SPS STATION KEEPING USING SOLAR RADIATION PRESSURE FOR PROPULSION

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ETI Emerald Telecommunications International Inc.

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Brief Introduction

- This study examines the use of Redirected Solar Radiation Pressure (RSRP) as an approach to Station Keeping
  for Solar Power Satellites (SPS)
  in Geo-Stationary Orbit (GEO), or near-GEO Geo-Synchronous Orbit (GSO).

- RSRP (colloquially referred to as “Solar Sailing”) involves the intentional redirection of incident solar radiation by reflection (or refraction) in a controlled direction so as to effect changes in the satellite orbit.

Background: SPS Motivation

Why SPS?

The Solar Power Satellite (SPS) concept proposes to tap the vast supply of solar energy available in space and to provide that energy to Earth based consumers (while having a negligible environmental impact).

SPS offers the potential to significantly reduce humanity's production of CO_2, by offsetting other Earth-based power-producing technologies which emit carbon dioxide.

Note the potential scale: SPS could be a significant contributor, possibly even the dominant contributor, to the future world energy supply.

Background: RSRP Motivation

Why RSRP?

Given that an SPS will by subject to significant Solar radiation pressure in any case, why not take advantage of the Solar radiation pressure as an approach to station keeping?

- thereby eliminating the need for propellant (reducing operational costs),
- and incidentally, providing an indefinite operational lifetime.

Background: Scale of RSRP

- The effect of Solar Radiation Pressure is best characterised by the cross-section to mass ratio, σ, or equivalently from the domain of Solar sailing by the "Lightness number".

Case		σ m^2/kg	Lightness Number *(dimensionless)*	Effect of Solar Radiation Pressure
Optically inert object		0.00	0	none
Typical Communications Satellite	low	0.01	0.000008	Orbit perturbation
	high	0.10	0.00008	
NASA SPS circa 1980 (est.)		0.44	0.0003	
SPS Alpha circa 2014 (est.)		0.73	0.0006	
Generic 1 GW SPS with RSRP		1.42	0.0011	
Solar Sail	8 g/m^2	130	0.1	Practical near-future Solar Sailing
	< 1 g/m^2	1300	1 (or greater)	Fanciful science fiction

Main message:

- RSRP is several orders of magnitude below "true Solar sailing".
- An SPS (even without RSRP) will be subject to significant Solar radiation pressure effects.

Study Scope

- For this study we used the SPS-alpha design as a basis of estimate for selected performance parameters (primarily SPS mass).

- Otherwise, this study is nominally “architecture-agnostic” such that the results should be applicable to any SPS architecture.

- SPS attitude control is not addressed in this study.
  It is likely that an RSRP based SPS attitude control strategy would be significantly dependent on the SPS architecture: in particular, ensuring that the redirected solar radiation does not impact other surfaces of the SPS.

- No effort was made to optimize the performance of the RSRP Station Keeping strategies.

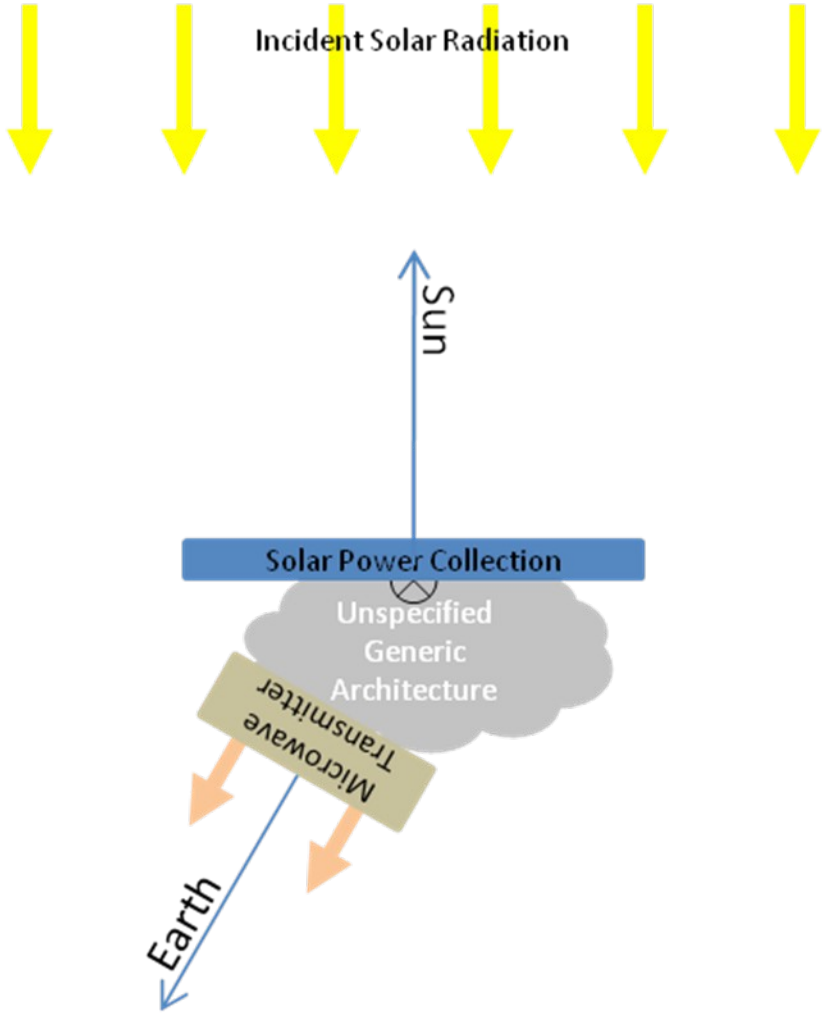
Generic 1 GW SPS Baseline …

Nominally based on SPS-Alpha:

- 1 GW power at Ground Station output.
- SPS mass (excluding station keeping) at 4.4 kg/kW: 4400 Mg.

Derived:

- effective cross section to mass ratio, σ, of: 0.73

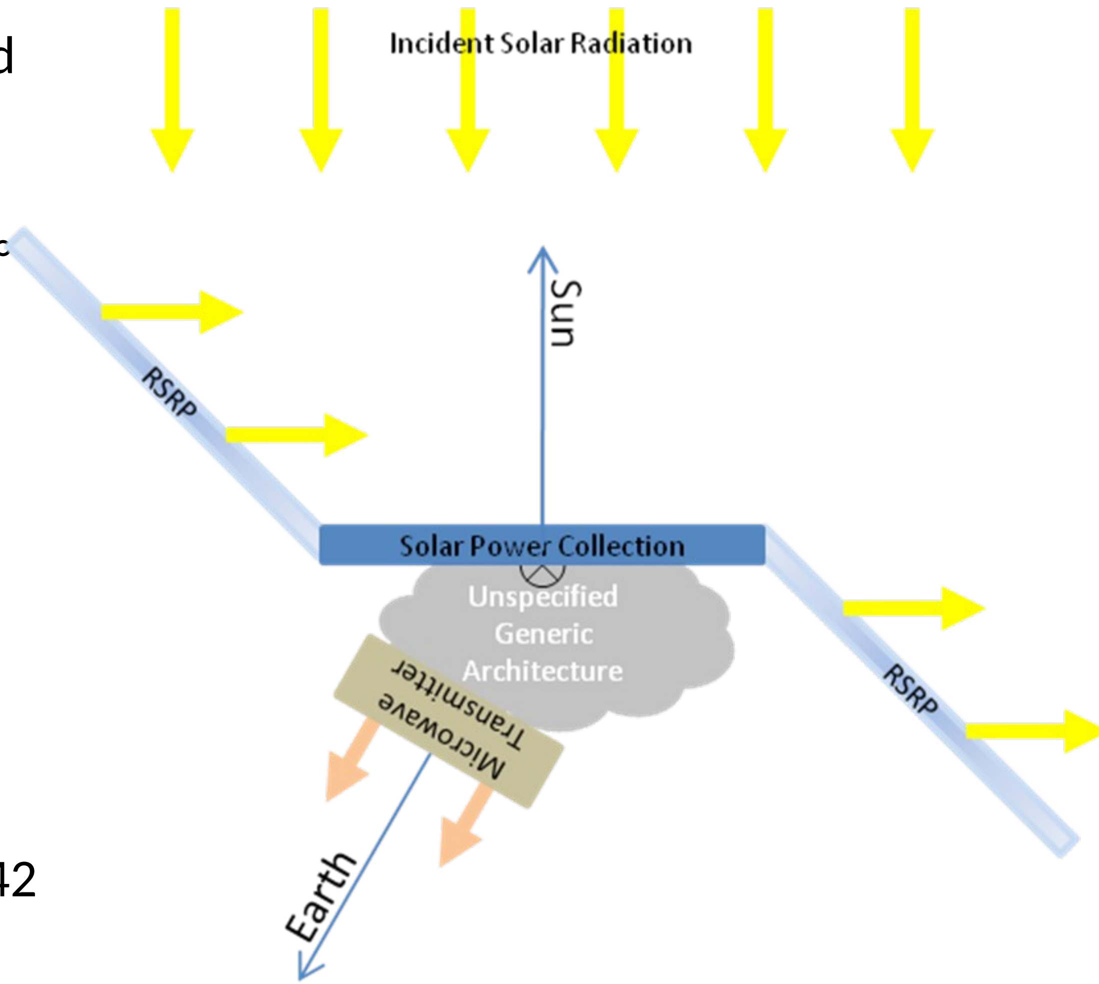


... SPS Baseline with RSRP

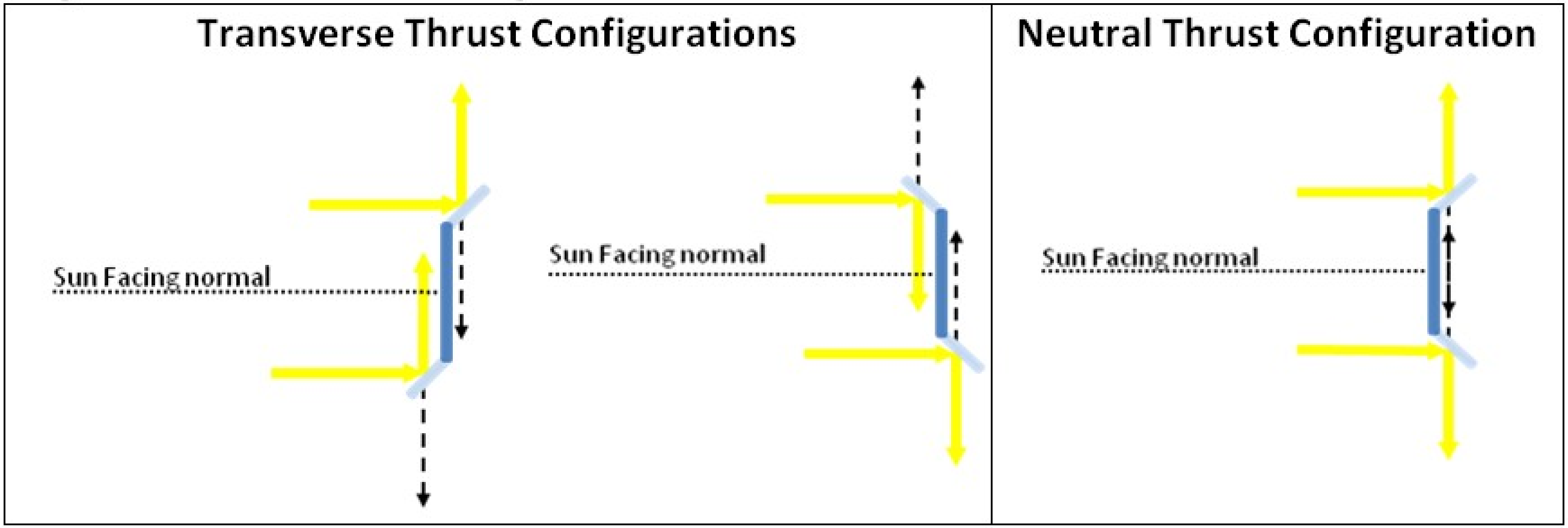
- 1 GW power at Ground Station output.
- RSRP Solar radiation Angle of Incidence: 45°
- RSRP thrust capability: 0.00000402 m/s^2 (4.02×10^{-6} m/s^2).

Derived:

- SPS mass (including RSRP station keeping): 6565 Mg.
- effective cross section to mass ratio, σ, of: 1.42



RSRP Thrust Configurations



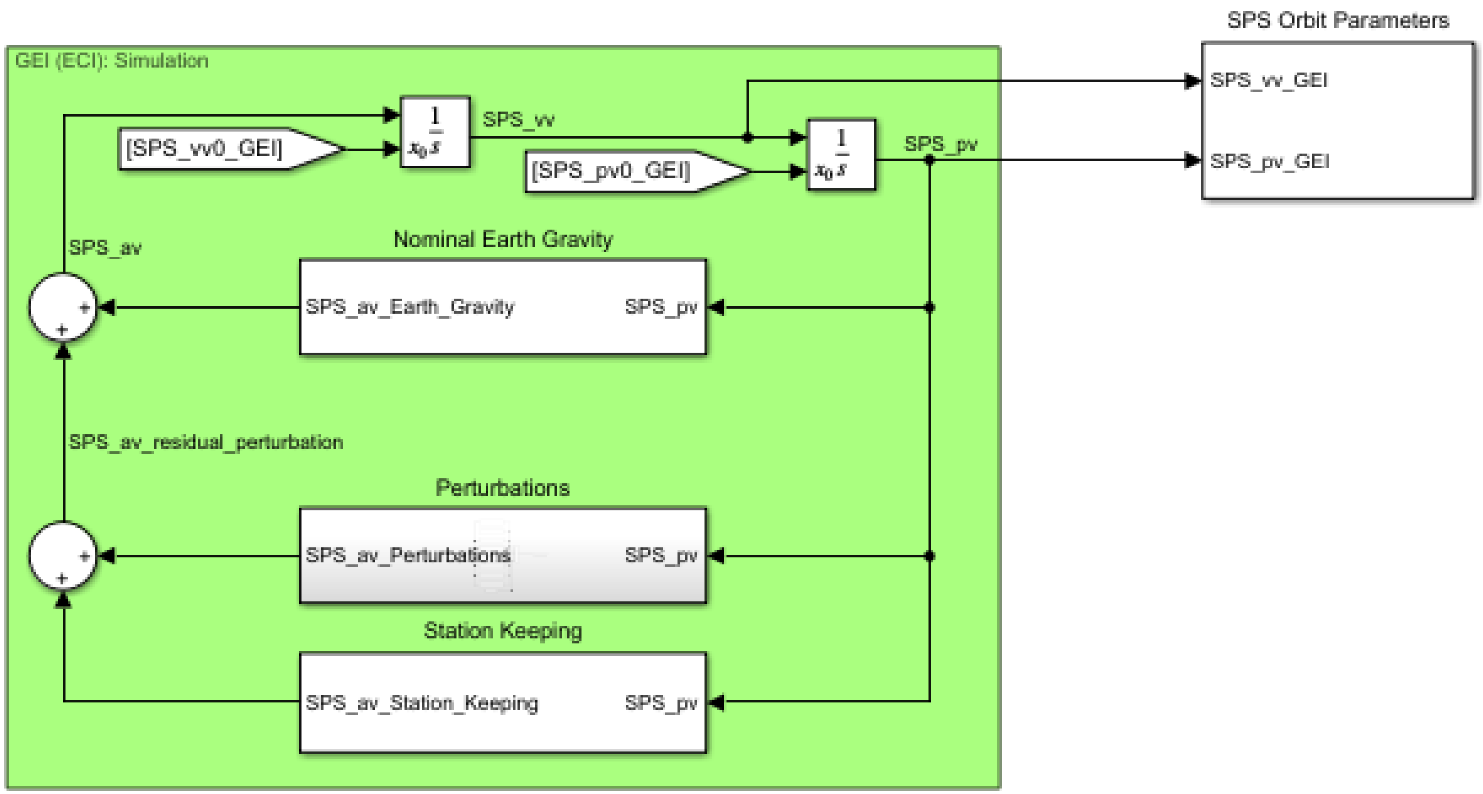
- Perpendicular to incident Solar Radiation oriented in-plane or out-of-plane (i.e., relative to SPS orbit plane).

- Maintaining constant Solar radiation angle of incidence for thermal considerations.
- Thrust configuration changes (at a minimum) every six hours.

Study Approach:
Simulation corroborated by analysis

Main Simulation Integration Loop

- Matlab SimuLink R2021b



Simulation Details

Simulations were performed:

- in the GEI frame of reference (Geocentric Equatorial Inertial),
- using numerical integration in terms of position, velocity, and acceleration (also known as Cowell's method).

Integration Algorithm:

- Runge-Katta with a fixed step size (Matlab Ode4),
- typically 19 simulated years using a 2 seconds step size,
- producing 2.5GB/simulated year.

Note, the longest periodic effect of interest is the 18.6 year period of the precession of the line-of-nodes of the Lunar orbit.

Perturbation Modeling

- Solar gravity
- Lunar gravity
- Solar Radiation Pressure (constant, ignored $1/r^2$)
- Thermal Re-radiation
- Non-spherical-Earth (NSE) gravity, “aspherical geopotential”, modeled as constants per Soop (page 71 and Table 2 pages 287 through 292),
  - valid near GEO,
  - specifically “J2” effects limited to near 0° inclination.
- Microwave Power Beam thrust

An embedded Sun-Earth-Moon (SEM) Model provides context for Solar gravity, Lunar gravity, Solar radiation pressure (and thermal re-radiation) perturbation modeling.

Perturbation Effects

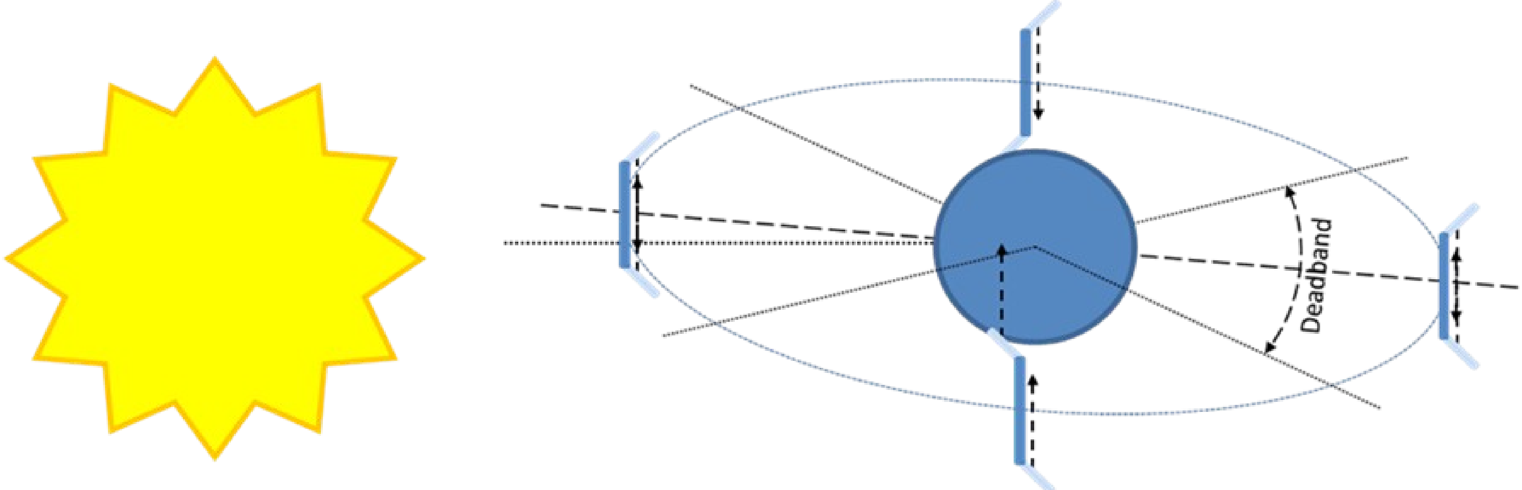
- Simulation confirms that perturbation effects are substantively decoupled

Perturbation	Effect
Solar and Lunar gravity	Orbit inclination growth
NSE gravity	Orbit inclination precession (not incorporated in simulation)
Solar Radiation Pressure	Eccentricity and Eccentricity vector circle
Thermal Re-radiation	Eccentricity and Eccentricity vector circle (beneficial – can be engineered to slightly oppose solar radiation pressure)
NSE gravity	Longitude drift
Power Beam thrust	Longitude drift (beneficial – can be used to oppose NSE gravity)

- Station Keeping control strategy development
  - NSSK: Orbit inclination control
  - EWSK: Eccentricity control (with orbit inclination control active)
  - EWSK: Longitude drift control (with orbit inclination and eccentricity control active)

NSSK: Orbit Inclination Control

Looking somewhat “edge-on” to the Earth equatorial plane:



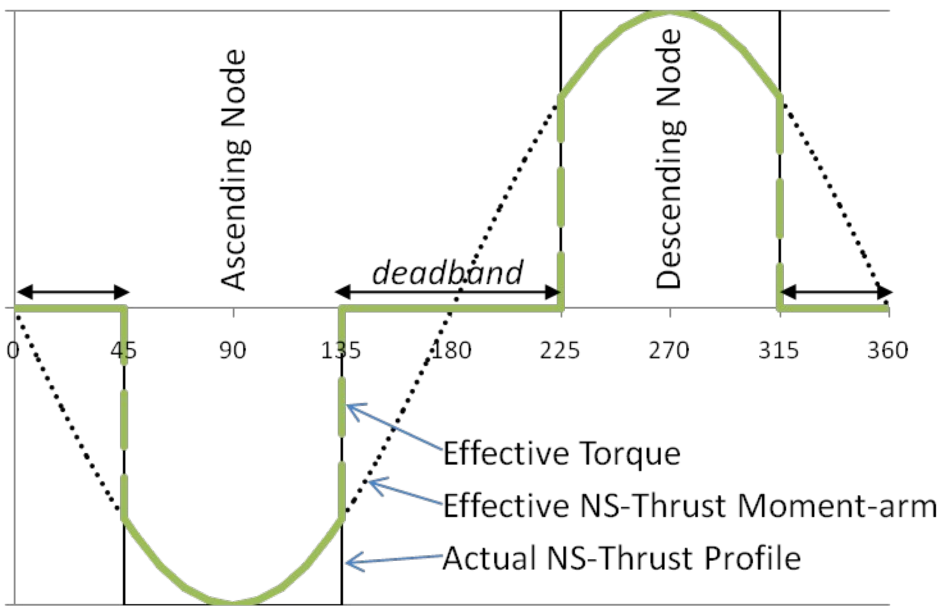
Strategy:

- Continuous constant thrust “north” (+z-axis) near the descending node.
- Continuous constant thrust “south” (-z-axis) near the ascending node.
- Neutral thrust in the deadband.

NSSK: Continuous Thrust and Deadband Effects

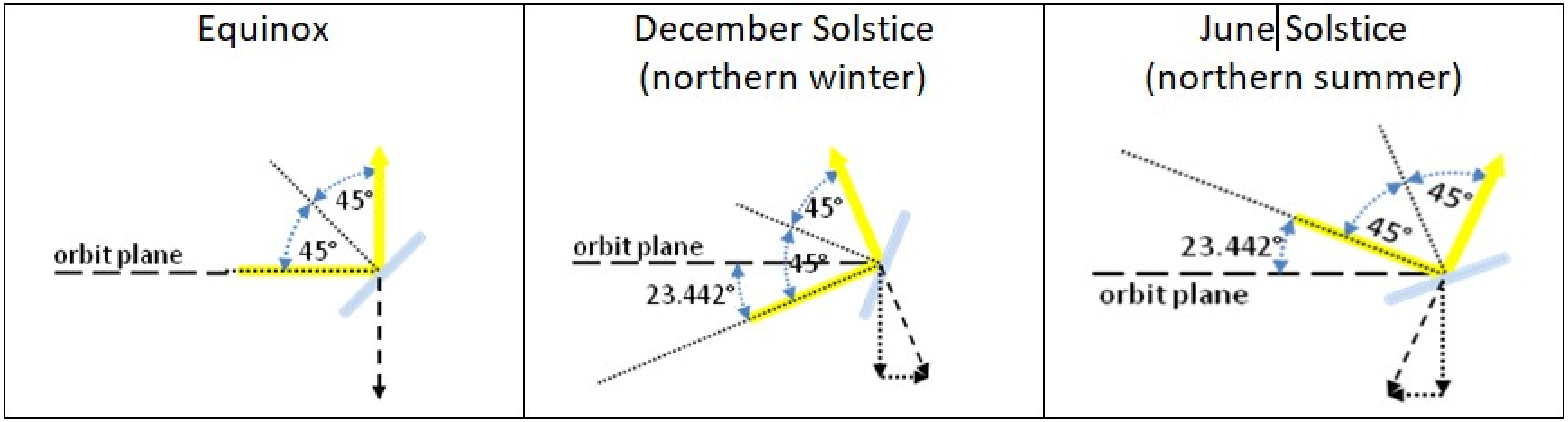
- RSRP provides a continuous thrust over an extended period of time. Therefore the RSRP thrust is less effective than an ideal instantaneous ΔV.
  Part of the RSRP thrust causes precession rather than reduced inclination.

- A control deadband prevents “wasted” thrust when it would produces precession more so than inclination reduction
  (and the RSRP can be used for in-plane control while in the deadband).



Thrust Profile

NSSK: Earth’s Obliquity Effect



- Unique to RSRP.

- Out-of-plane thrust reduced to 91.7% of nominal (i.e., cos(23.442°)) at solstices (for the Solar radiation angle of incidence of 45° case).
- Time-weighted annual average thrust reduced to 95% of nominal.

NSSK: Derivation of Required Specific-Thrust Capability

- Based on combined effects (and preliminary simulation results) … derive the required specific-thrust … for NSSK.

An instantaneous orbit change thrust strategy performed with (one or more) instantaneous orbit changes at the ascending or descending nodes would require a ΔV given by: $orbit\ velocity * (2 * \sin(inclination/2))$. (The nominal GEO orbit velocity is 3074.70 m/s.)	ΔV: 48.2 m/s/year	(0.00000153 m/s^2)
A constant thrust strategy factor of $\pi/2$	ΔV: 75.7 m/s/year	0.00000240 m/s^2
A 45° control dead-band factor of $1/\cos 45°$	ΔV: 53.5 m/s/year	0.00000339 m/s^2
Earth Obliquity factor $1/0.95$		0.00000357 m/s^2

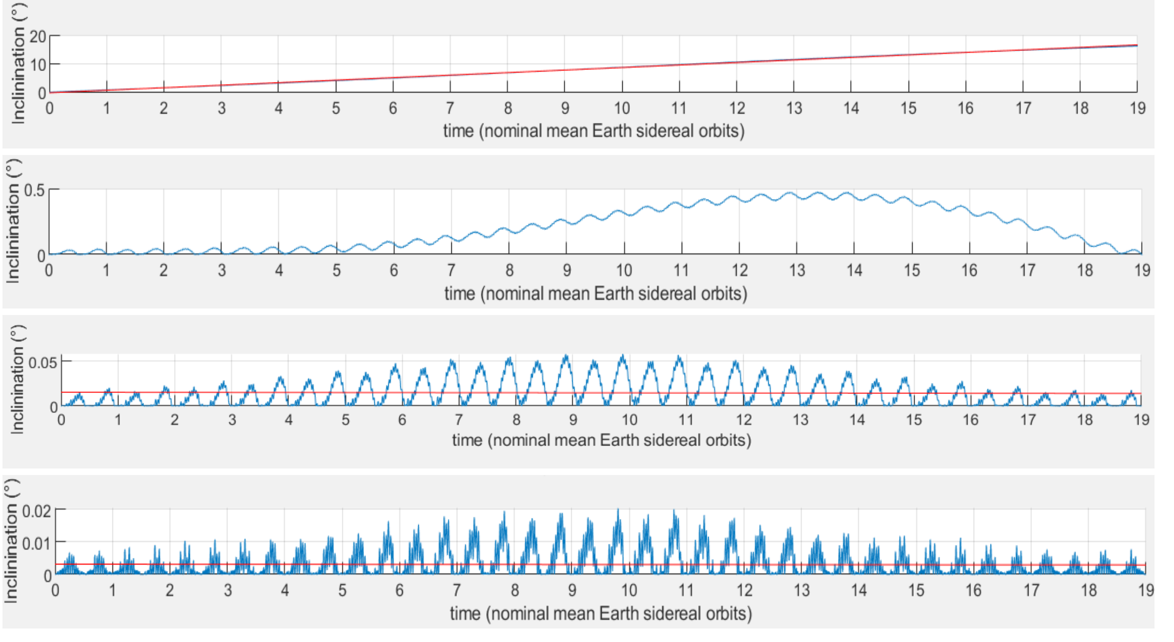
Minimum inclination control specific-thrust required	0.00000357 m/s^2
Generic 1 GW SPS Baseline RSRP specific-thrust capability	0.00000402 m/s^2

NSSK: Orbit Inclination Control

Simulated orbit inclination growth over a 19 year period (i.e., spanning the 18.6 year period of the precession of the line-of-nodes of the Lunar orbit).

Out-of-plane control thrust:

- No control
- 0.00000357 m/s^2
- 0.00000402 m/s^2
- 0.00000500 m/s^2



EWSK: Eccentricity Control

Helpful background (it is helpful to be familiar with):

- eccentricity vector
- “eccentricity vector circle”
- “natural eccentricity”
  also “proper eccentricity”, “free eccentricity”, and “forced eccentricity”.

Background: Eccentricity Vector Circle

Solar radiation pressure naturally changes any orbit according to a cyclical pattern with a period of one year.

There are two particular cases of interest …

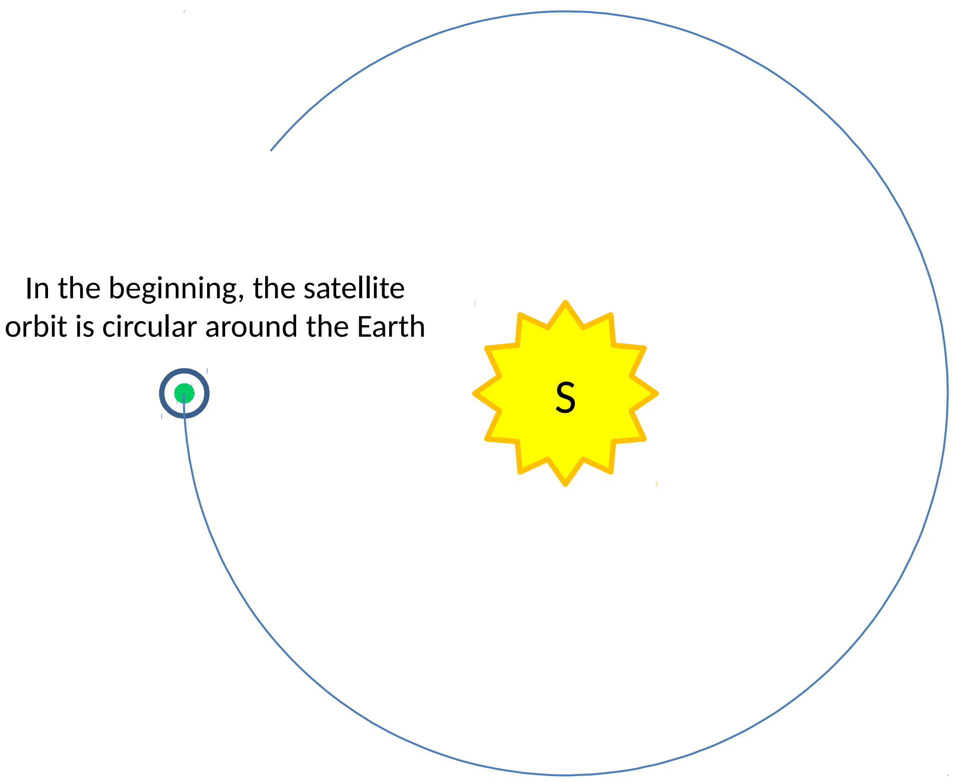
- starting with a circular orbit (the usual case for a small satellite)
- starting with the "natural eccentricity" orbit.

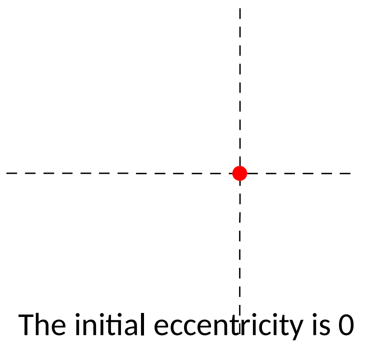
a circular Orbit

- Solar radiation pressure aggregate effects starting with a circular orbit …

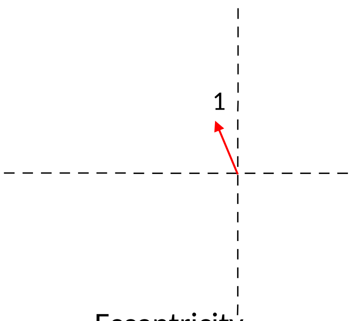
- which implies that the so-called “forced-eccentricity” is exactly opposite of the initial “free eccentricity” (or “proper eccentricity”, or “natural eccentricity”).

Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

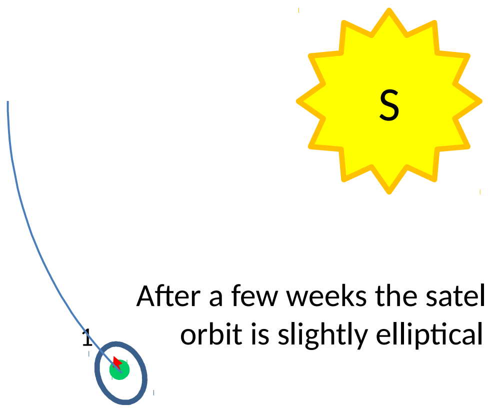




Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

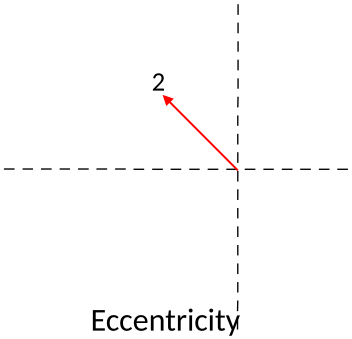


Eccentricity increases

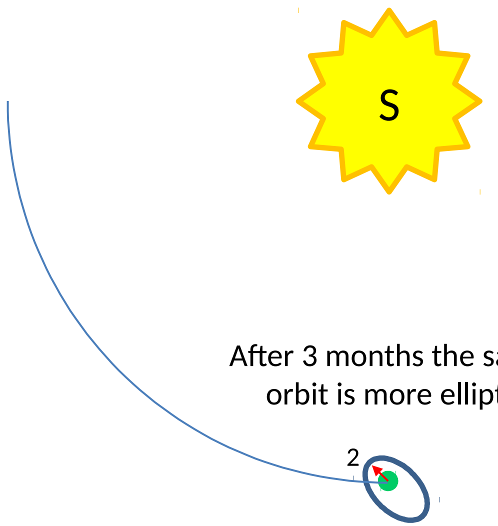


After a few weeks the satellite orbit is slightly elliptical

Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

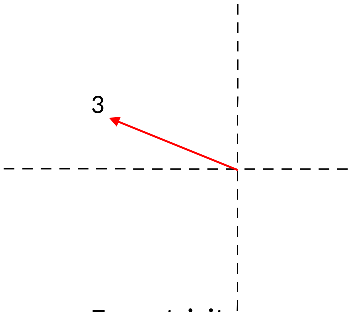


Eccentricity increases more

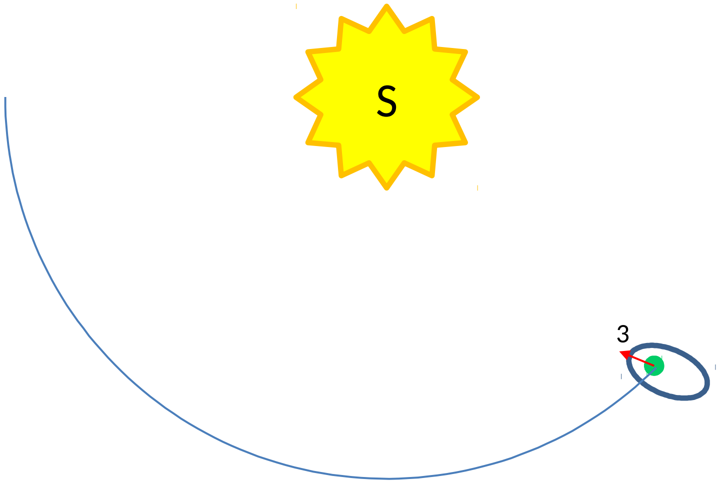


After 3 months the satellite orbit is more elliptical

Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

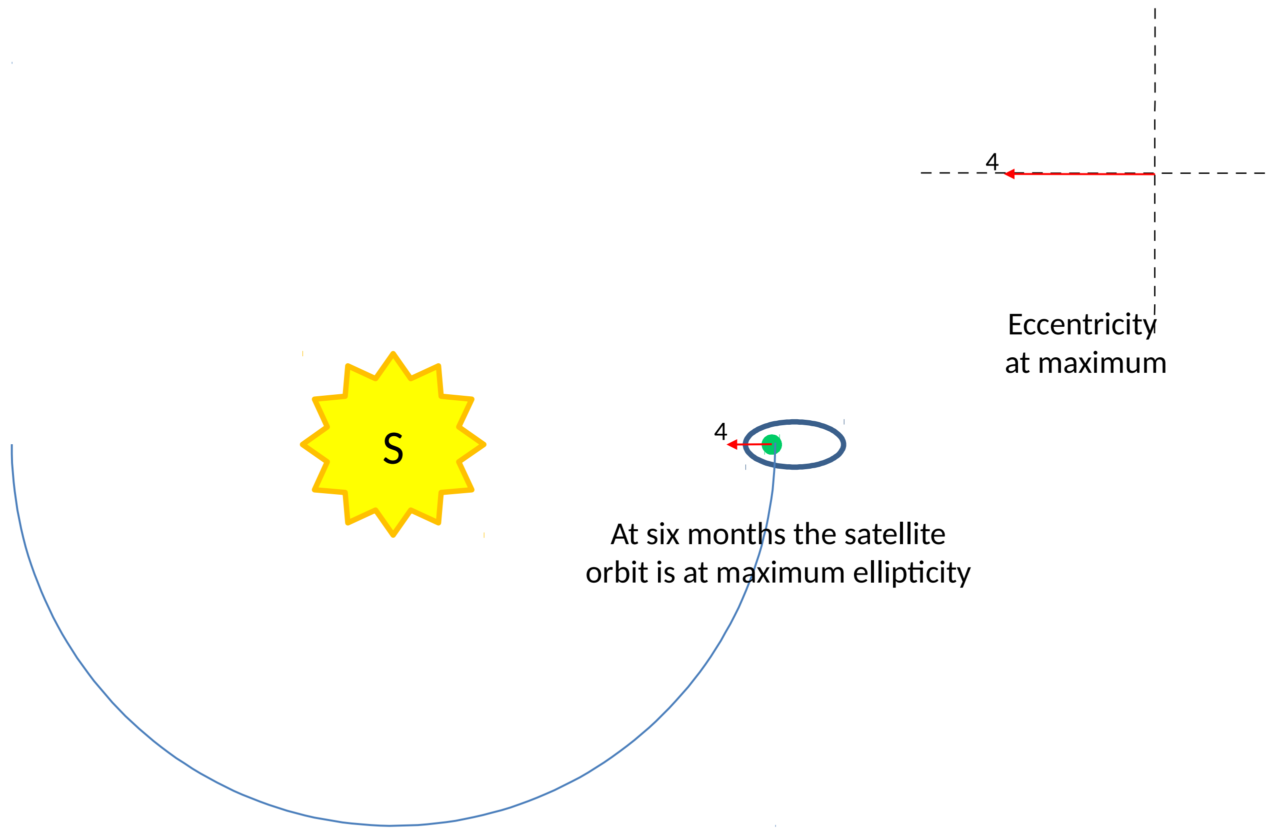


Eccentricity
still increasing

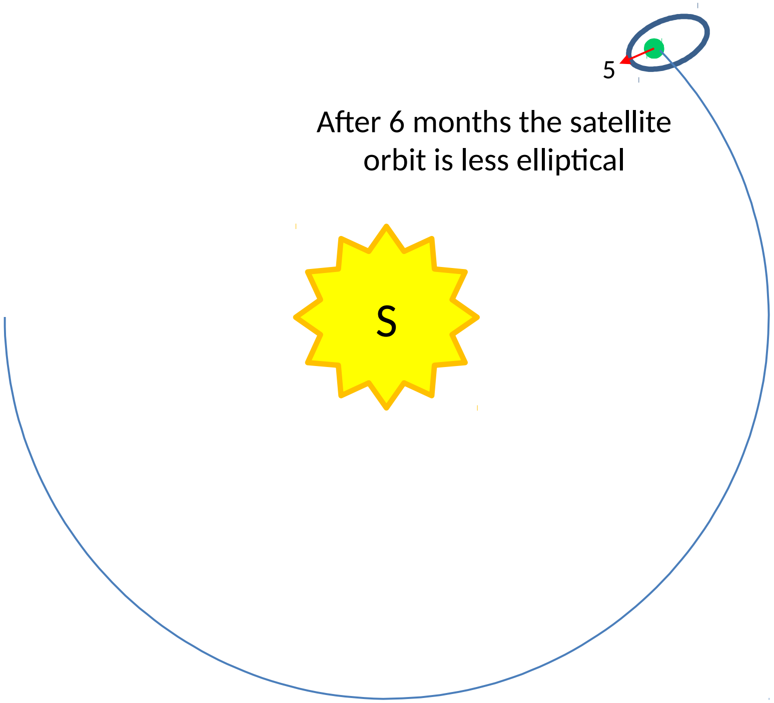


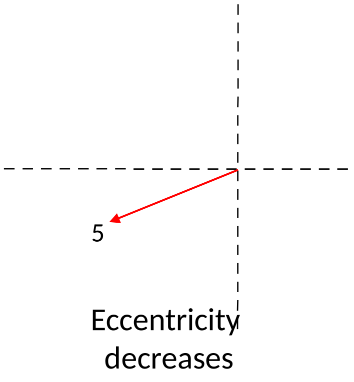
The satellite orbit is
even more elliptical

Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

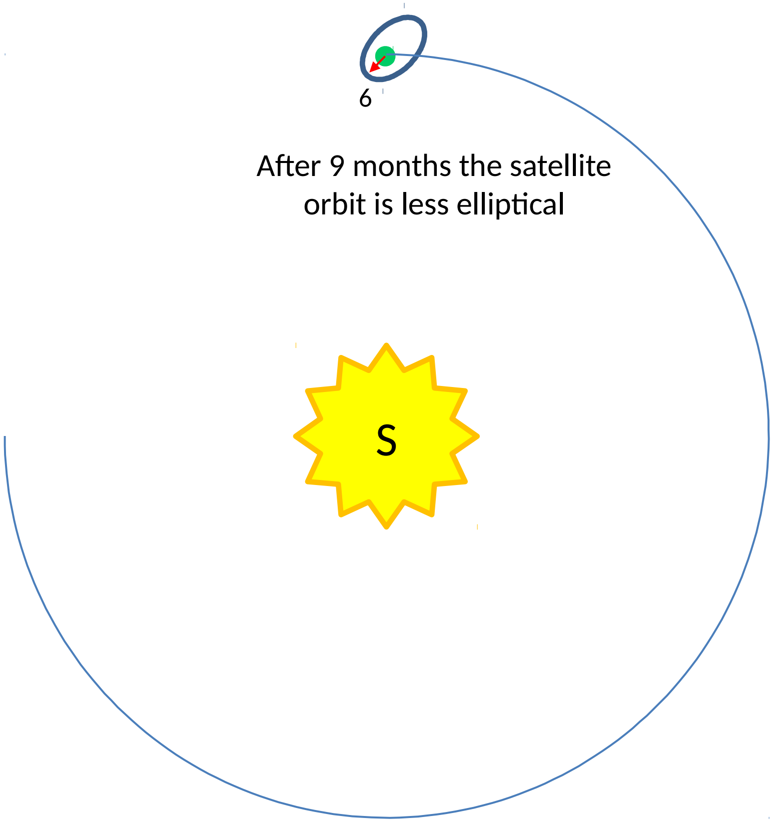


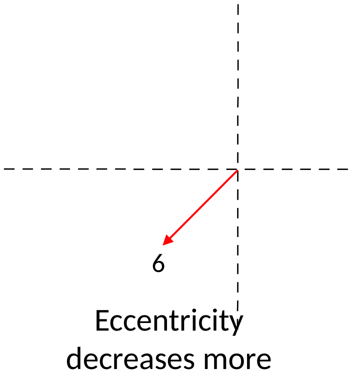
Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit



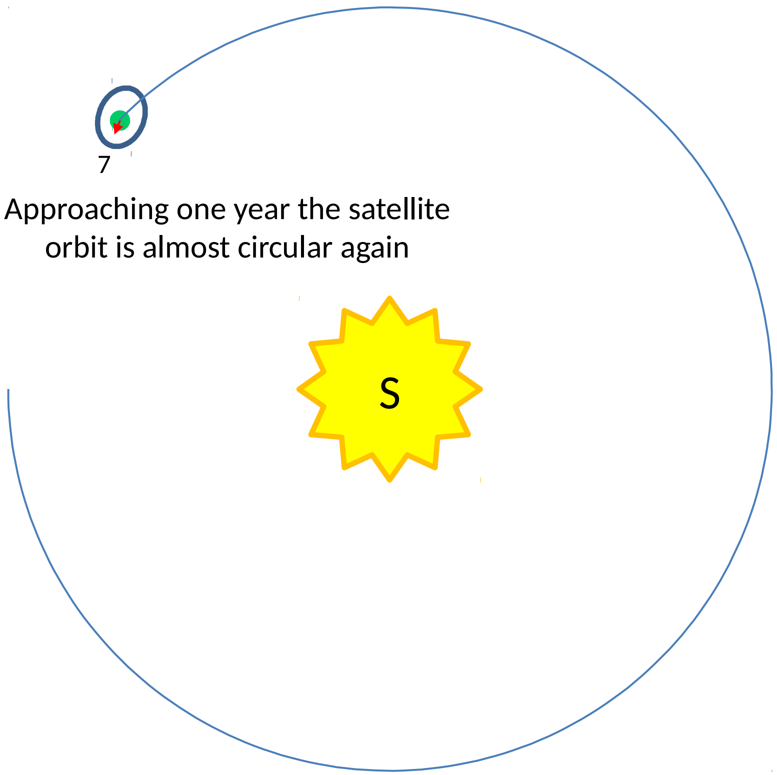


Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

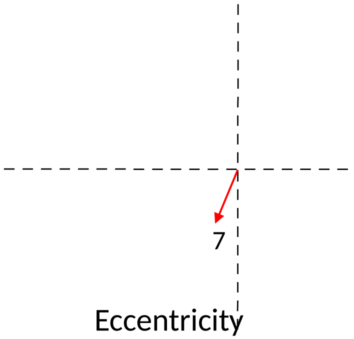




Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit

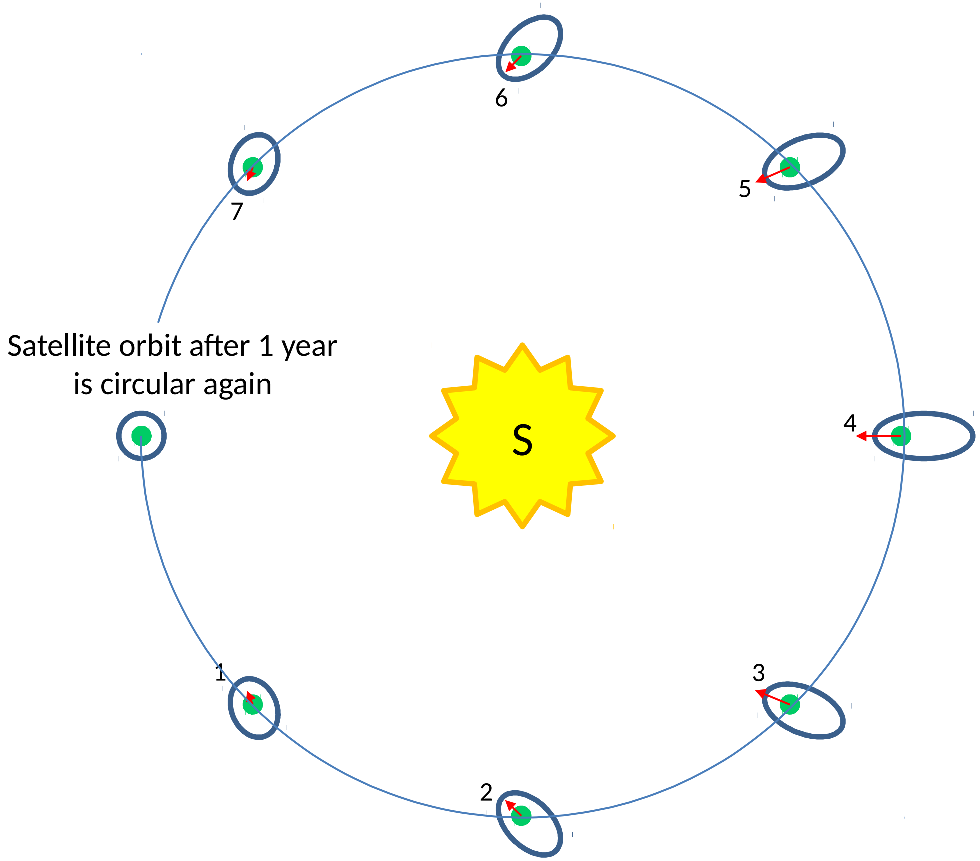


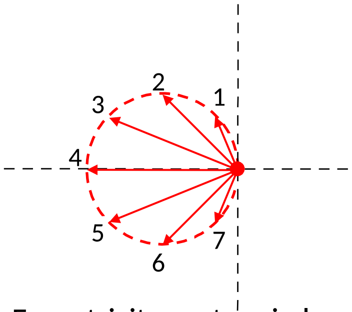
Approaching one year the satellite orbit is almost circular again



Eccentricity still decreasing

Eccentricity and Eccentricity Vector Evolution beginning with a circular orbit





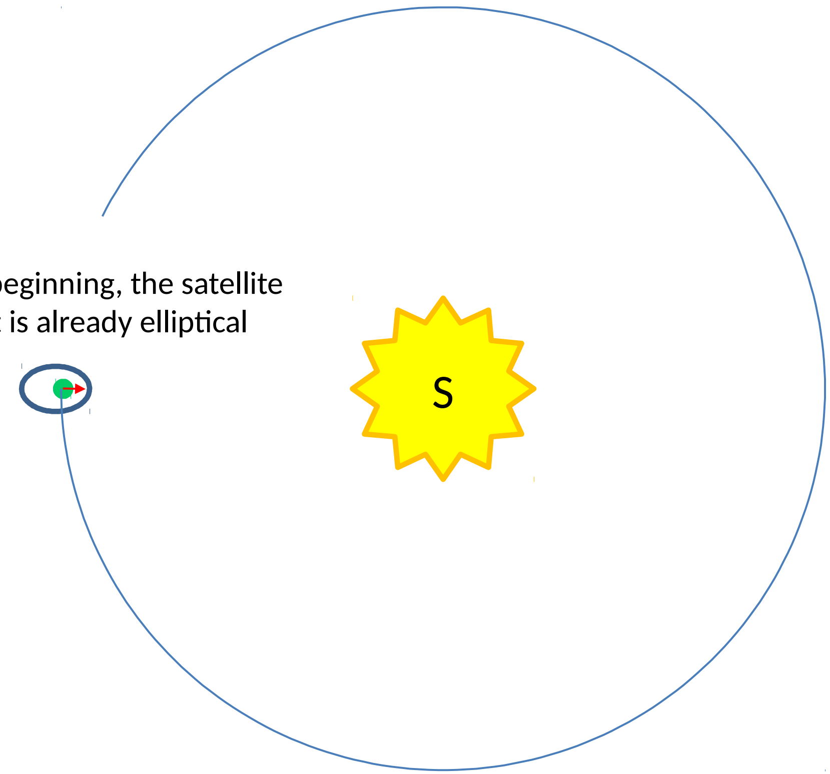
Eccentricity vector circle

A “natural eccentricity” Orbit

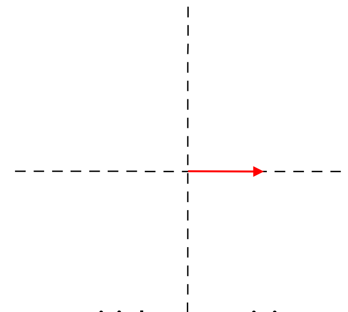
- Solar radiation pressure aggregate effects starting with a “natural eccentricity” orbit …

- which implies that the so-called “forced-eccentricity” is 0
(while the “free eccentricity”, “proper eccentricity”, or “harmonic eccentricity” has to be set as appropriate for the satellites’ cross-section to mass ratio).

Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

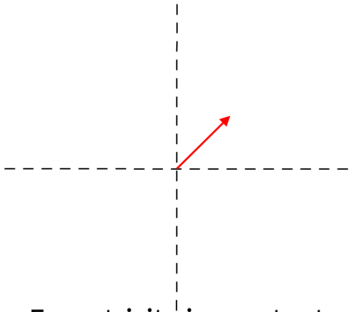


In the beginning, the satellite orbit is already elliptical

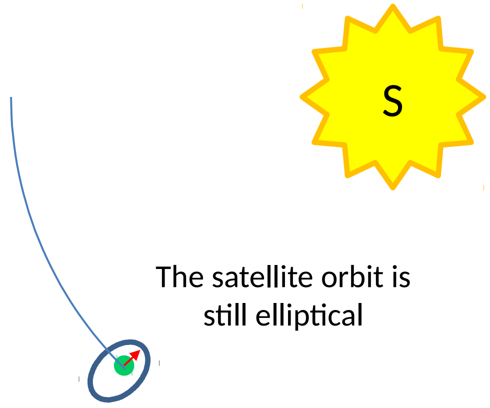


Initial eccentricity

Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

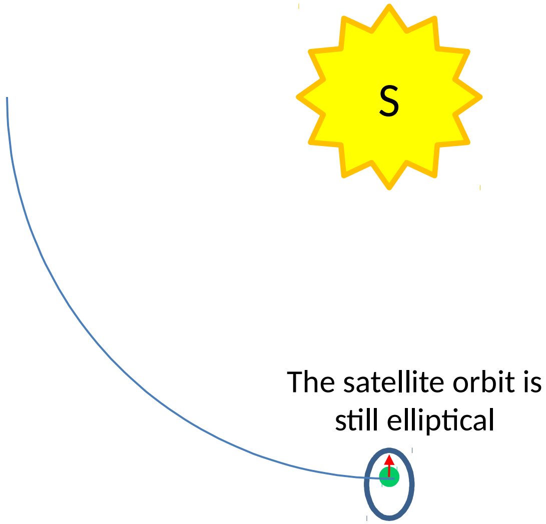


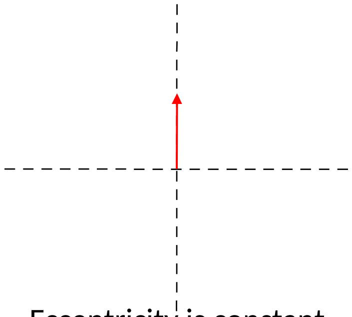
Eccentricity is constant



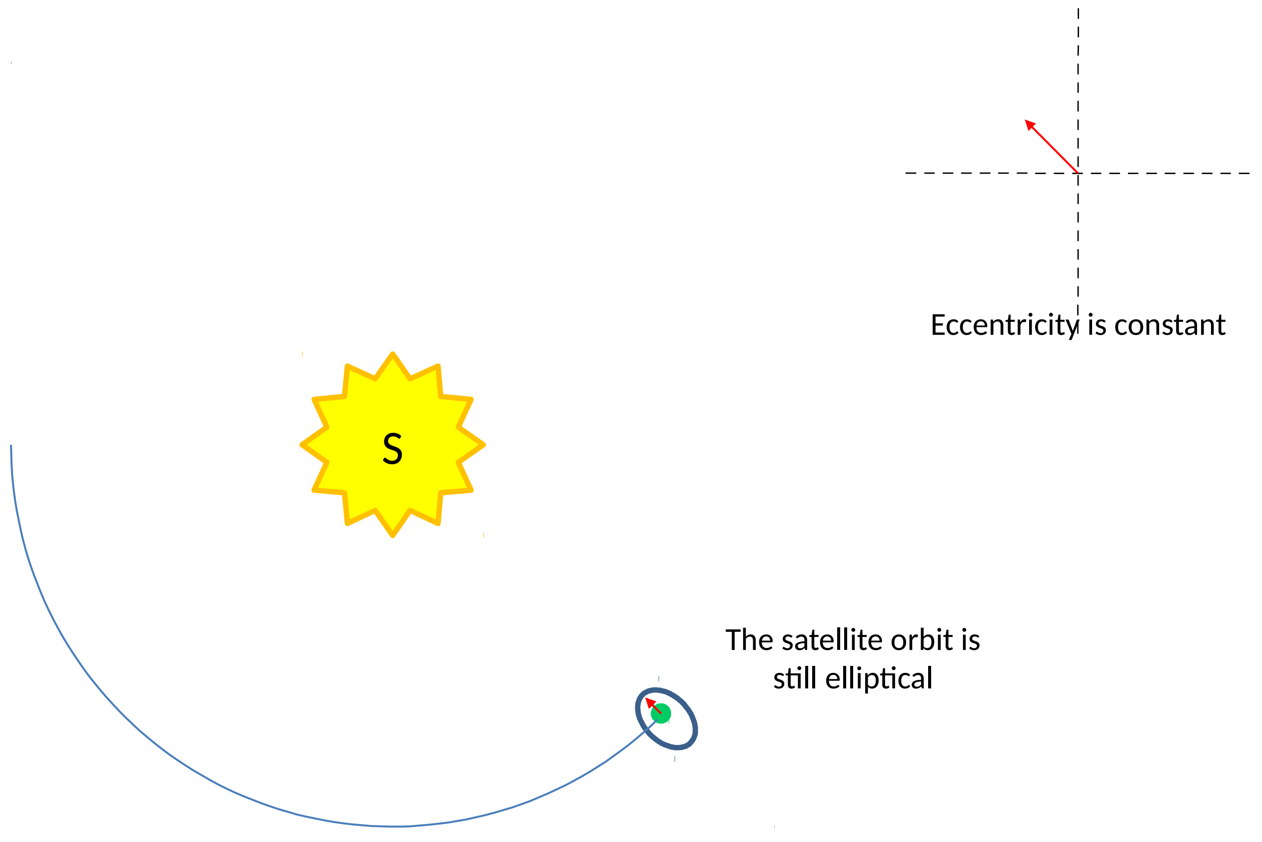
The satellite orbit is still elliptical

Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

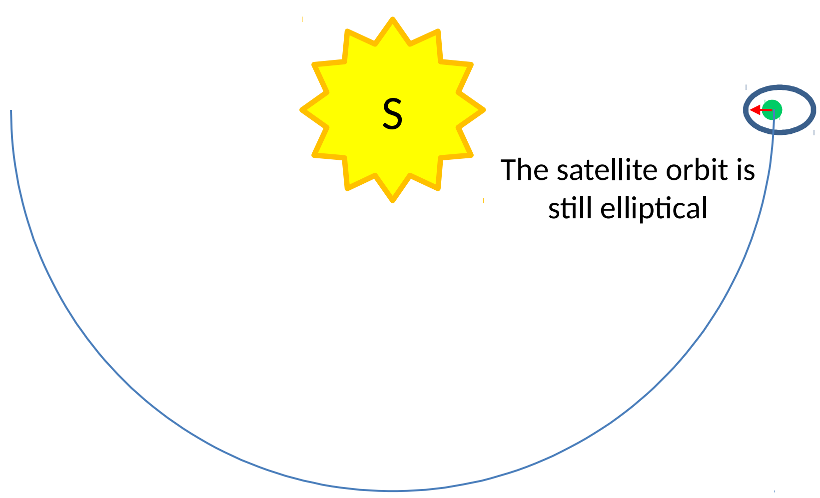


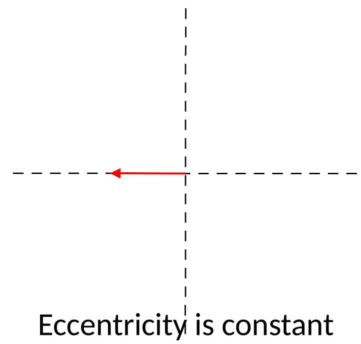


Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

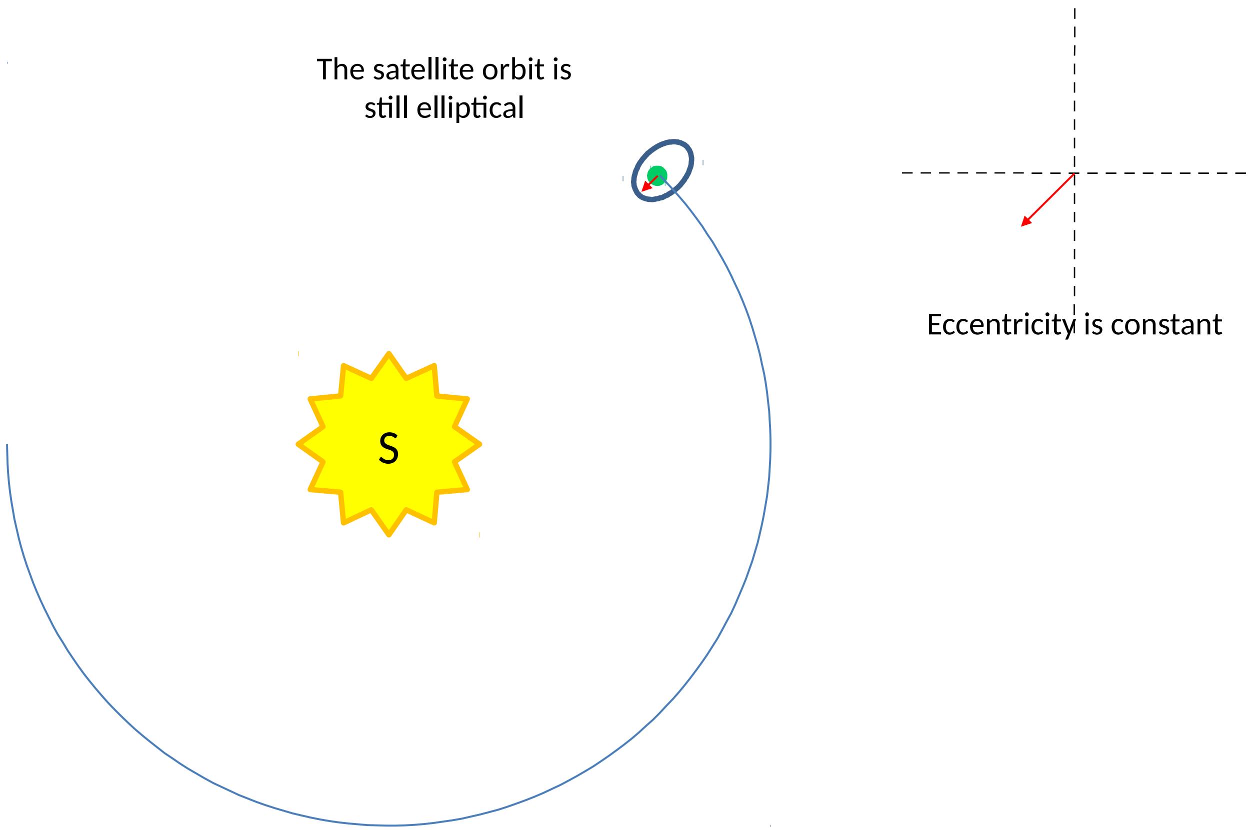


Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

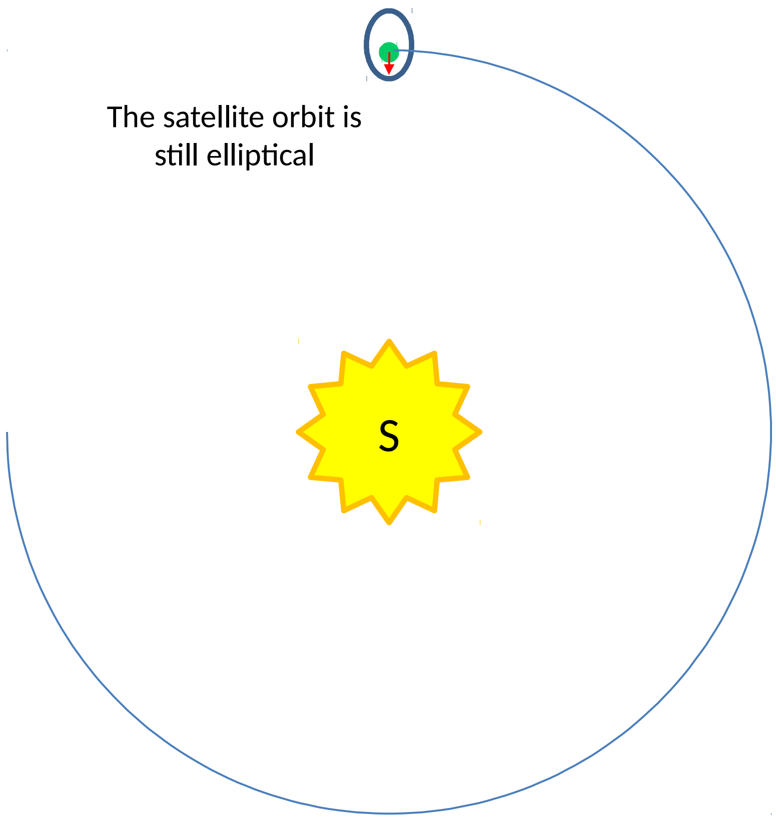


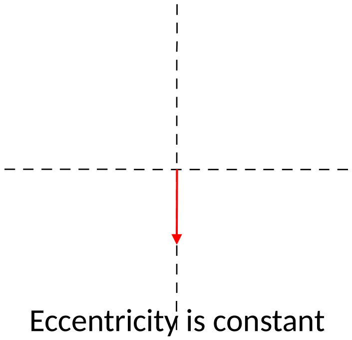


Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity

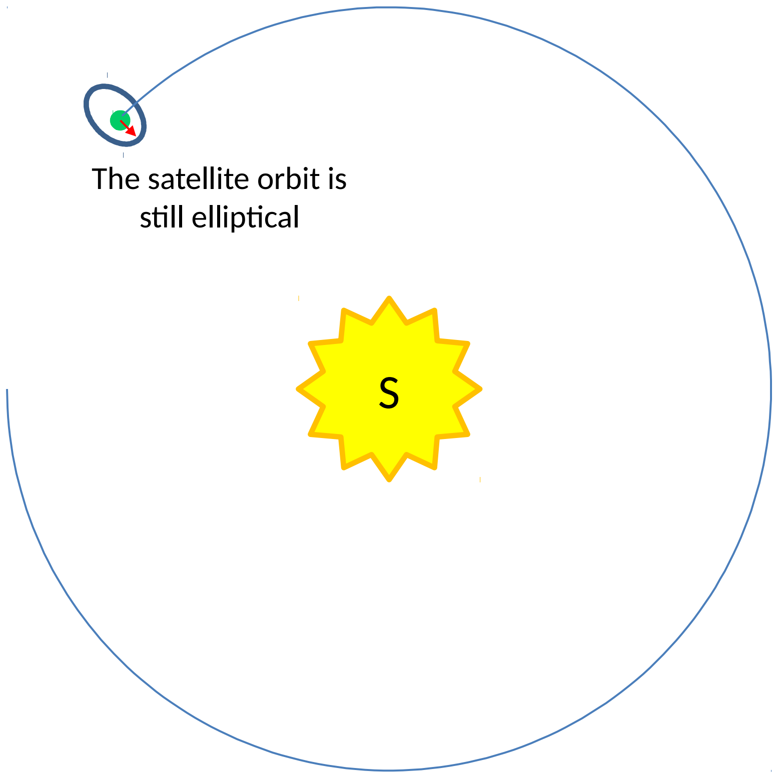


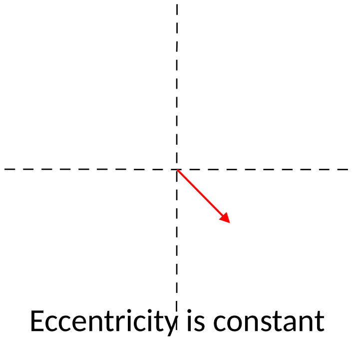
Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity



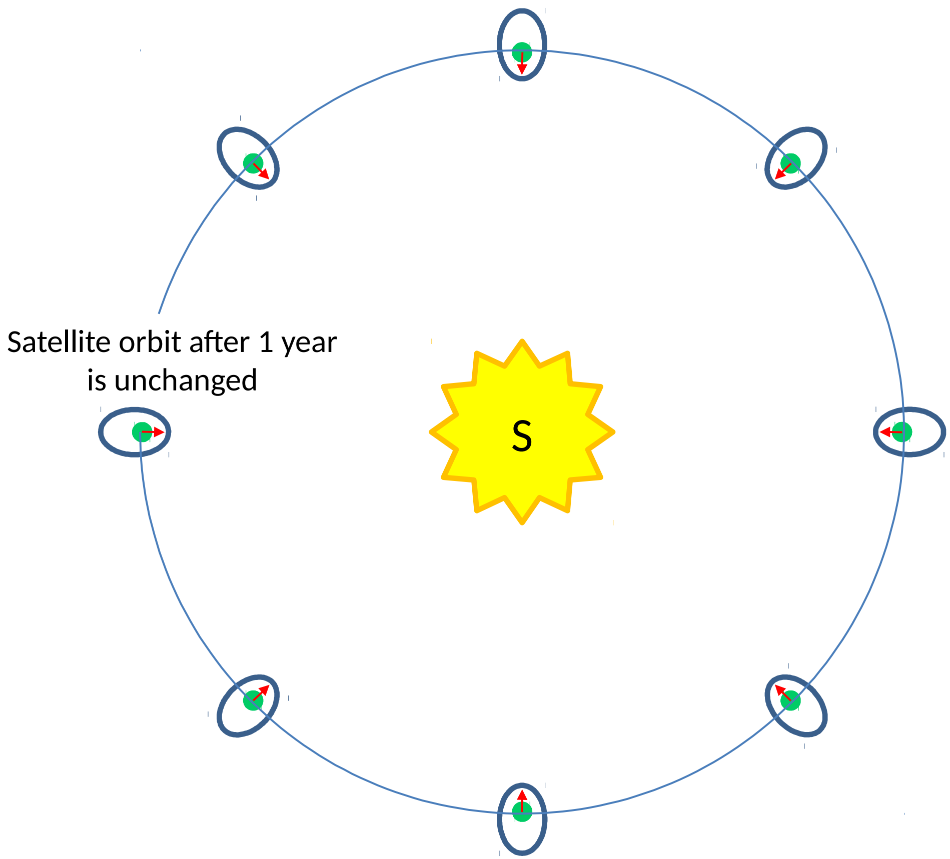


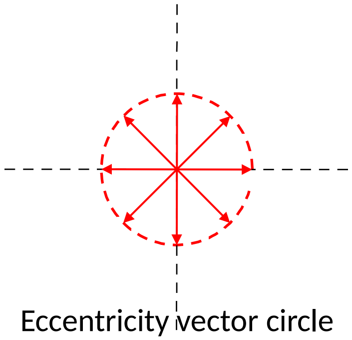
Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity





Eccentricity and Eccentricity Vector Evolution with Constant Eccentricity





Eccentricity Vector Radius Summary

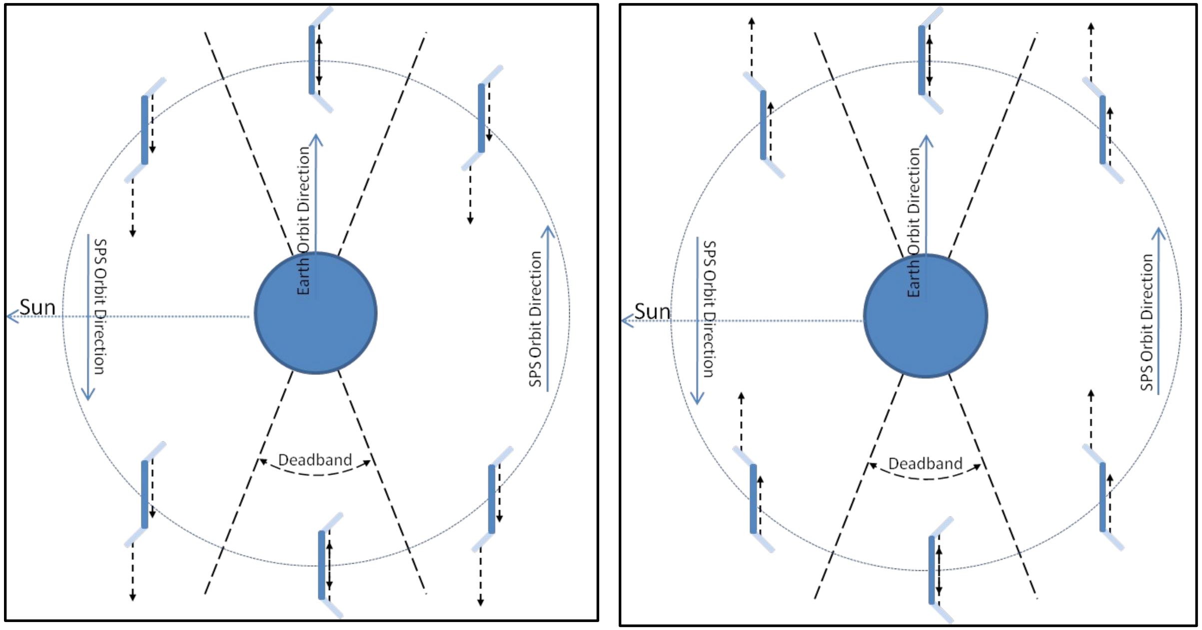
- Solar radiation pressure forces **all** satellites to exhibit a cyclical change in orbit eccentricity called the natural eccentricity.
- The magnitude of this effect is proportional to the cross-section to mass ratio (of the satellite).

- Existing communication satellites have a relatively small cross-section to mass ratio (0.01 to 0.1) so the natural eccentricity effect is dominated by other orbit perturbations.

- An SPS with propellant based station keeping has a higher cross-section to mass ratio (0.73) so that Solar radiation pressure is now the dominant perturbation.
- An SPS with RSRP station keeping has an even higher cross-section to mass ratio (1.42) so that Solar radiation pressure is even more dominant.

EWSK: Eccentricity Control

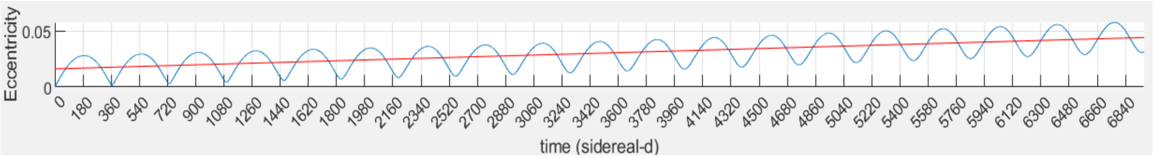
- Shift eccentricity vector Sunward (left) or anti-Sunward (right)



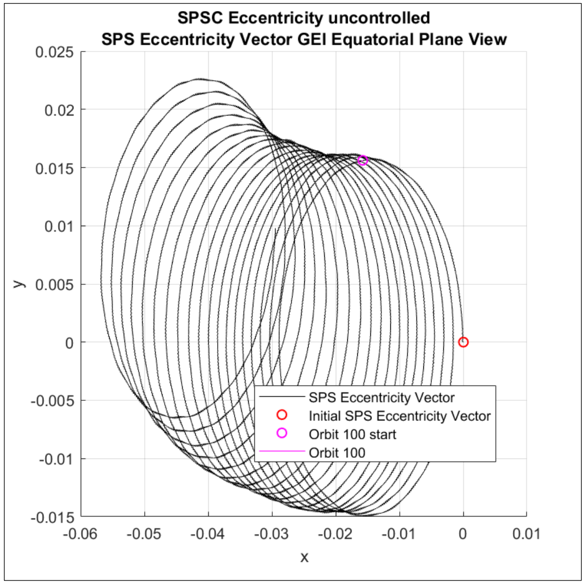
- Strategy
  - Shift eccentricity Sunward when eccentricity is above the natural eccentricity.
  - Neutral thrust otherwise.

EWSK: Uncontrolled Eccentricity

- Uncontrolled eccentricity evolution

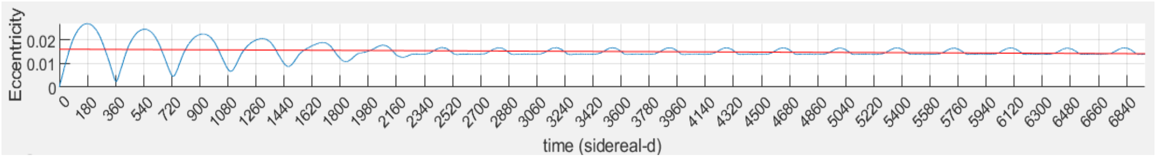


- Uncontrolled eccentricity vector evolution (including long duration drift of the forced eccentricity)
  – The eccentricity vector radius (EVR) is 0.014 in the x-dimension, and 0.015 in the y-dimension.

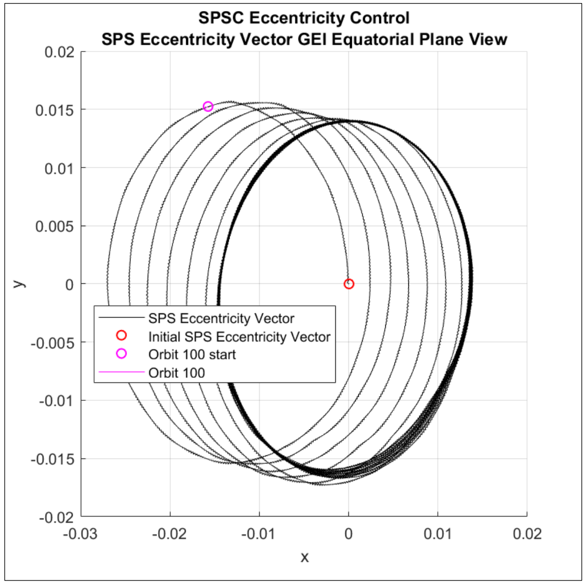


EWSK: Controlled Eccentricity

- Controlled eccentricity evolution



- Controlled eccentricity vector evolution
  - The eccentricity vector radius (EVR) is 0.0145.



Note, once the eccentricity vector circle is "centered" (i.e., the forced eccentricity is 0) the RSRP station keeping is nearly entirely in the neutral thrust configuration.

EWSK: Eccentricity Control

Supplementary analysis:

- Limitations on RSRP eccentricity control

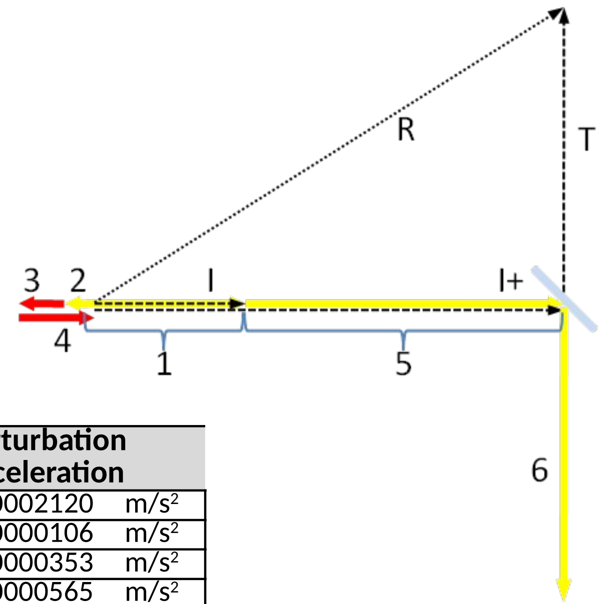
- Optimal RSRP Solar radiation angle of incidence

Note, in the next two slides (for simplicity) we refer to the EVR, which is the Eccentricity Vector (circle) Radius, nominally the same as the free eccentricity.

Also, EVR-neutral and EVR-active are used to distinguish between the EVR when the in-plane thrust configuration is neutral (i.e., no in-plane thrust) and active (i.e., in-plane thrust is active). Refer to slides 10 and 43.

No way to decrease EVR

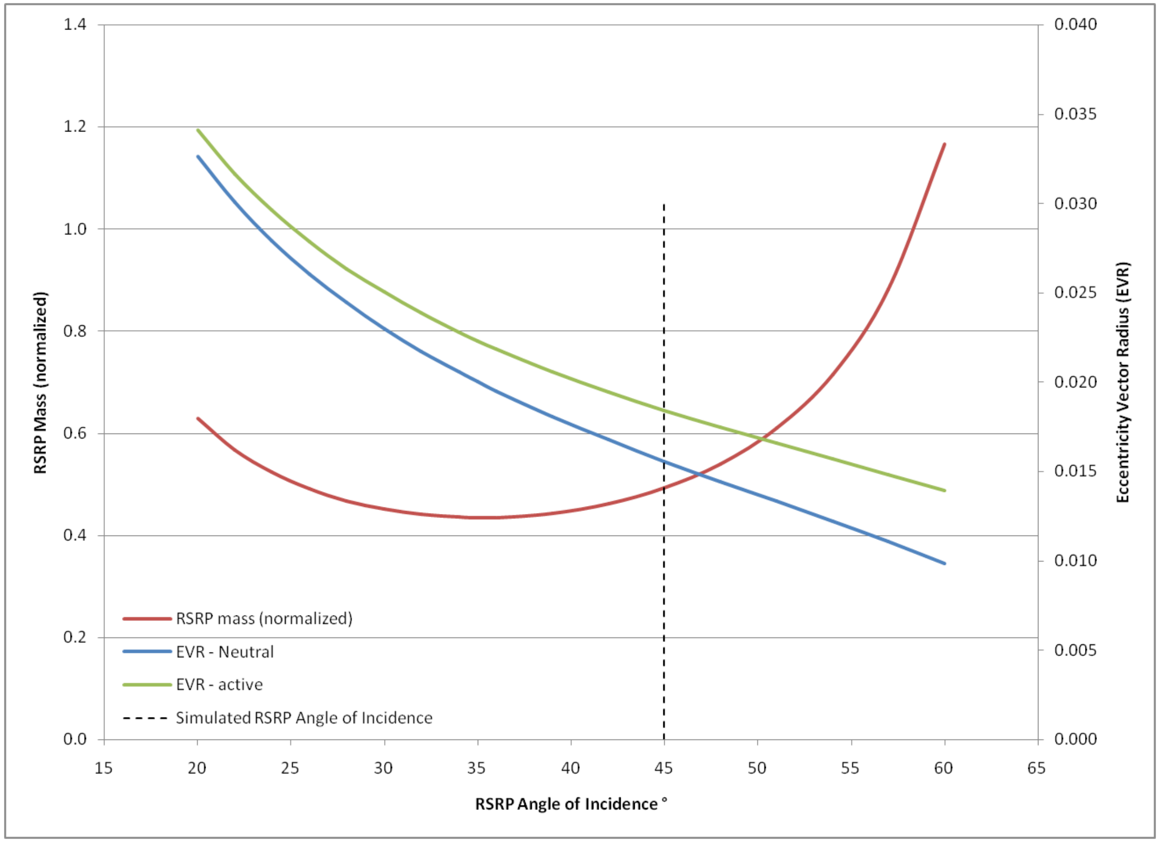
- The Resultant vector R must always be greater than the original vector I (regardless of the RSRP angle of incidence).



	Contributing Factor (as per the Generic 1 GW SPS Baseline Design)	Perturbation Acceleration	
1	SPS, excluding RSRP, incident solar radiation	0.000002120	m/s^2
2	SPS, excluding RSRP, reflected solar radiation (at 5%)	0.000000106	m/s^2
3	Sun facing thermal re-radiation	0.000000353	m/s^2
4	Anti-Sun facing thermal re-radiation	-0.000000565	m/s^2
I	Net SPS, excluding RSRP, anti-Sunward perturbation	0.000002010	m/s^2
5	RSRP sub-system incident solar radiation	0.000004230	m/s^2
I+	Net SPS anti-Sunward perturbation (including I)	0.000006240	m/s^2
6	RSRP sub-system redirected solar radiation (95% at 90°)	0.000004020	m/s^2
T	Net RSRP thrust capability	0.000004020	m/s^2
R	Maximum composite radiation perturbation (excluding Power Beam thrust)	0.000007240	m/s^2

RSRP Angle of Incidence and EVR

- The optimal RSRP angle of incidence has not been determined.

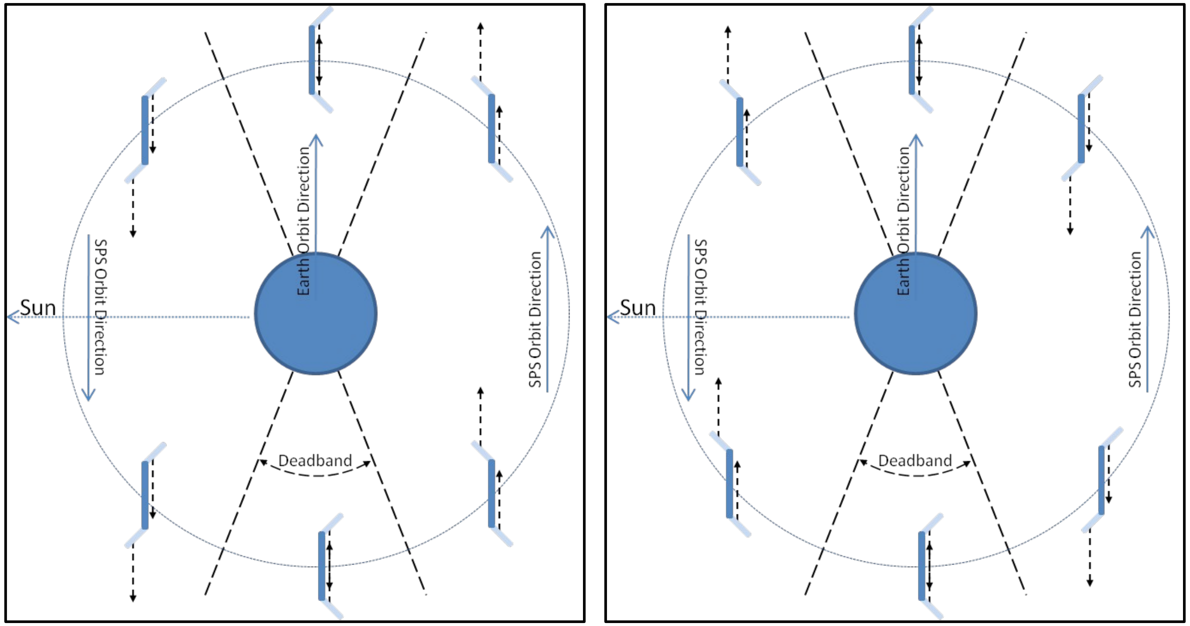


EWSK – Longitude Drift Control

- Note, simulation attempts to control longitude drift were unsuccessful until eccentricity control was implemented.
- Main perturbation is aspherical geopotential.
- Eccentric orbit includes cyclic drift.

EWSK: Longitude Drift Control

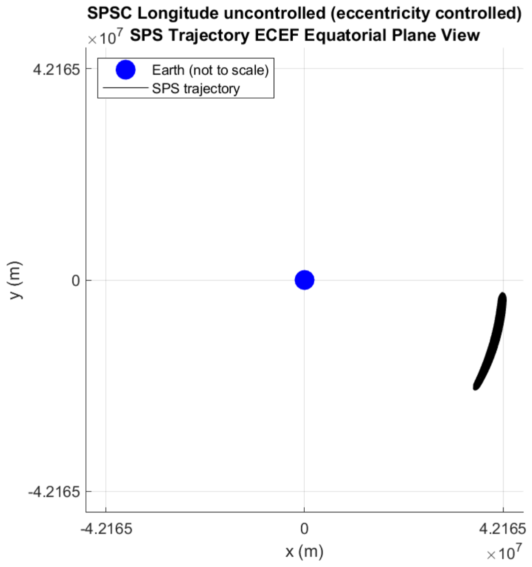
- Raise orbit (left) or lower orbit (right)



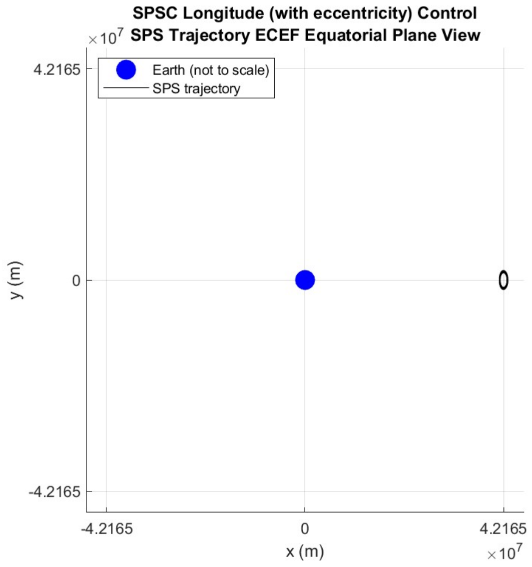
- Strategy
  - Raise orbit to drift west or lower orbit to drift east (effect has lag!).
  - Neutral thrust otherwise.

EWSK: Longitude Drift

- Uncontrolled longitude drift over a six month period from summer to winter.



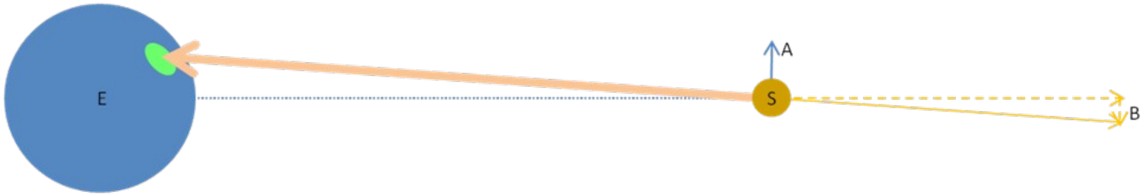
- Controlled longitude drift over the same six month period.



- “Excursions”:
  ±2.52° of longitude
  ±925000 m altitude

EWSK: Microwave Power Beam

- Earth, Ground Station (green), and SPS as viewed from above North Pole.



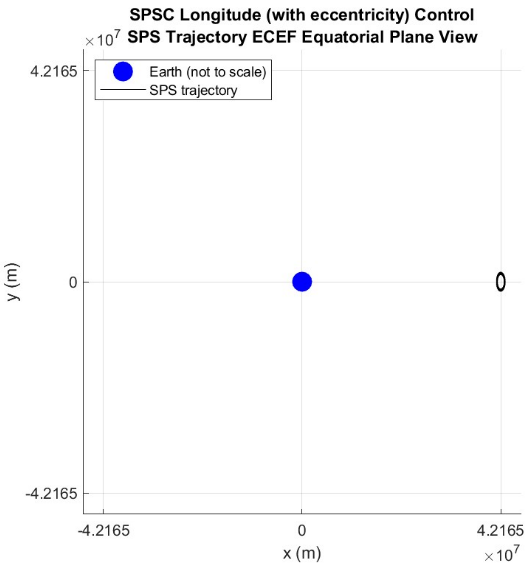
- The Microwave Power Beam (solid brown) contains momentum such that the SPS is thrust away from the Ground Station. A component of that thrust “B” is in the direction of the orbit and may oppose the aspherical geopotential “A”.

Relative Ground Station Location		Nominal SPS Acceleration Components		
Latitude ° North	Delta Longitude ° East	Radial m/s^2	Transverse m/s^2	Out-of-plane m/s^2
0	0	0.0000006350	0	0
52.23	0.00	0.0000006296	0.0000000000	-0.0000000830
52.23	10.00	0.0000006295	-0.0000000111	-0.0000000828
52.23	20.00	0.0000006292	-0.0000000218	-0.0000000824
52.23	30.00	0.0000006289	-0.0000000317	-0.0000000818

- The maximum aspherical geopotential is 0.0000000656 m/s^2 at 117.5°E longitude.

Summary: Main Result

- Station Keeping can be performed using RSRP, based on simulation including
  - Solar gravity
  - Lunar gravity
  - Solar radiation pressure
  - Thermal re-radiation
  - Aspherical geopotential (limited)
  - Microwave Power Beam thrust.



- The resulting orbit is slightly elliptical and maintains a fixed orientation with the Ground Station (as seen in an ECEF rotating frame of reference).
- This orbit passes through the GEO altitude twice daily at two fixed points located at +2.52 ° and -2.52° of Longitude relative to the nominal assigned “station”.

Conclusion: SPS Station Keeping options

Either (presumptive default)

- Force GEO circular orbit in accordance with existing GEO orbit slot assignment practices
  - Can't be done with RSRP.
  - Propellant "ΔV" requirements dominated by Solar Radiation Pressure of 94 m/s/year in addition to NSSK (about 50 m/s/year).

Or (proposed)

- Allow near-GEO elliptical orbit with "natural eccentricity" requires revised GEO orbit slot assignment practices
  - Achievable with RSRP (no propellant, indefinite lifetime)
  - Propellant "ΔV" requirements for NSSK only (about 50 m/s/year)

Additionally

- So-called "Laplace-plane" orbit may substantially reduce NSSK to near 0.

Discussion

- Questions?

Remaining Activities

- Minutes

Closing Remarks

- Thank you for this opportunity.

Please feel free to contact us regarding any follow-up issues that may arise.

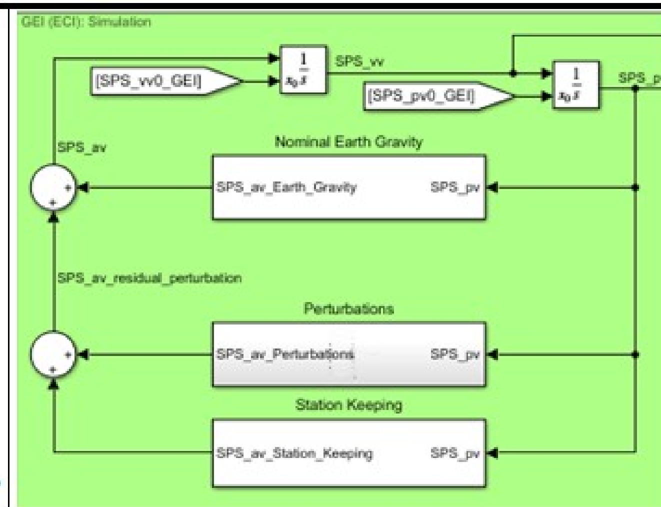
End.

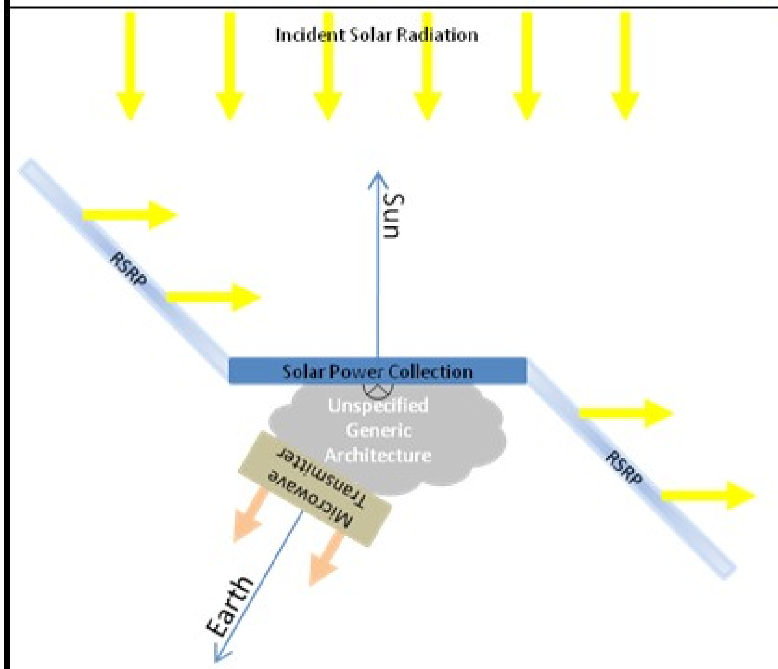
SPS Station Keeping
Using Solar Radiation Pressure
for Propulsion

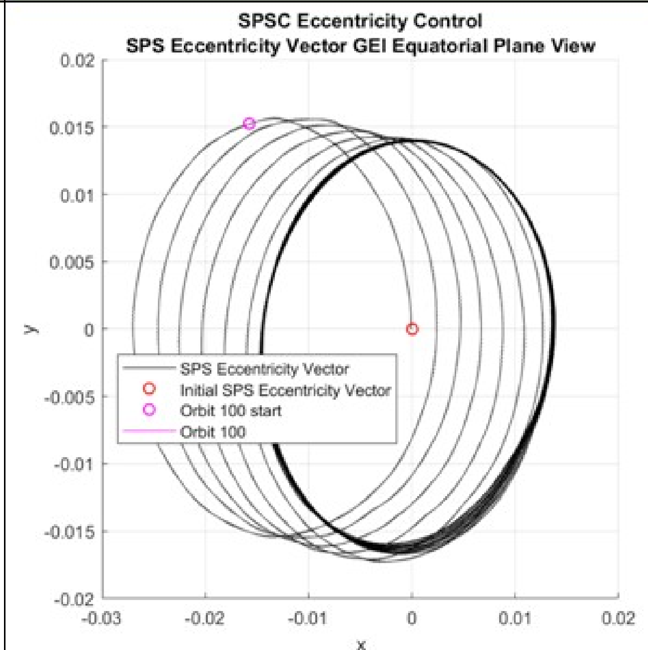
ESA STAR AO 2-1789/21/NL/GLC/ov

A simulation and analysis of
the application of “solar sailing” technology
to the control and maintenance of
a Solar Power Satellite orbit.

ETI Emerald Telecommunications International Inc.







Background: Laplace Plane orbit

A so-called Laplace plane orbit is one where the orbit plane is between the ecliptic plane and the Earth equatorial plane, in such manner that the Solar and Lunar gravity perturbations are balance against the Earth's equatorial bulge perturbation. The inclination of this plane is dependent on the orbit altitude (and varies according to the 18.6 year cycle of the Lunar line-of-nodes).

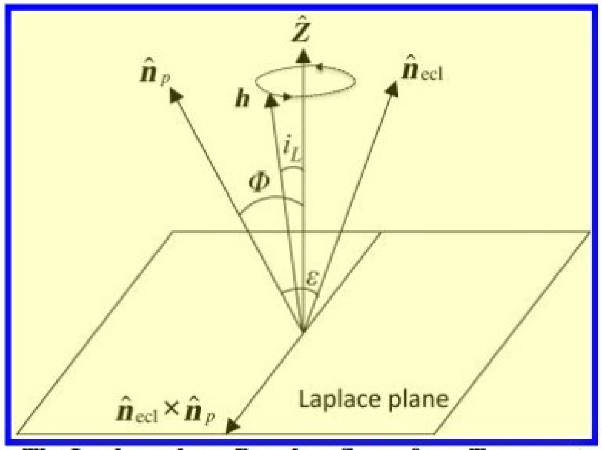


Fig. 3 The Laplace plane. Based on figure from Tamayo et al. [14].

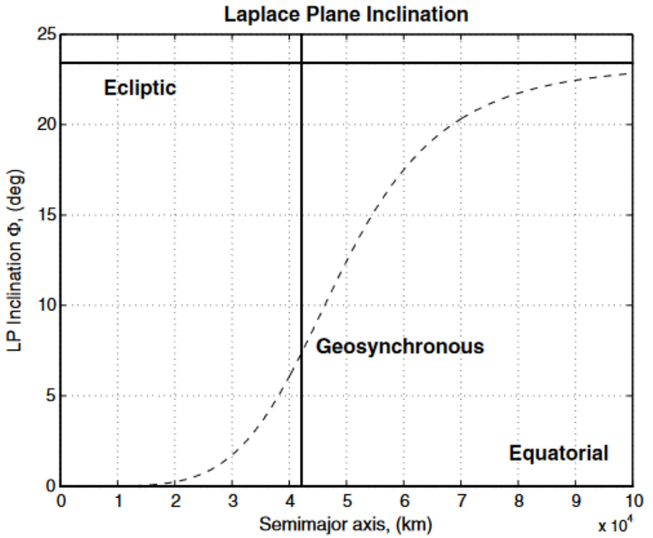


Fig. 4 Laplace plane inclination with respect to Earth's equatorial plane for various semimajor axis [17].

Figures from: McNally, Ian
"Locating Large Solar Power Satellites in the Geosynchronous Laplace Plane"
University of Glasgow
DOI: 10.2514/1.G000609