Orbit Options for Near-Term Space Solar Power

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Presentation to the
Space Power Workshop
Organized by The Aerospace Corporation
Power Systems Architecture Session
April 20, 2021

Based on a presentation of the same title presented at the SPS 2018 Symposium / International Space Development Conference, Los Angeles, CA, May 23-27, 2018

Approved for Public Release

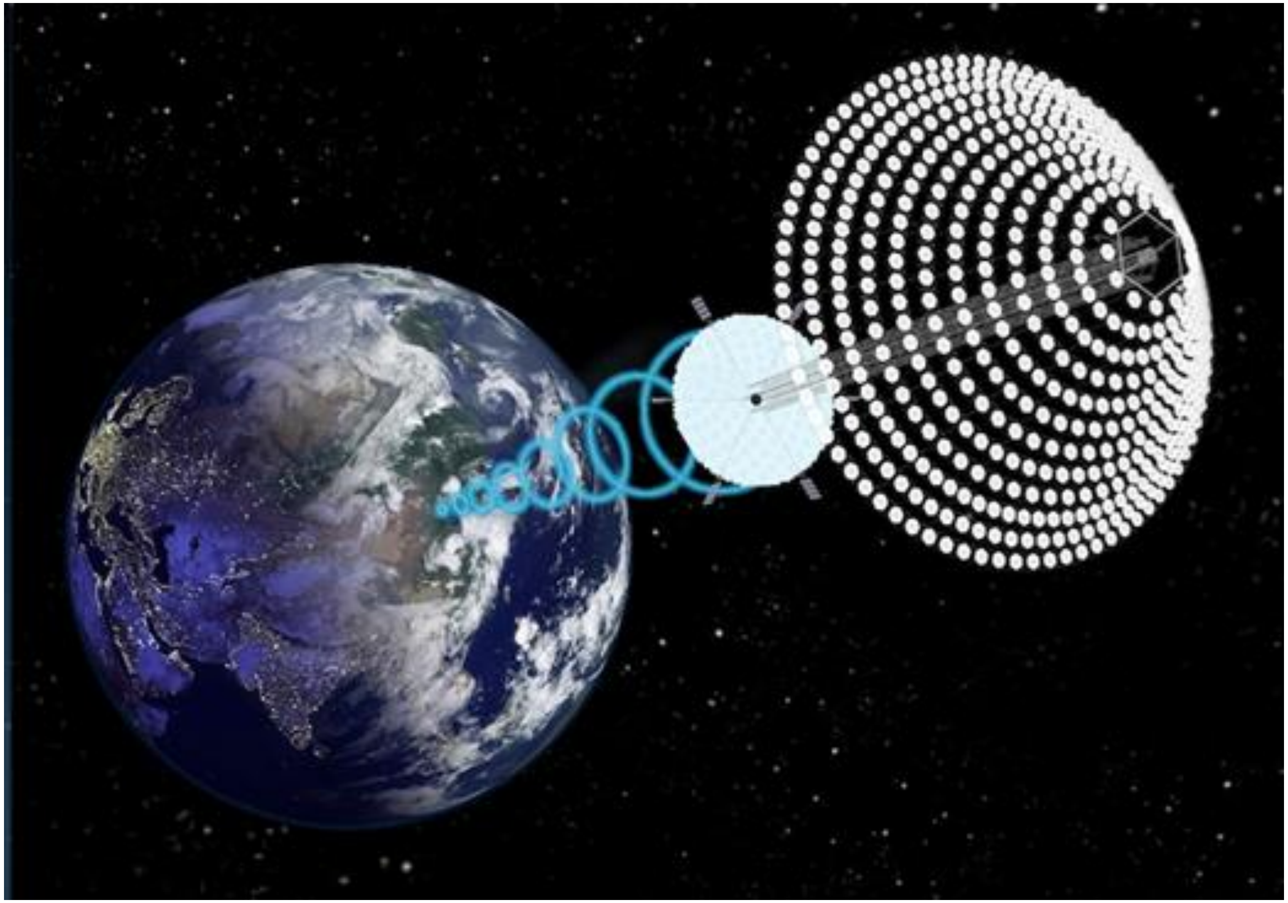
Introduction

- Studies of space solar power (SSP) for the commercial grid have usually considered transmitting power from geostationary orbit (GEO), via microwaves at frequencies below 10 GHz, where the atmosphere is relatively transparent.
- Due to beam divergence from that distance at such frequencies, system sizes must be large, leading to power levels of 1000 MW or more
- The scale of the systems makes competing with traditional energy sources challenging
- Recent studies have considered SSP for nearer-term niche uses in remote locations
- Many remote locations are typically powered by generators, which depend on fuel delivered at great cost, often through hazardous environments.
- Power requirements for such users may range from a few hundred kilowatts to several megawatts.
- Some remote facilities are at high latitudes, which are inaccessible from geostationary orbit, so orbits that are lower, and/or elliptical, will be considered
- Since non-GEO orbits do not remain over their intended ground sites, systems or constellations, of satellites must be designed, in which beam handoffs can provide a given ground site with power much of the time, while making maximum use of the satellites as multiple satellites serve multiple ground sites

Location of Potential Ground User Sites

- The number of potential ground sites is potentially unlimited
- For non-GEO orbits, access is largely independent of longitude
  - Exceptions are sparse constellations of satellites with repeating ground track orbits, particularly elliptical orbits
- Therefore, three ground regions were chosen:
  - Low latitude, within ±10° of the equator
  - Middle latitude, 30° to 35°
  - High latitude, above 60°

SPS ALPHA: Adaptable to Multiple Orbits



- Solar Power Satellite by means of Arbitrarily Large Phased Array (SPS-ALPHA) concept developed by John C. Mankins, Mankins Space Technology, Inc.; image used with permission
- Shown here in GEO, and can be adapted for low and high inclination Low Earth Orbits

Constellation Development Process: Ground Rules and Assumptions

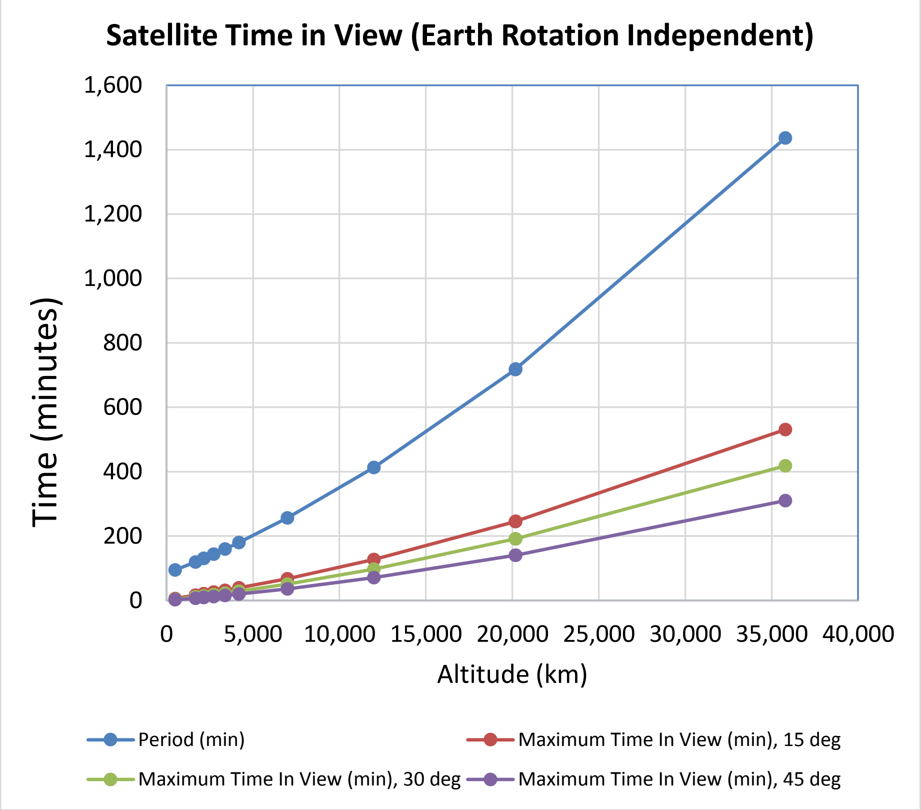
- Performed Excel analysis to estimate access times
  - 15°, 30°, 45° minimum elevation angles considered
  - Assumed 90% coverage duty cycle at ground sites
  - 30° minimum elevation angle selected for further analysis in STK
    - 15° leads to excessive losses due to elongation of beam and increased slant range
    - 45° may be too restrictive in terms of access time, but may be worthwhile, due to lower losses
  - Twelve orbits initially considered
  - Excel model assumes satellite passes directly over ground site, and ignores Earth's rotation
  - Shadowing of satellites not yet considered
- Ran cases for low, middle, and high latitudes
- Orbit propagated for one calendar year starting at vernal equinox of 2028
- 90% coverage duty cycle retained to estimate number of satellites needed

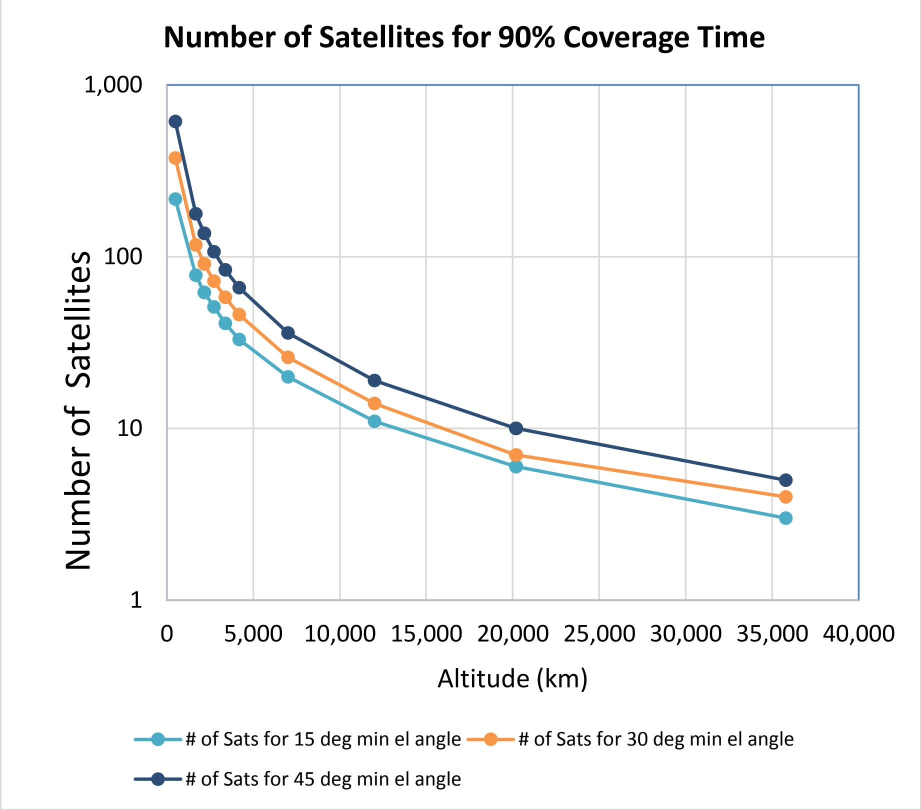
Excel Access Time Analysis

						Excel				Excel		
Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Equivalent Circular Altitude (km)	Inclination (deg)	No. Orbits/Day	Period (min)	Maximu m Time In View (min), 15	Maximu m Time In View (min), 30	Maximu m Time In View (min), 45	# of Sats for 15 deg min el angle	# of Sats for 30 deg min el angle	# of Sats for 45 deg min el angle
LEO	500.0	500.0	500.0	28.50	15.2	94.6	6.0	3.5	2.1	217	375	613
Sun Sync Repeat	1,676.5	1,676.5	1,676.5	102.94	12.0	119.9	16.7	11.1	7.3	78	117	178
LEO ALPHA	2,158.6	2,158.6	2,158.6	28.50	11.0	130.8	20.9	14.3	9.5	62	91	137
Sun Sync Repeat	2,158.6	2,158.6	2,158.6	105.93	11.0	130.8	20.9	14.3	9.5	62	91	137
Sun Sync Repeat	2,719.9	2,719.9	2,719.9	110.06	10.0	143.9	25.9	18.1	12.2	51	72	107
Sun Sync Repeat	3,383.6	3,383.6	3,383.6	116.03	9.0	160.0	31.9	22.7	15.5	41	58	84
CASSIOPeiA	7414.00	963.00	4188.50	116.60	8.0	180.16	39.37	28.51	19.75	33	46	66
Low Van Allen Gap	7,000.0	7,000.0	7,000.0	55.00	5.6	256.7	67.8	50.8	36.1	20	26	36
High Van Allen Gap	12,000.0	12,000.0	12,000.0	55.00	3.5	413.2	127.2	97.6	70.7	11	14	19
Molniya	39,850.50	500.00	20,175.25	63.55	2.0	717.69	245.55	191.36	140.43	6	7	10
GPS	20,200.0	20,200.0	20,200.0	55.00	2.0	718.7	245.9	191.7	140.7	6	7	10
GEO	35,786.0	35,786.0	35,786.0	<1	1.0	1,436.1	531.3	418.6	310.0	3	4	5

- Shadowing not yet considered
- Red numbers indicate that for elliptical orbits, Excel assumed circular orbits having the same semi-major axes, and hence, same periods
  - This will tend to underestimate access times for a location under the apogee
- The Excel estimates for maximum time in view are surprisingly good
  - Will tend to underestimate for prograde orbits, and overestimate for retrograde orbits (that is, inclination >90°)
  - Excel will tend to overestimate the total number of satellites needed to achieve a given duty cycle, because it assumes only one pass per day (though this can be changed by the user)

Excel Access Time Analysis





- Shadowing not yet considered
- For elliptical orbits, used circular orbits having the same semi-major axes, and hence, same periods
  - This will tend to underestimate access times for a location under the apogee of an elliptical orbit
- The Excel estimates for maximum time in view are surprisingly good
  - Will tend to underestimate for prograde orbits, and overestimate for retrograde orbits (that is, inclination >90°)
  - Excel will tend to overestimate the total number of satellites needed to achieve a given duty cycle, because it assumes only one pass per day (though this can be changed by the user)

STK Access Time Analysis for Low Latitudes

						30 deg min el angle, single sat pass						
Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Equivalent Circular Altitude (km)	Inclination (deg)	No. Orbits/Day	Min Time in View (min)	Max Time in View (min)	Avg Time in View (min)	Avg Accesses / Day	Total Access Time / Year (min)	Duty Cycle	# Sats for 30 deg min el angle
LEO	500.0	500.0	500.0	28.50	15.2	0.07	3.66	2.87	2.38	2,487.77	0.005	191
Sun Sync Repeat	1,676.5	1,676.5	1,676.5	102.94	12.0	9.20	10.90	10.09	2.00	7,366.2	0.014	65
LEO ALPHA	2,158.6	2,158.6	2,158.6	28.50	11.0	0.33	15.52	11.25	6.40	26,297.9	0.050	18
Sun Sync Repeat	2,158.6	2,158.6	2,158.6	105.93	11.0	8.03	12.95	10.31	3.00	11,287.4	0.021	42
Sun Sync Repeat	2,719.9	2,719.9	2,719.9	110.06	10.0	0.12	16.21	11.62	3.59	15,227.4	0.029	32
Sun Sync Repeat	3,383.6	3,383.6	3,383.6	116.03	9.0	20.86	21.44	21.15	2.00	15,442.3	0.029	31
CASSIOPeiA	7414.00	963.00	4188.50	116.60	8.0	0.68	19.42	14.64	2.52	13,486.7	0.026	36
Low Van Allen Gap	7,000.0	7,000.0	7,000.0	55.00	5.6	3.65	56.03	44.82	2.61	42,712.2	0.081	12
High Van Allen Gap	12,000.0	12,000.0	12,000.0	55.00	3.5	7.43	114.00	92.93	1.88	63,659.1	0.121	8
Molniya	39,850.50	500.00	20,175.25	63.55	2.0	0.00	0.00	0.00	0.00	0	0.000	N/A
GPS	20,200.0	20,200.0	20,200.0	55.00	2.0	8.13	389.75	231.51	1.04	88,206	0.168	6
GEO	35,786.0	35,786.0	35,786.0	<1	1.0	525,600.0	525,600.0	525,600.0	0.00	525,600	1.000	1

- Shadowing not yet considered

STK Access Time Analysis for Middle Latitudes

						30 deg min el angle, single sat pass						
Orbit Description	**Apogee Altitude (km)**	**Perigee Altitude (km)**	**Equivalent Circular Altitude (km)**	**Inclination (deg)**	**No. Orbits/Day**	**Min Time in View (min)**	**Max Time in View (min)**	**Avg Time in View (min)**	**Avg Accesses / Day**	**Total Access Time / Year (min)**	**Duty Cycle**	**# Sats for 30 deg min el angle**
LEO	500.0	500.0	500.0	28.50	15.2	0.12	2.75	2.13	1.96	1,525.89	0.0029	311
Sun Sync Repeat	1,676.5	1,676.5	1,676.5	102.94	12.0	7.59	10.37	8.65	3.00	9,472.5	0.0180	50
LEO ALPHA	2,158.6	2,158.6	2,158.6	28.50	11.0	0.48	15.11	12.58	3.92	17,969.9	0.0342	27
Sun Sync Repeat	2,158.6	2,158.6	2,158.6	105.93	11.0	6.74	13.14	10.39	4.00	15,175.5	0.0289	32
Sun Sync Repeat	2,719.9	2,719.9	2,719.9	110.06	10.0	0.19	17.04	13.79	3.21	16,138.1	0.0307	30
Sun Sync Repeat	3,383.6	3,383.6	3,383.6	116.03	9.0	9.90	20.99	17.03	4.00	24,865.6	0.0473	20
CASSIOPeiA	7414.00	963.00	4188.50	116.60	8.0	0.70	41.44	34.41	5.40	67,855.8	0.1291	7
Low Van Allen Gap	7,000.0	7,000.0	7,000.0	55.00	5.6	7.35	56.50	49.30	3.14	56,451.0	0.1074	9
High Van Allen Gap	12,000.0	12,000.0	12,000.0	55.00	3.5	2.09	118.41	102.80	1.97	74,019.1	0.1408	7
Molniya	39,850.50	500.00	20,175.25	63.55	2.0	660.73	660.73	660.73	1.00	241,826.4	0.4601	2
GPS	20,200.0	20,200.0	20,200.0	55.00	2.0	6.05	321.05	229.38	1.11	92,668.6	0.1763	6
GEO	35,786.0	35,786.0	35,786.0	<1	1.0	525,600.0	525,600.0	525,600.0	0.00	525,600.0	1.0000	1

- Shadowing not yet considered

STK Access Time Analysis for High Latitudes

					30 deg min el angle, single sat pass						
Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Inclination (deg)	No. Orbits/Day	Min Time in View (min)	Max Time in View (min)	Avg Time in View (min)	Avg Accesses / Day	Total Access Time / Year (min)	Duty Cycle	# Sats for 30 deg min el angle
LEO	500.0	500.0	28.50	15.2	0.00	0.00	0.00	N//A	0.00	0.0000	N/A
Sun Sync Repeat	1,676.5	1,676.5	102.94	12.0	5.87	10.97	9.23	7.00	23,587.5	0.0449	21
LEO ALPHA	2,158.6	2,158.6	28.50	11.0	0.00	0.00	0.00	N//A	0.00	0.0000	N/A
Sun Sync Repeat	2,158.6	2,158.6	105.93	11.0	11.54	14.06	13.02	6.00	28,506.2	0.0542	17
Sun Sync Repeat	2,719.9	2,719.9	110.06	10.0	11.71	17.45	15.58	6.00	34,123.2	0.0649	14
Sun Sync Repeat	3,383.6	3,383.6	116.03	9.0	8.00	21.75	18.27	5.00	33,336.7	0.0634	15
CASSIOPeiA	7414.00	963.00	116.60	8.0	1.69	54.72	45.61	5.52	91,818.4	0.1747	6
Low Van Allen Gap	7,000.0	7,000.0	55.00	5.6	3.34	52.88	42.74	2.97	46,331.9	0.0882	11
High Van Allen Gap	12,000.0	12,000.0	55.00	3.5	3.92	107.90	84.86	2.11	65,428.7	0.1245	8
Molniya	39,850.50	500.00	63.55	2.0	130.41	551.70	479.75	2.01	351,654.4	0.6691	2
GPS	20,200.0	20,200.0	55.00	2.0	8.82	234.16	185.40	1.23	83,242.7	0.1584	6
GEO	35,786.0	35,786.0	<1	1.0	0.00	0.00	0.00	N//A	0.00	0.0000	N/A

- Shadowing not yet considered

Satellite Shadowing Analysis (1 of 2)

- Shadowing analysis is complicated by the fact that shadowing is often seasonally-varying
- 500 km, 28.5° LEO orbit, shadowing time per orbit is roughly 28 to 36 minutes, with 35 minutes being typical; this is 37% of the 94.6-minute period
- LEO ALPHA 2158.6 km, 28.5°: time in shadow typically runs from about 27 minutes through about 35 minutes. Since the satellite has a 131 minute period, the maximum shadowing time would be at most 27%, often less, so a 25% estimate is reasonable
  - Minimum shadowing time is zero -- that is, there are periods of several days in which the satellite is never in shadow.
  - Shadowing of the satellite by the Moon occurs occasionally

Satellite Shadowing Analysis (2 of 2)

- A previous study (Potter and Davis, 2009[1]) has shown that the sun-synchronous repeating ground track orbits for the 10, 11, and 12 orbit/day cases are in sunlight continuously, and the 9 orbit/day case is in sunlight continuously, except for a few minutes/day during December
  - This assumes that the ground track is over the terminator. Other orientations of the line of nodes will result in shadowing, typically 35 minutes/orbit
- A satellite in equatorial circular GEO will be in shadow for up to 72 minutes/day within a few weeks of the equinoxes, around midnight local time
  - Analysis for the year under consideration also shows three incidences of a GEO SPS being in the Moon's penumbra for up to 67 minutes

[1] Potter, Seth, and Davis, Dean, "Orbital Reflectors for Space Solar Power Demonstration and Use in the Near Term," AIAA Space 2009 Conference and Exposition, 14-17 September 2009, Pasadena, CA, paper no. AIAA-2009-6675.

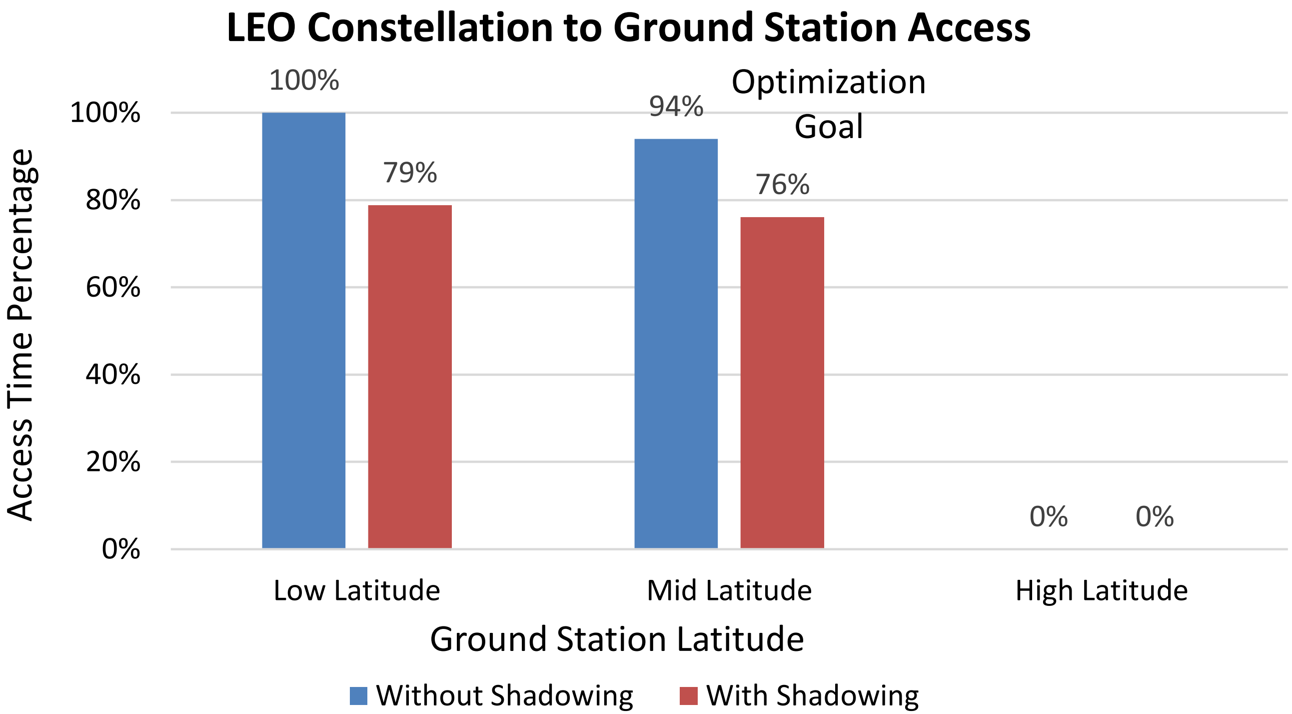
Downselection of Orbits for Constellation Analysis

- The orbits shaded in green span the trade space of reasonable solutions, and will be subjected to further analysis for constellation configuration; i.e., number of orbital planes, number of satellites per plane, and phasing of satellites between planes
  - Only one plane need be considered for GEO
  - Very low LEO requires too many satellites to achieve a high duty cycle early operating capability; such satellites are in shadow during a higher percentage of their orbital period than satellites in higher orbits
  - Molniya orbits, while possibly desirable for high-latitude locations, are constrained by a high apogee
    - System sizes will likely be similar to GEO SPS's
    - CONOPS may be similar to SPS's in the CASSIOPeiA orbit
    - Therefore, detailed separate consideration for Molniya may not be necessary

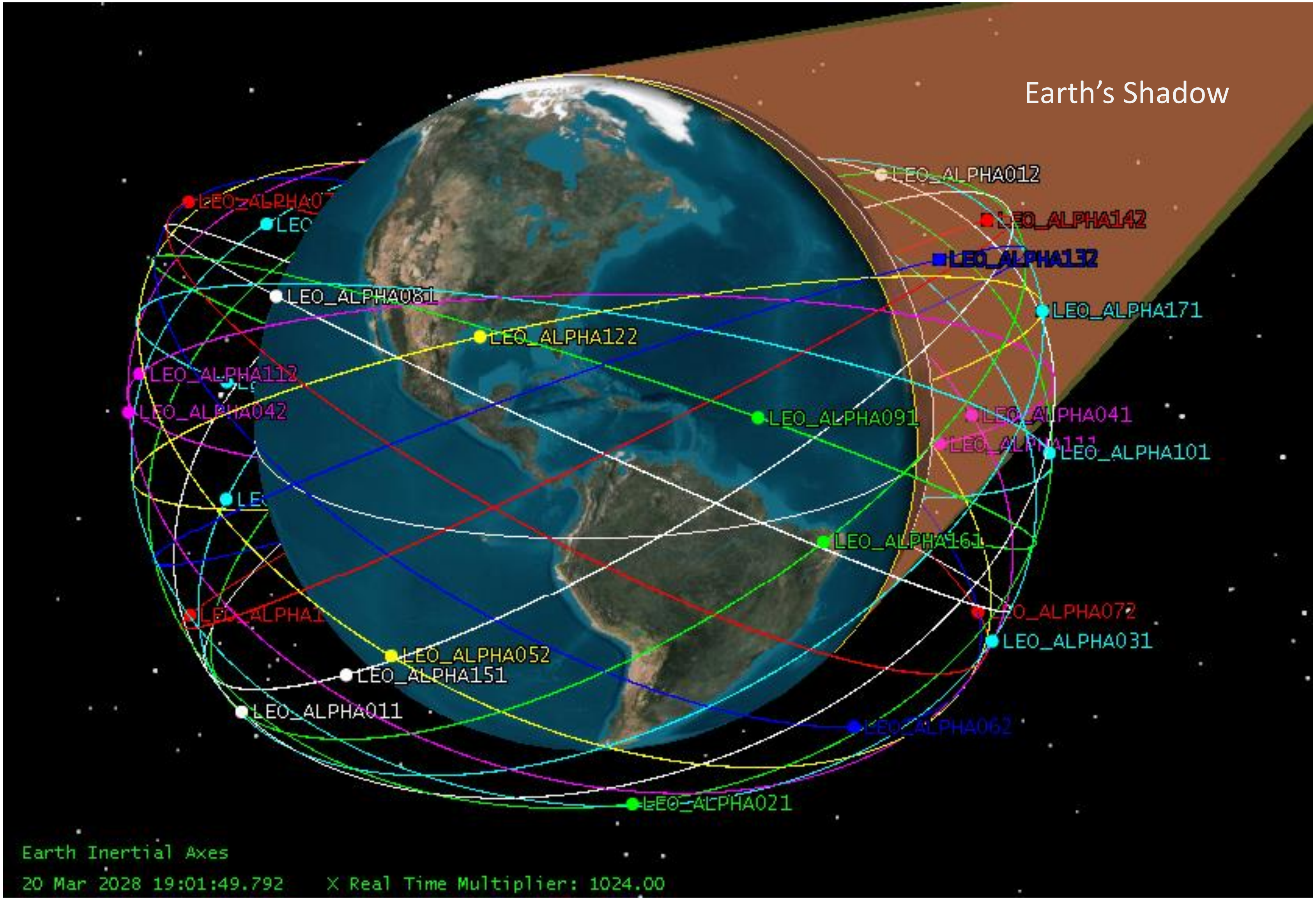
Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Inclination (deg)	No. Orbits/Day	Period (min)
LEO	500.0	500.0	28.50	15.2	94.6
Sun Sync Repeat	1,676.5	1,676.5	102.94	12.0	119.9
LEO ALPHA	2,158.6	2,158.6	28.50	11.0	130.8
Sun Sync Repeat	2,158.6	2,158.6	105.93	11.0	130.8
Sun Sync Repeat	2,719.9	2,719.9	110.06	10.0	143.9
Sun Sync Repeat	3,383.6	3,383.6	116.03	9.0	160.0
CASSIOPeiA	7414.00	963.00	116.60	8.0	180.16
Low Van Allen Gap	7,000.0	7,000.0	55.00	5.6	256.7
High Van Allen Gap	12,000.0	12,000.0	55.00	3.5	413.2
Molniya	39,850.50	500.00	63.55	2.0	717.69
GPS	20,200.0	20,200.0	55.00	2.0	718.7
GEO	35,786.0	35,786.0	<1	1.0	1,436.1

LEO ALPHA: Constellation Development

- **Orbital parameters**
  - Altitude = 2158.6 km
  - Inclination = 28.5°
  - Eccentricity = 0 (circular)
- **Constellation**
  - Type: Walker Delta with 360° spread in Right Ascension of Ascending Node (RAAN)
  - **Number of satellites: 34**
  - Number of orbital planes: 17 (hence, 2 satellites per plane)
  - Phase factor: 3 (thus, true anomaly difference between adjacent satellites in adjacent planes is 3 x 360°/34 = 31.76°
  - Walker notation: i:t/p/f = 28.5°:34/17/3

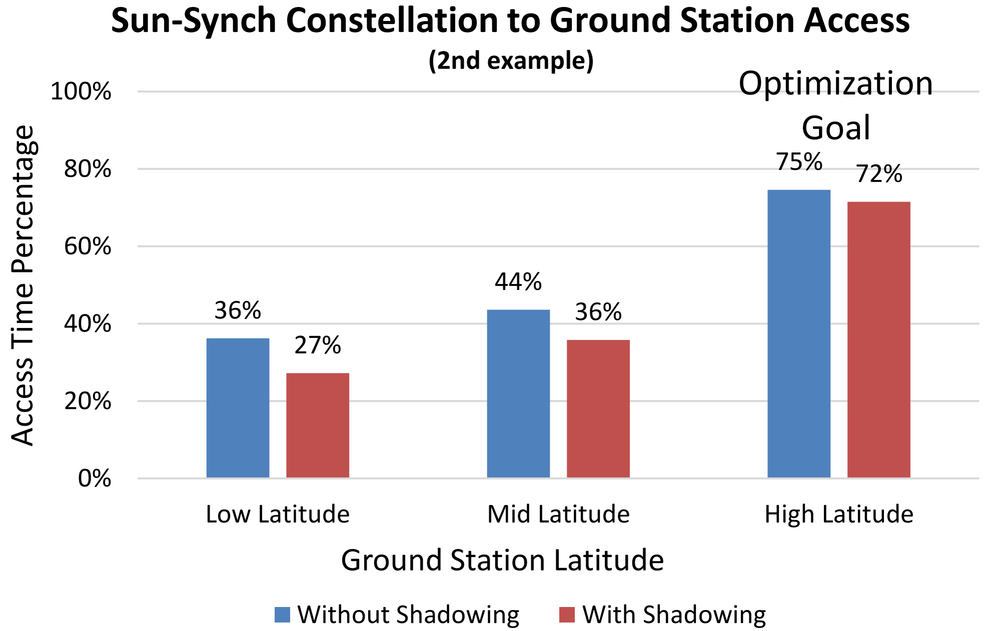


LEO ALPHA: Constellation Development

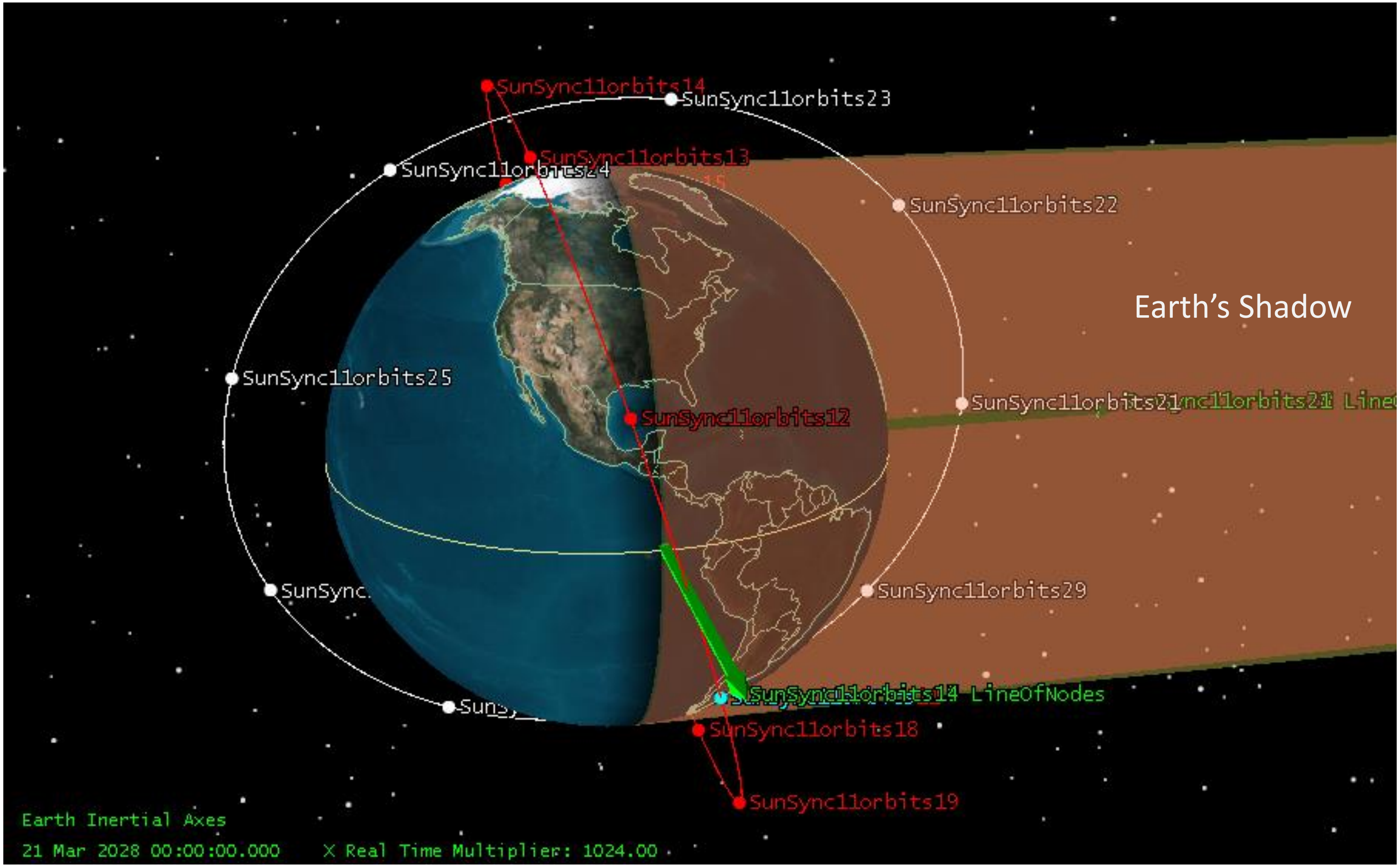


Sun-Synch 11 Orbits/Day: Constellation Development

- **Orbital parameters**
  - Altitude = 2158.6 km
  - Inclination = 105.93°
  - Eccentricity = 0 (circular)
  - Position of initial (seed) orbit: Right Ascension of Ascending Node (RAAN) = 90° at the vernal equinox; thus, initial orbit is around the day-night terminator, though the other plane in the constellation will be around the 12 midnight – 12 noon circle
- **Constellation**
  - Type: Walker Delta, with 180° RAAN spread
  - **Number of satellites: 18**
  - Number of orbital planes: 2 (hence, 9 satellites per plane)
  - Phase factor: 1 (thus, true anomaly difference between adjacent satellites in adjacent planes is 1 x 360°/18 = 20°
  - Walker notation: i:t/p/f = 105.93°:18/2/1



Sun-Synch 11 Orbits/Day: Constellation Development

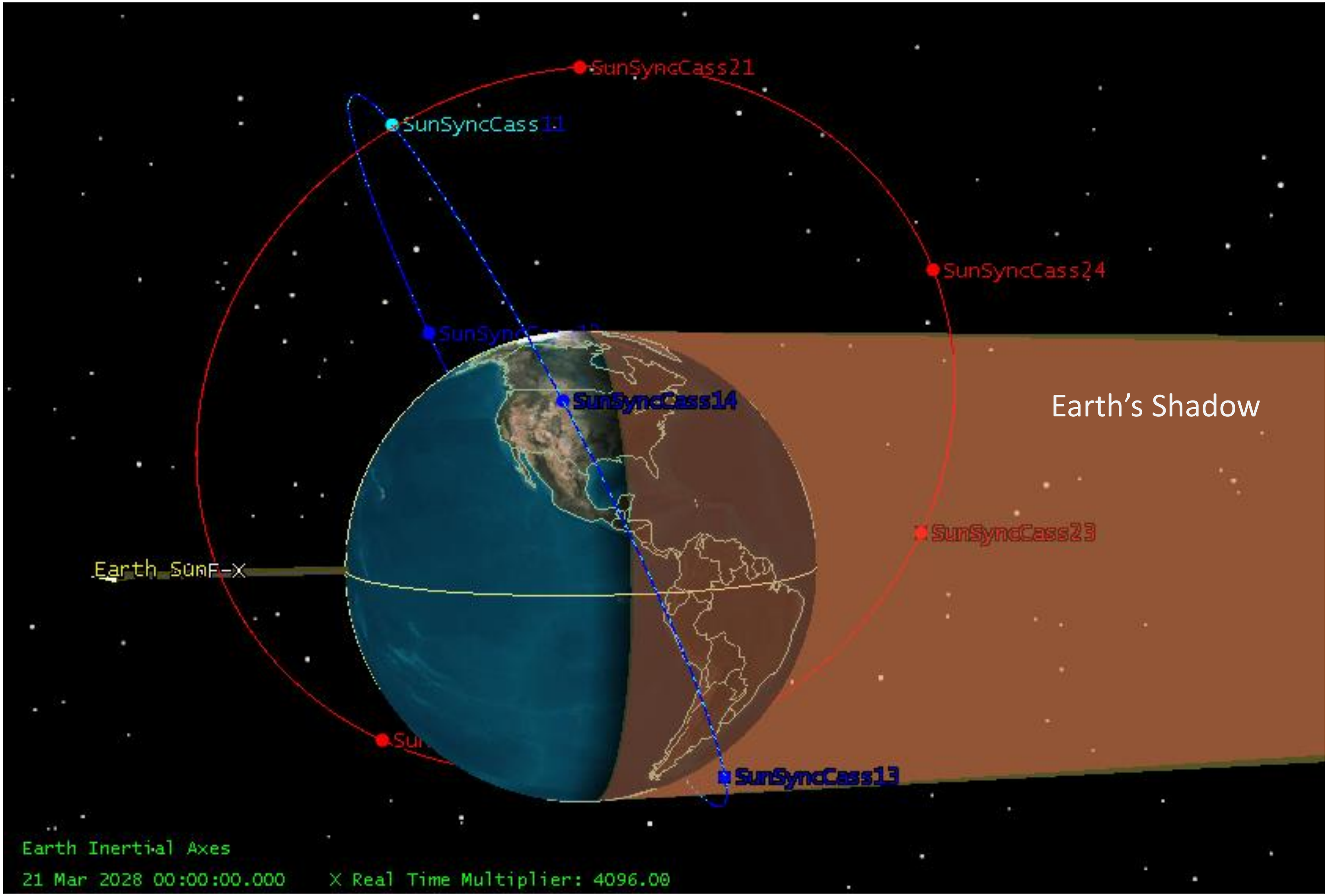


CASSIOPeiA Orbit: Constellation Development

- Orbit proposed by Ian Cash for CASSIOPeiA Solar Power Satellite
- Orbital parameters
  - Apogee = 7,414 km
  - Perigee = 963 km
  - Inclination = 116.6°
  - Argument of Perigee = 270°, hence, apogee is over northern hemisphere
  - Eccentricity = 0.305
- Constellation
  - Type: Walker Delta, with 180° RAAN spread
  - Number of satellites: 8
  - Number of orbital planes: 2 (hence, 4 satellites per plane)
  - Phase factor: 1 (thus, true anomaly difference between adjacent satellites in adjacent planes is 1 x 360°/8 = 45°
  - Walker notation: i:t/p/f = 116.6°:8/2/1
  - Note: May also consider a 5-satellite, 5-plane constellation, as per Ian Cash's paper

Analysis in Progress

CASSIOPeiA Orbit: Constellation Development



Conclusions

- Preliminary results have validated a methodology to span the trade space of satellite orbits and ground sites, and provide a reasonable estimate of the number of satellites required to achieve a required rectenna contact time duty cycle
- The solution space is sufficient to map on to several promising SPS concepts
- Coverage gaps may be filled by more satellites, energy storage on the ground, energy storage onboard the satellites, or some combination of these
- A comparative cost analysis can give insight into the proposed systems

Acknowledgments

The author would like to thank the following:

- Ms. RuthAnne Darling and Dr. Paul Jaffe for guidance and recommendations
- The Aerospace Corporation for the opportunity to present to this Workshop
- Dr. Paul Jaffe and Mr. John C. Mankins for system concept development
- Mr. John C. Mankins and Mr. Gary Barnhard for the opportunity to present in the SPS 2018 Symposium / International Space Development Conference, Los Angeles, CA, May 23-27, where a version of this presentation was first given