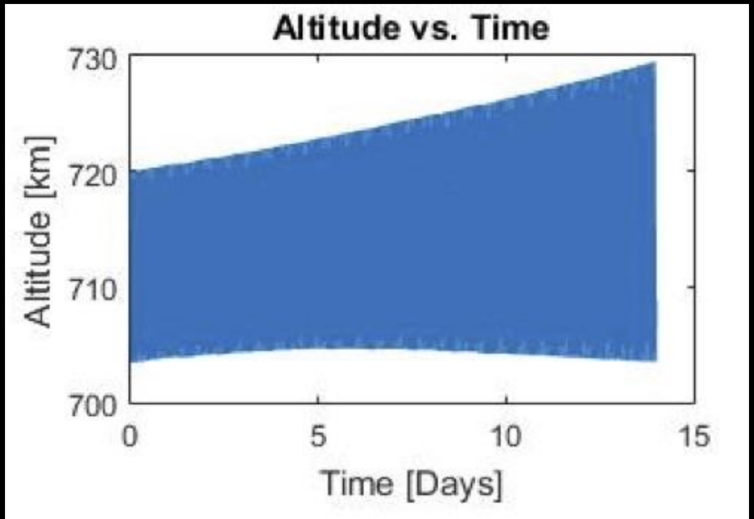
- LightSail 2 solar sail
  - launch April 2018 or later
    - 14 days checkout
    - 28 days solar sailing
  - 5.67 X 5.67 = 32 m^2
  - 5 kilograms
  - 92 % specular reflective
    at 1064 nm wavelength
  - Initial Orbit
    - 720 km circular
    - 24° inclination
  - NASA SAA8-1417702 - Available for EBEX after 6 weeks and solar sailing on-orbit



Orbit at beginning of EBEX experiment

- Sail orientation is controlled using torque rods and a single-axis momentum wheel
- Expected apogee rate of change: 700 m/day during first two weeks





- Attitude control modes
  - Solar sailing (on-off to solar vector)
  - Laser propulsion (sail normal co-aligned with velocity vector, max drag)
  - No control
- Capability of aligning sail normal along inertial velocity vector, with pointing errors of < 30 deg

Ground Site Candidates

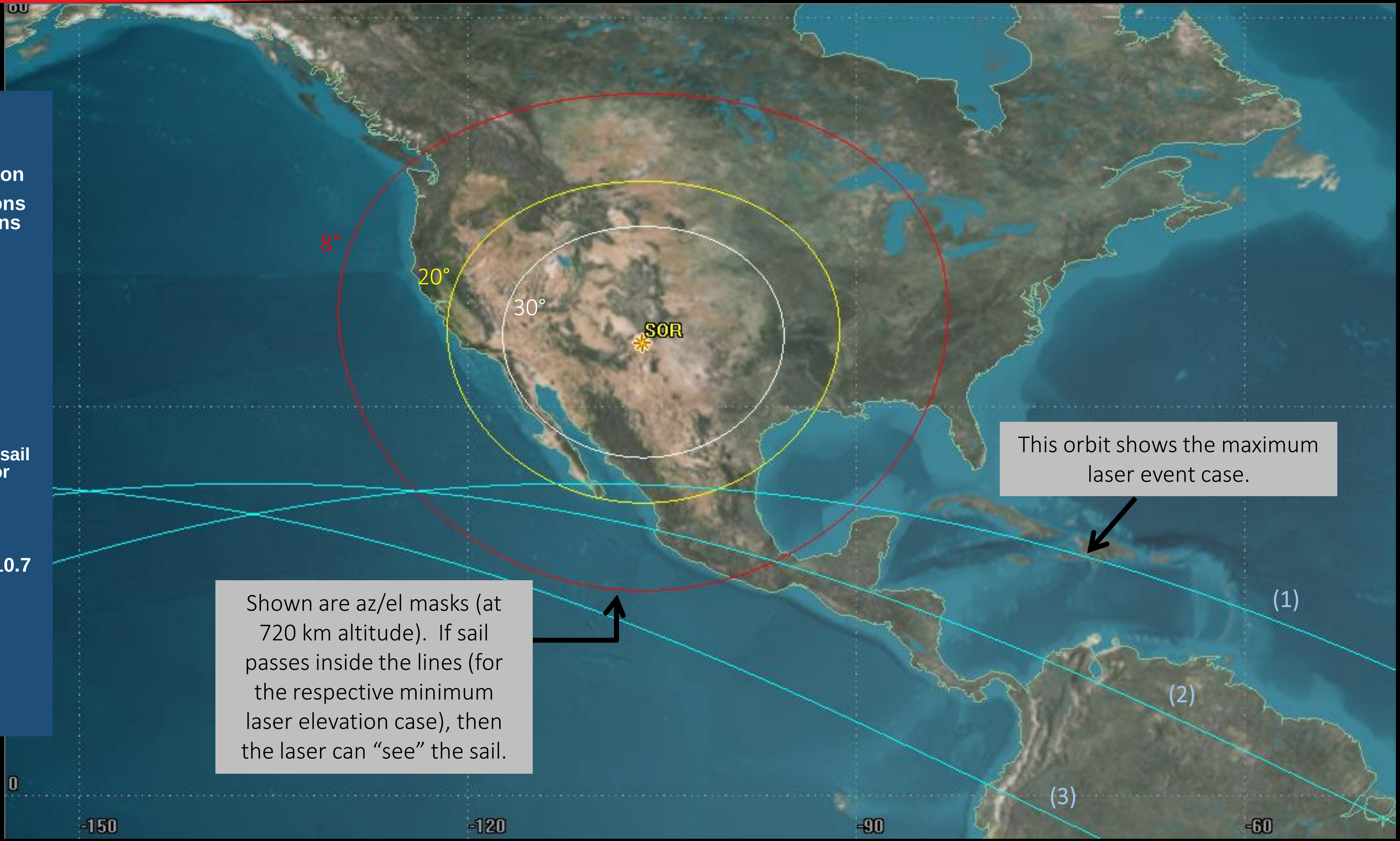
- For this assessment only considered sites that had previously hosted outdoor high energy laser operations or were controlled-access, space observation installations
- Site latitude with respect to orbital inclination important

Ground Site	Latitude (deg)	Longitude (deg)	Altitude (km)
Haleakala	20.7085	-156.258	3.057
Huntsville, AL	34.6064	-86.6557	0.171
Kwajalein	8.71955	167.719	0.05904
North Obscura Peak, NM	33.7522	-106.372	2.400
Santa Cruz	37.1399	-122.202	0.710
Santa Rosa Island, FL	30.3979	-86.7291	0.000
Starfire Optical Range	34.9642	-104.464	1.871
White Sands	32.6325	-106.332	1.205

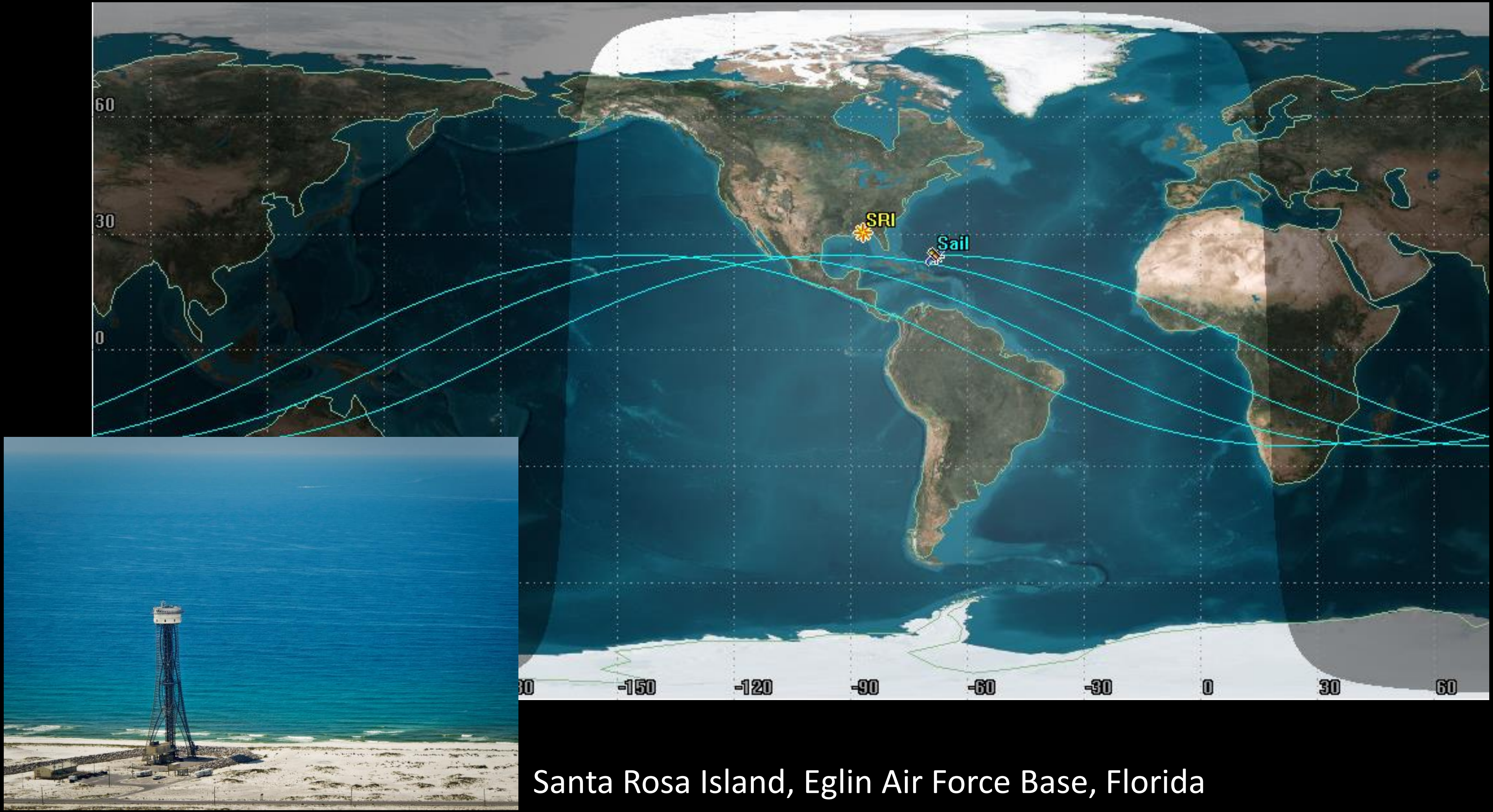
Effect of Minimum Elevation Limits

[source: Dan Thomas/MSFC]

- **Orbit:**
  - **720 km circular orbit at 24° inclination**
  - **Initial state not known, so simulations run over 160 days to capture patterns**
- **Orbit propagator:**
  - **HPOP**
  - **12 x 12 gravity model (WGS84_EGM96.grv)**
  - **Sail drag coefficient = 3.3**
  - **Area to mass of sail = 3.667 m²/kg**
    - **Assumed avg. area of non-flat sail perpendicular to velocity vector over one orbit.**
  - **Atmospheric density model: NRLMSISE 2000**
  - **Default solar flux/geomag: Daily F10.7 = 90, Avg. F10.7 = 90, Kp = 3.0**
  - **Third body gravity: Sun, Moon**
  - **Integrator: RKF 7(8)**
  - **Eclipsing Bodies: Earth, Moon**



Three Successive Orbit Tracks for Santa Rosa Island, Eglin AFB, FL

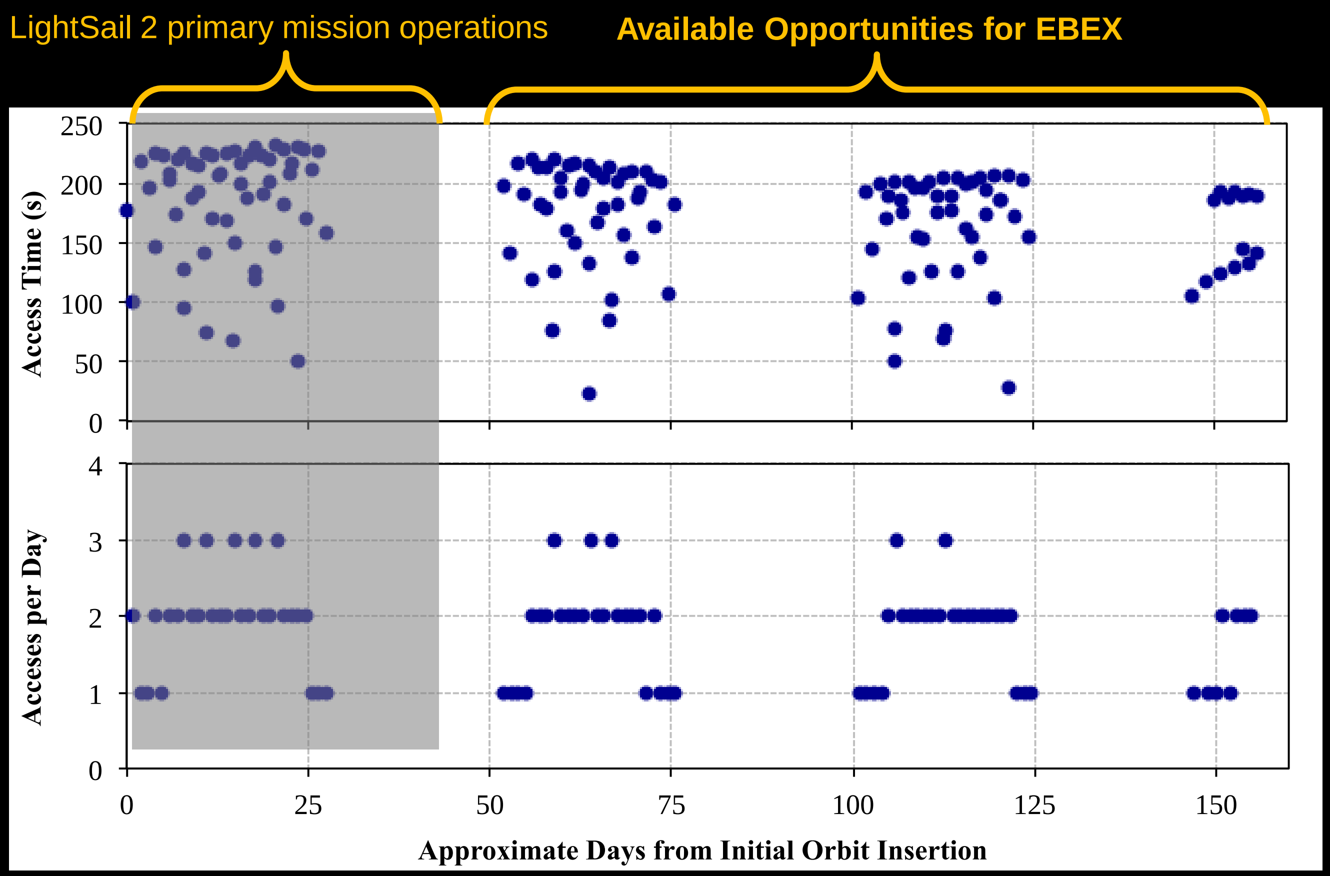


Santa Rosa Island, Eglin Air Force Base, Florida

[source: Dan Thomas/MSFC]

Review of Access Times

- **Durations of each access, number of accesses per day, and maximum gap between accesses:**

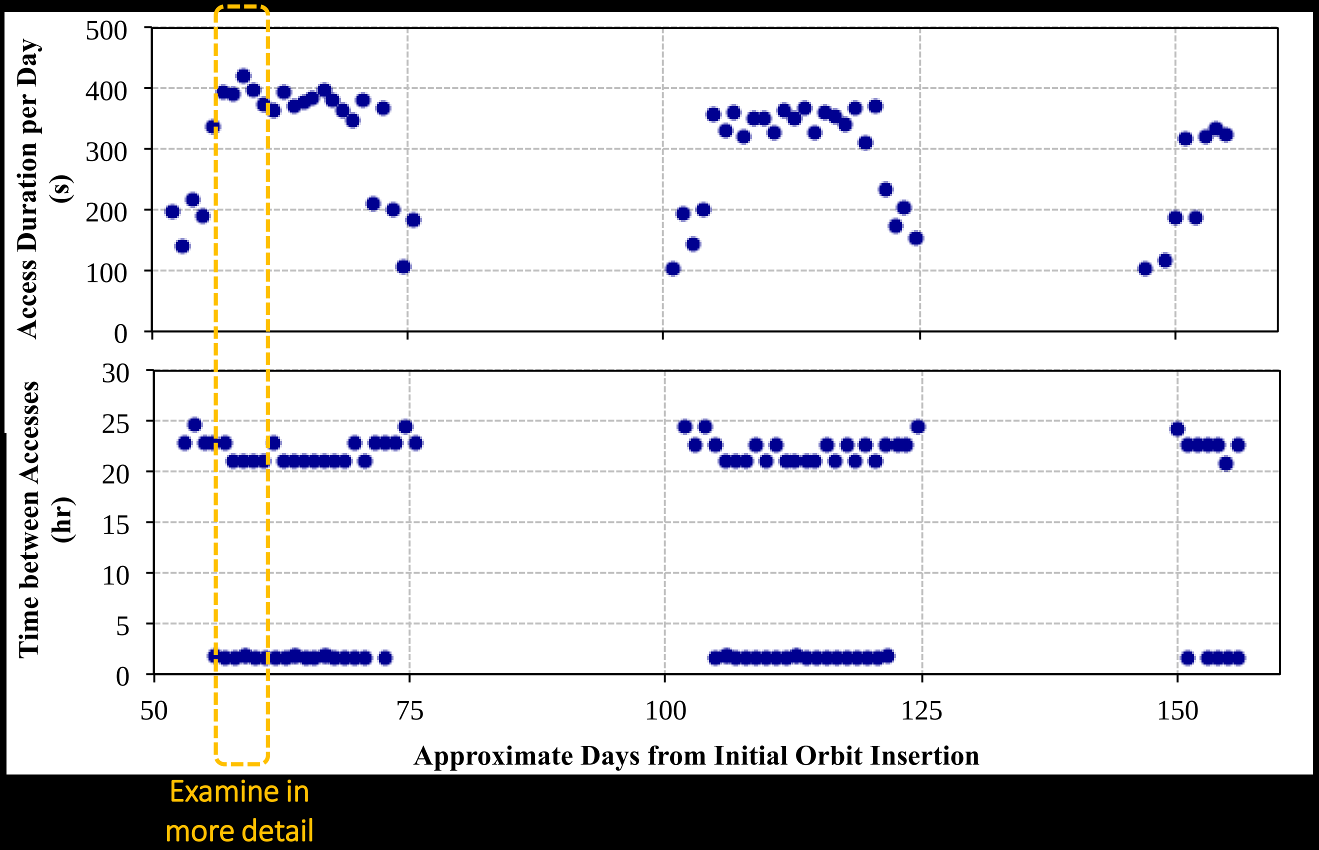


Santa Rosa Island, Eglin AFB, FL to LightSail 2

[source: Dan Thomas/MSFC]

Laser Propulsion Opportunities

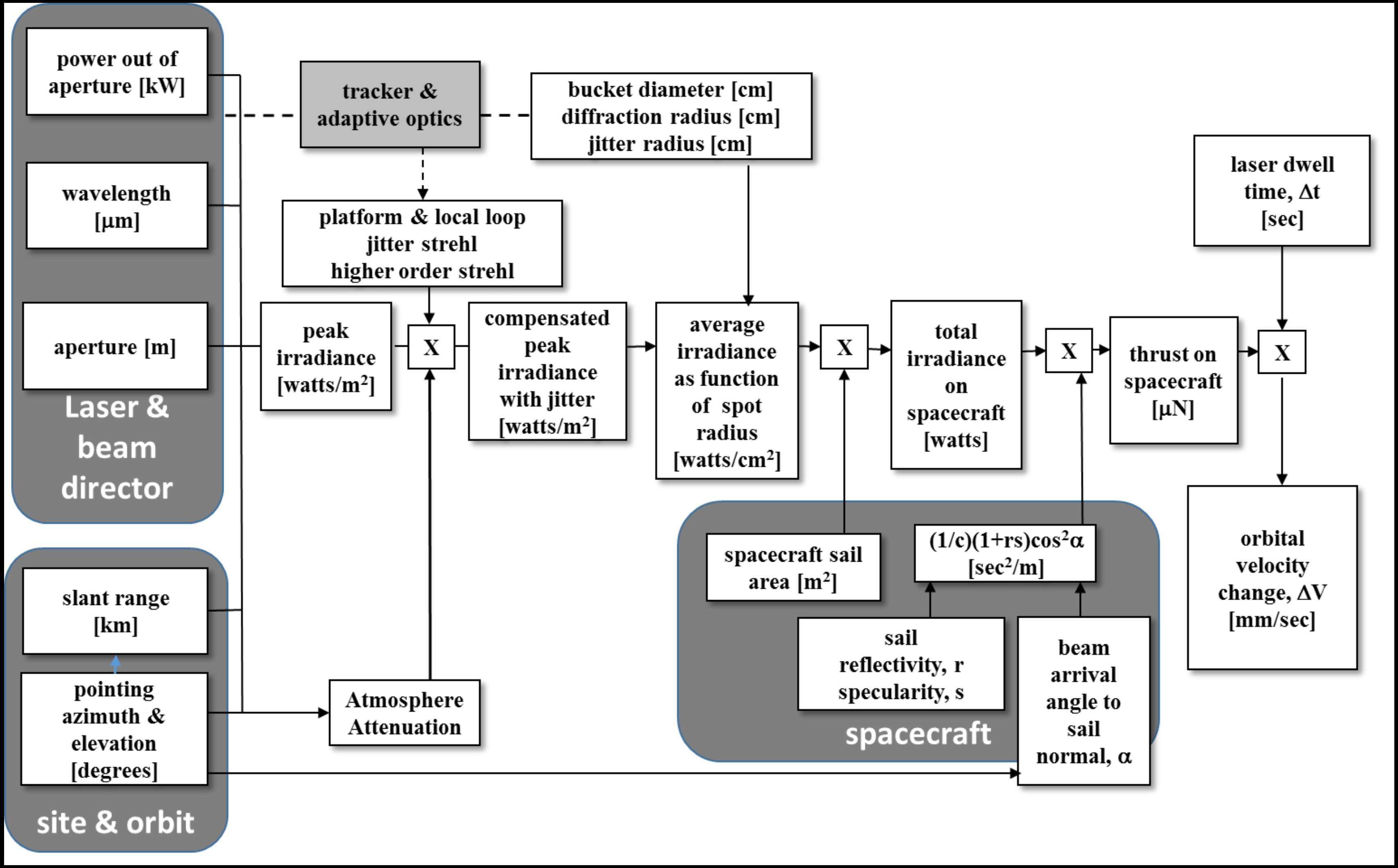
- **Sum of accesses for each day and time between each access**
  - **Want high total duration/day with small times between each opportunity**



Santa Rosa Island, Eglin AFB, FL to LightSail 2

[source: Dan Thomas/MSFC]

Performance Analysis Method



- Method based on:
- "Beam Control for Laser Systems", by Dr. Paul Merritt, published by the Directed Energy Professional Society, Albuquerque, N.M., 2012, Library of Congress Control Number: 2010929641]
- "Linear Photonic Thrust Model and its Application to the L'Garde Solar Sail Surface", by Gyula Greschik, 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8-11, 2013, Boston, Massachusetts

Power Delivered to Orbit

Let $\sigma^2 = \sigma_D^2 + \sigma_j^2$

$$I_{ave}(r_A) = \frac{1}{\pi r_A^2}\int_0^{2\pi}\int_0^{r_A} I_{PJ} e^{\frac{-r^2}{2(\sigma_D^2+\sigma_j^2)}} r\,dr\,d\theta$$

$$I_{ave}(r_A) = \frac{1}{\pi r_A^2}\int_0^{2\pi}\int_0^{r_A} I_{PJ} e^{\frac{-r^2}{2\sigma^2}} r\,dr\,d\theta = \frac{I_{PJ}}{\pi r_A^2}\int_0^{2\pi} d\theta \int_0^{r_A} e^{\frac{-r^2}{2\sigma^2}} r\,dr = \frac{I_{PJ}2\pi}{\pi r_A^2}\int_0^{r_A} e^{\frac{-r^2}{2\sigma^2}} r\,dr$$

$$I_{ave}(r_A) = \frac{2I_{PJ}\sigma^2}{r_A^2}\left[1-e^{\frac{-r_A^2}{2\sigma^2}}\right] = \frac{2I_{PJ}(\sigma_D^2+\sigma_j^2)}{r_A^2}\left[1-e^{\frac{-r_A^2}{2(\sigma_D^2+\sigma_j^2)}}\right] \qquad (2.10)$$

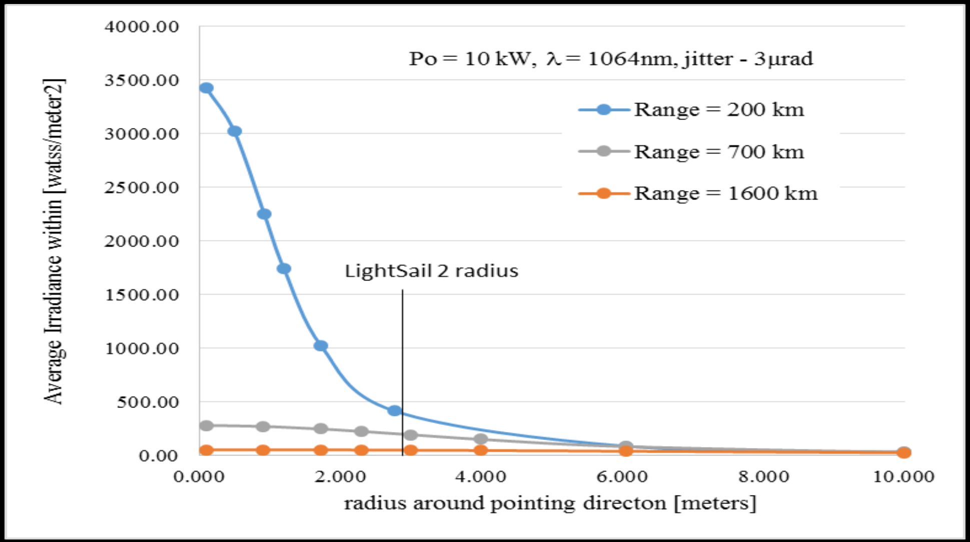
Power in spot, P = I_{ave} * Area

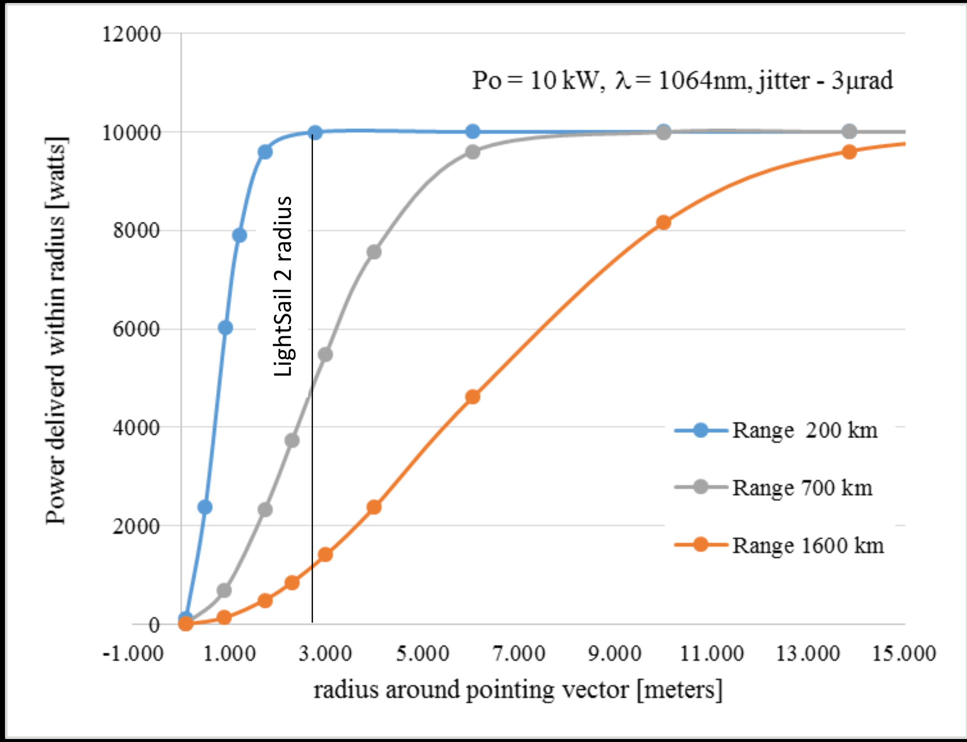
where Area = p r_A^2

s_j = jitter

s_D = diffraction

$I_{pj} = I_{peak} * s_j$

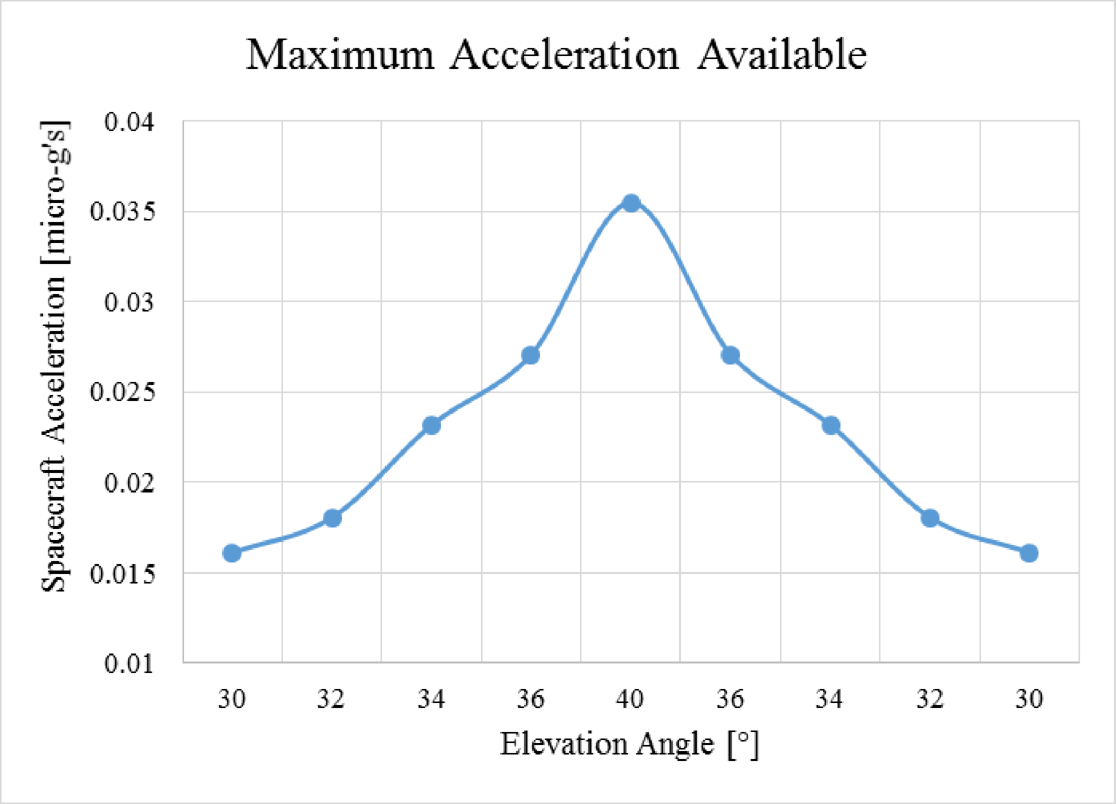


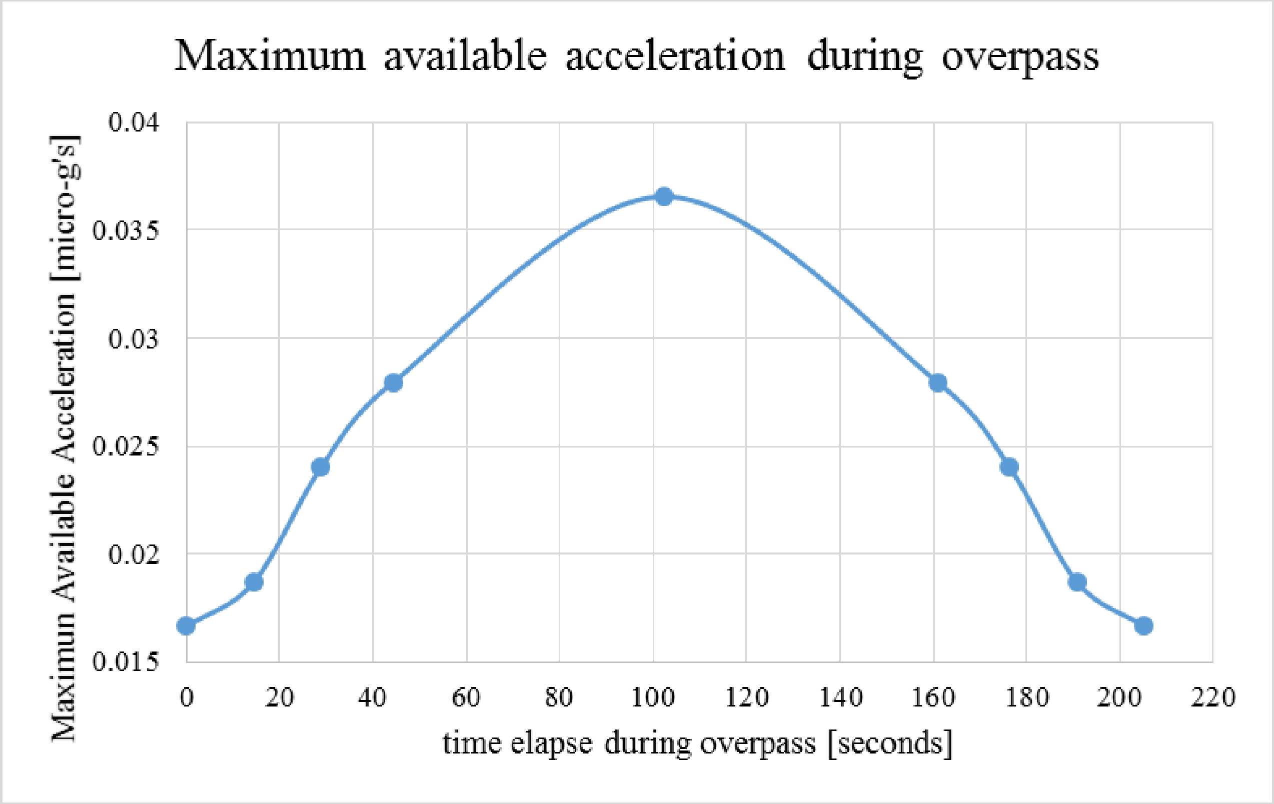


Diffraction and jitter combine to “spill” ~50% of energy past LightSail 2 at 700 km orbit altitude

Max Effect of Laser on LightSail 2

- 10kw, 1064 nm cw laser
- 30 cm beam director aperture
- 3 μrad jitter, $M^2 = 1.1$
- 32 m^2 Sail Area, 0.92 specular reflection
- 5 kilogram spacecraft mass
- 720 km circular orbit @ 24 ° inclination
- Ground site: Eglin AFB, FL
- 0.71 transmittance factor
- $\sigma_{DIFF} = R * 0.45\ \lambda/D$





Max ΔV of Laser on LightSail 2

- 10kw, 1064 nm cw laser
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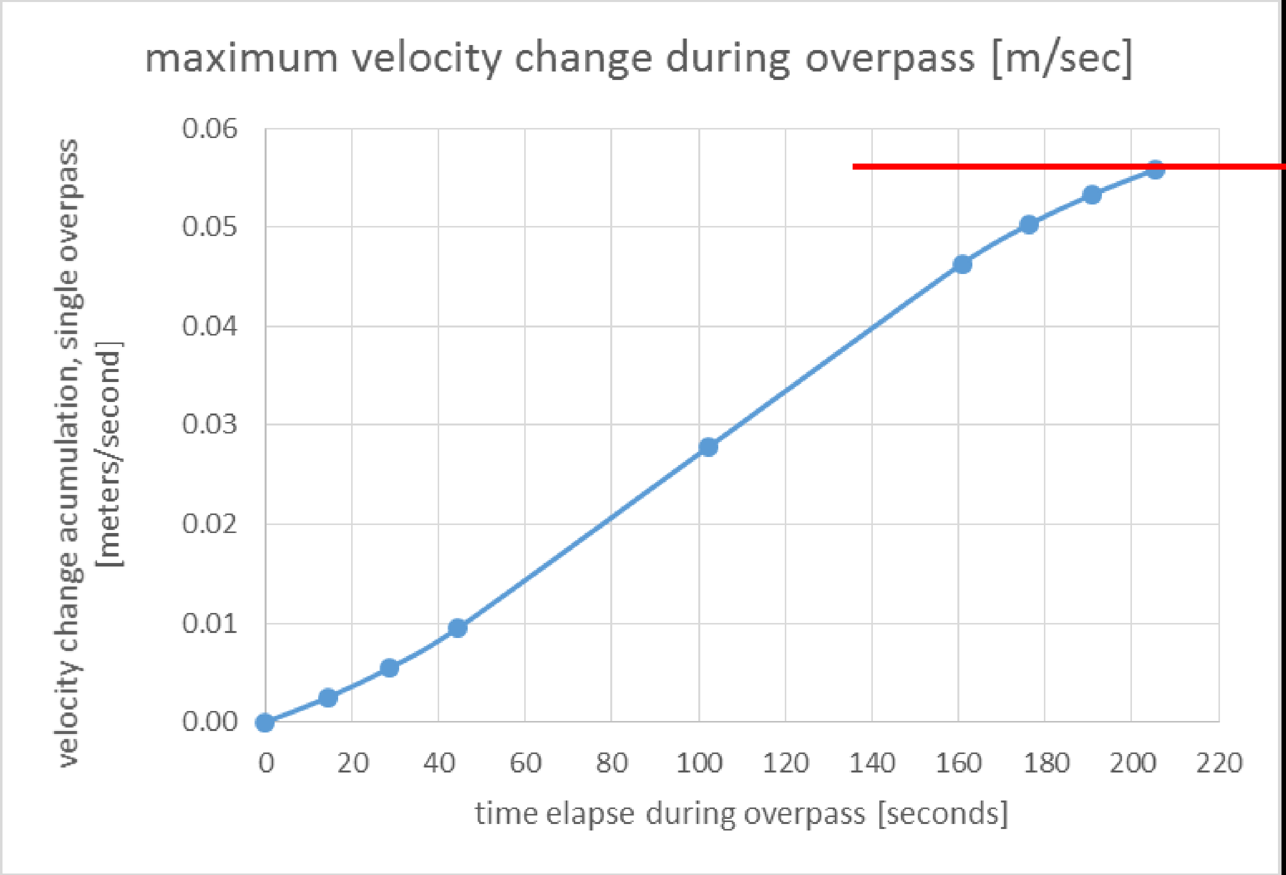

Single overpass max cumulative ΔV = 0.056 m/sec

0.1 m/sec ΔV goal may be exceeded with two or more accesses

An optimum spacecraft attitude program required to achieve max results

AMOS vs. other sites

Site	Laser [1] [watts]	Aperture D [m]	wavelength λ [μm]	mittance τ, ref	Jitter [1] [μ rad]	[watts] at Elevation		(μ N) at Elevation			on 5kg [μ g]	time [sec]	ΔV [mm/sec]
						20 deg	90 deg	20 deg	90 deg	Median			
AMOS, HI	1000	3.67	1.064	0.95	0.1	402	540	2.7	3.6	3.1	0.06	600	0.38
AMOS, HI	180	3.67	11.17	0.99	0.1	131.7	131.8	0.9	0.9	0.9	0.02	600	0.11
AMOS, HI	50	0.2	0.539	0.91	0.1	16	28	0.1	0.2	0.1	0.003	600	0.017
AMOS, HI	10000	0.5	1.064	0.95	3.0	324	436	2.2	2.9	2.5	0.052	600	0.30
AMOS, HI	50000	0.5	1.064	0.95	3.0	1620	2179	10.8	14.5	12.7	0.26	600	1.52
SOR, NM	10000	3.5	1.064	0.88	0.1	4396	5622	29.3	37.5	33.4	0.68	180	1.20
SOR, NM	6000	0.5	1.064	0.88	0.1	3021	3863	20.1	25.8	22.9	0.47	180	0.83
SOR, NM	50	0.2	0.539	0.88	0.1	25.2	32.2	0.2	0.2	0.2	0.004	180	0.007
SOR, NM	50	0.2	1.178	0.88	0.1	25.2	32.3	0.2	0.2	0.2	0.004	180	0.007
WSMR,NM	10000	0.5	1.064	0.95	3.0	324	436	2.2	2.9	2.5	0.05	180	0.09
WSMR,NM	25000	0.5	1.064	0.95	3.0	810	1089	5.4	7.3	6.3	0.13	180	0.23
WSMR,NM	50000	0.5	1.064	0.95	3.0	1620	2179	10.8	14.5	12.7	0.26	180	0.46
RSA, AL	25000	0.5	1.064	0.71	3.0	63	455	0.4	3.0	1.7	0.04	120	0.04
RSA, AL	50000	0.5	1.064	0.71	3.0	250	731	1.7	4.9	3.3	0.07	120	0.08

(1) Contains speculative values when official characteristics are not available

- 3-5X longer accesses
- 70% shorter slant range
- 2-3X more access per day
- 3-6X less attenuation in atmosphere

Calculations assume 100% of delivered laser power is utilized
Sail may be larger than spot at high orbital altitudes.
No reduction for sail attitude/receiving area
Perfect normal reflection from sail assumed
23 km visibility (i.e. clear weather) assumed

2018-2019 Candidate Missions

Orbit Change Determination

- Will utilize available tracking information to build a high precision orbital propagation model including all relevant forces.
- Deviations from expected orbit will indicate the propulsive event from laser
- Analysis can be performed during mission and/or post-mission
- Results may be enhanced by involving additional tracking stations, optical Tracklet data, and select experts.