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Sun-synchronous repeat ground tracks and other useful orbits for future space missions

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Abstract

The development of oceanography and meteorology has greatly benefited from satellite-based data of Earth's atmosphere and ocean. Traditional Earth observation missions have utilized Sun-synchronous orbits with repeat ground tracks due to advantages in visible and infrared wavelengths. However, diversification of observation wavelengths and miniaturization of satellites, are enabling new kinds of satellite missions that provide big data from swarms and constellations. This paper proposes several unconventional orbits for future space missions.

Keywords: Sun-synchronous orbit, repeat ground tracks, Earth observation, remote sensing.

Introduction

The first-generation weather satellites used non-polar (i.e. low inclination) low-Earth orbits (LEOs) as illustrated by Television and Infrared Observation Satellites (1960). Since the second generation marked by the Nimbus series (1964), near-polar (i.e. high inclination) Sun-synchronous orbits (SSOs) have become the norm in Earth observation [1]. Remote sensing satellites in SSOs cross a given latitude band at the same mean local time throughout a year, providing uniform illumination conditions in visible or infrared wavelengths. Many satellites in SSOs also have repeat ground tracks (RGTs). Satellites with RGTs visit a given longitude band at the same mean local time. Therefore, having both SSOs and RGTs is ideal for observing locations with certain latitude-longitude combinations at a designated time of a day.

On the other hand, radio-frequency measurements do not necessarily require SSOs; NASA's Cyclone Global Navigation Satellite Mission (CYGNSS), launched in 2016, measures GPS signals reflected from the oceans to measure wind speeds and does not use SSOs. Another example without SSOs is the Sentinel-6 satellite for radar altimetry of the oceans, which will be launched between 2020 and 2030 by the European Organisation for Metrological Satellites (EUMETSAT) [2]. Given the broadening applications of space-borne remote sensing, non-conventional, "tweaked" versions of SSO-RGT standards could be useful. This paper discusses such cases, including tidal synchronous orbits or Sun-synchronous drifting orbits.

Background

The procedures for calculating standard Earth observation orbits (SSO, RGT) are first re-visited. The condition for either Sun-synchronism (SSO) or ground repetitions (RGT) is then tweaked such that new class of orbits could be derived.

Sun Synchronous Orbits

Earth's equatorial radius is greater than its polar radius due to its spin and equatorial bulge. The torques exerted by this extra equatorial mass cause nodal regression of a satellite orbit, similar to a spinning top that wobbles due to gravity [3, 4]. The polar orbit in Fig. 1(A) is a case where the orbit is fixed in the inertial frame due to zero regression. Although the local sidereal time remains the same throughout a year, the local solar time varies according to Earth's position relative to the Sun. To provide uniform solar illumination for satellite imaging, the nodal regression should match Earth's yearly revolution rate around the Sun.

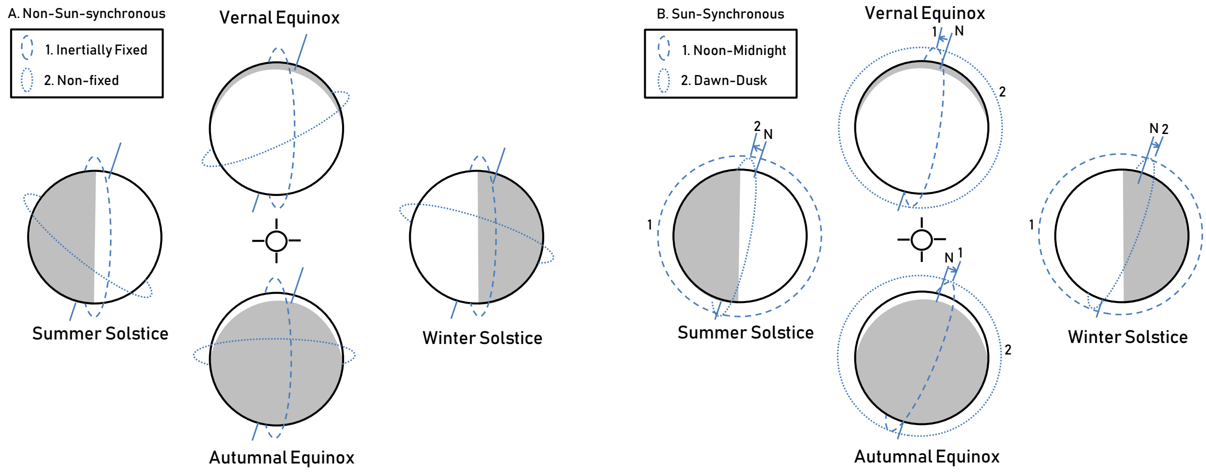

Fig. 1: Satellite orbits that are not Sun-synchronous (A) and Sun-synchronous (B).

Equation 1 gives the satellite orbit's regression rate, which is 360° ÷ 365.2422day = 0.9856 °/day = 2×10^{-7} rad/s in SSOs [3]; *dΩ/dt* means the time derivative of longitude of ascending node *Ω* and is a function of semi-major axis (*a*), eccentricity (*e*) and inclination (*i*). R_E is Earth's equatorial radius, J_2 is Earth's oblateness coefficient (1.08263×10^{-3}), and μ_E is Earth's standard gravitational parameter (3.986×10^{5} km^{3}s^{-2}). Figure 2 depicts semi-major axis and inclination of Sun-synchronous whose *dΩ/dt* value equals 0.9856°/day or 2×10^{-7} rad/s.

$$\dot{\Omega} = -\frac{3R_E^2 J_2\sqrt{\mu_E}}{2a^{7/2}(1-e^2)^2}cos(i) \quad (1)$$

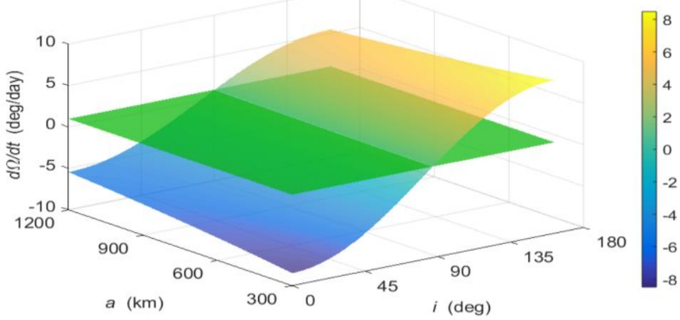

Fig. 2: Effect of semi-major axis (a) and inclination (i) on the orbit nodal regression rate (deg/day) with zero eccentricity (e = 0). The line intersection defines circular SSOs.

Repeat Ground Tracks

An orbit has repeat ground tracks (RGTs) if a satellite's ground track exactly repeats its pattern after a certain number of days. With an Earth nodal period T_N and a satellite orbital period T_S, the satellite completes N_S revolutions around Earth after N_D nodal days.

$$N_S T_S = T_N N_D \quad (2)$$

Equation 3 is obtained after substituting definitions of T_N and T_S. The angular velocity of a satellite ($2\pi/T_S$) equals $n = (\mu_E/a^3)^{1/2}$. This angular velocity is changed by Δn in the numerator of Eqn 3 due to Earth's oblateness, which is shown in Eqn 4. The argument of perigee is also perturbed according to Eqn 5. Lastly, the spin rate of Earth is ω_E=360°÷ day=7.29×10^{-5} rad/s.

$$\tau = \frac{N_S}{N_D} = \frac{T_N}{T_S} = \frac{2\pi/(\omega_E-\dot{\Omega})}{2\pi/(\dot{M}+\dot{\omega})} = \frac{n+\Delta n+\dot{\omega}}{\omega_E-\dot{\Omega}} \tag{3}$$

$$\Delta n = \frac{3R_E^2 J_2\sqrt{\mu_E}}{4a^{7/2}(1-e^2)^{3/2}}(2-3\sin^2 i) \tag{4}$$

$$\dot{\omega} = \frac{3R_E^2 J_2\sqrt{\mu_E}}{4a^{7/2}(1-e^2)^{2}}(4-5\sin^2 i) \tag{5}$$

Sun Synchronous Orbits with Repeat Ground Tracks (SSRGTs)

Setting $d\Omega/dt = \omega_{ES}$ = 0.9856°/day and e=0 in Eqns 1, 3, 4, and 5 leads to Eqn 6 which defines circular SSOs with RGTs. The relationship among semi-major axis (altitude), inclination, and RGT ratio (N_S and N_D) is depicted in Fig.3 [5, 6]. Hereafter in this paper, SSOs with RGTs is further abbreviated as SSRGT to distinguish with orbits presented in the following sections.

$$\sqrt{\frac{\mu_E}{(R_E+h)^3}} + \frac{J_2R_E^2\sqrt{\mu_E}}{(R_E+h)^{7/2}}\left(\frac{8}{3}\frac{(R_E+h)^7\omega_{ES}^2}{J_2^2R_E^4\mu_E}+\frac{3}{2}\right) + (\omega_E-\omega_{ES})\tau = 0 \tag{6}$$

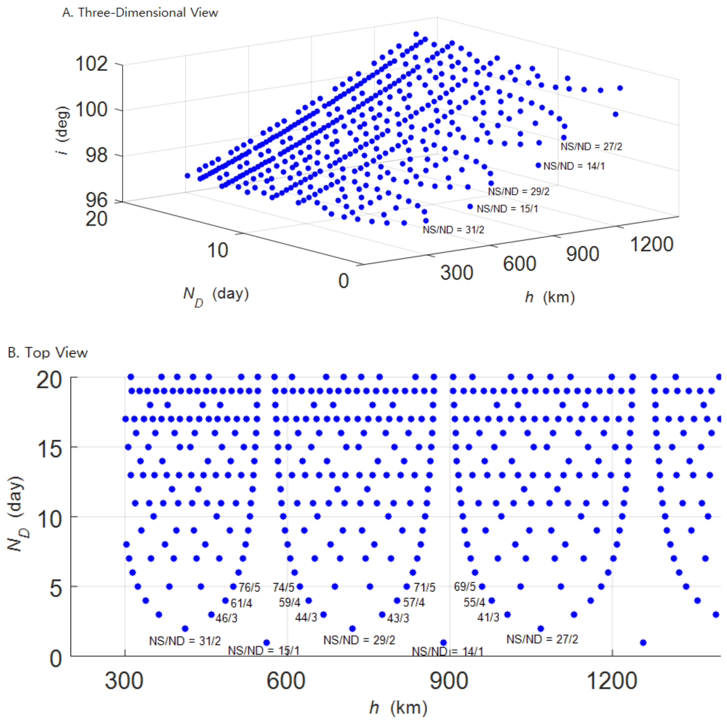

Fig. 3: SSRGT orbit altitude and inclination in (A) 3-dimentional view and (B) top view.

Methods

Sun Synchronous Orbits with Drift Ground Tracks (SSDGTs)

One variant of SSRGTs is Sun-synchronous orbits with drift ground tracks (SSDGTs) where the ground tracks migrate at a predefined speed. An SSRGT orbit with an RGT ratio of 15 has an altitude of 561 km, in which a satellite returns to the starting location every day after 15 revolutions. If the altitude is decreased to 500 km, the satellite will arrive 500 km east to the starting point, corresponding to a drift speed of 20 km/h at the equator. The drifting of ground tracks comes from the difference in orbital periods between an RGT orbit and a DGT orbit. If the semi-major axis (altitude) of the non-RGT orbit deviates from that of a RGT orbit by δa, the orbital period differs as expressed by Eqn 7, resulting in displacement shown in Eqn 8.

$$\delta T = 2\pi(\sqrt{\frac{(a+\delta a)^3}{\mu_E}} - \sqrt{\frac{a^3}{\mu_E}}) \tag{7}$$

$$\delta d = (\omega_E - \dot{\Omega})R_E \delta T \tag{8}$$

If $\delta a > 0$, the DGT orbital period increases, its ground tracks drifting westward. If $\delta a < 0$, the DGT with a shorter period will lead the counterpart RGT, drifting eastward. Figure 6 illustrates the relationship between $|\delta d/\delta T|$ and δa for altitudes from 400 km to 700 km. The drift velocity has very similar slopes regardless of altitudes, and ground track speeds increase by approximately 0.3 km/h as the altitude increases by 1 km. This characteristic may be useful in mobile target tracking because the resolution of satellite imagery is maximized when the distance between a satellite and a target is minimized. For instance, these kinds of orbits can be used for tracking hurricanes or glaciers [7].

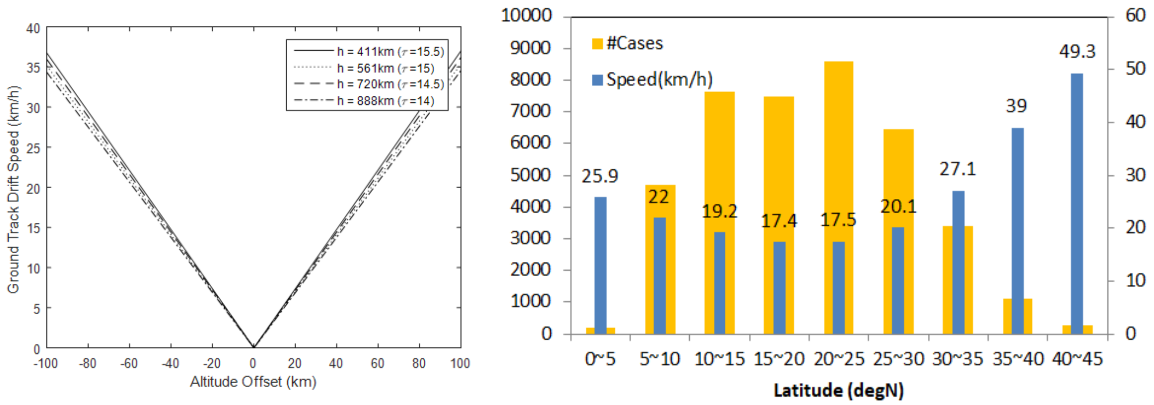

Fig. 4: Drift orbit groundtrack speed (A) and hurricane speed in Northern Atlantic Ocean (B).

Multi Sun Synchronous Orbits with Repeat Ground Tracks (MSSRGTs)

Ref 8 first proposed the concept of "multi-SSOs" but did not take RGTs into account [8]. Multi-SSOs have a nodal regression rate of $d\Omega/dt = \omega_{ES} + \Delta\omega_{ES}$ where $\Delta\omega_{ES}$ is a correction component. Substituting ω_{ES} with $\omega_{ES} + \Delta\omega_{ES}$ in Eqn 6, Fig 3 can be transformed into plots like Fig 5. The value of $\Delta\omega_{ES}$ is confined between -9°/day and +6°/day from the range of $d\Omega/dt$ in Fig 4. The multi SSRGTs will provide identical solar angles every $|360/\Delta\omega_{ES}|$ days, as illustrated in Fig 6. Although this frequency is much lower than regular SSOs, MSSOs can be used with low inclination vales (e.g. 17 deg in Fig 6B), providing more observations of low-latitude regions. Use of satellite swarms and advanced image post-processing techniques will also mitigate this drawback of waiting for identical solar illumination conditions [9, 10]. It is noteworthy as well that the feasible regions in Fig. 5 are smaller than those in Fig. 3.

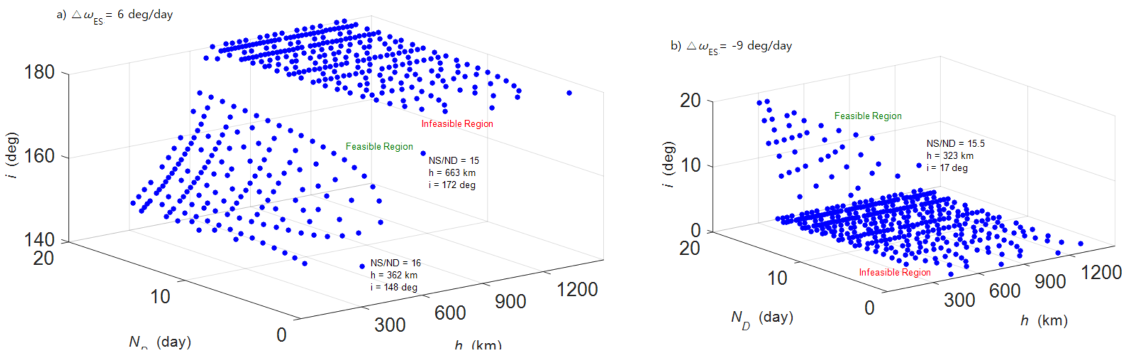

Fig. 5: SSRGT orbit altitude and inclination in (A) 3-dimentional view and (B) top view.

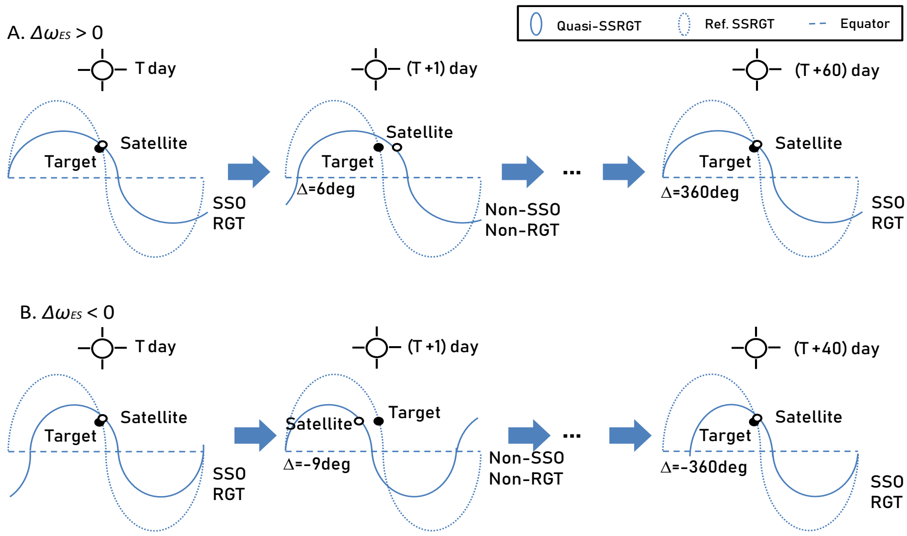

Fig. 6: SSRGT orbit altitude and inclination in (A) 3-dimentional view and (B) top view.

Tidal Synchronous Orbits (TSOs)

Besides the Sun, the Moon is another celestial body that exerts considerable gravitational forces on Earth, creating lunar tides. Bio-optical reflectance of coastal waters depends on local hydrographic features and phytoplankton composition, whose changes are attributable to lunar tides and can best be studied with satellite remote sensing. Tidal synchronous orbits (TSOs), first introduced in Ref. 15, are obtained by substituting Earth's spin rate ω_E in Eqn 3 with the Moon's rotation rate around Earth ω_{EM}. The Moon's revolution period (*i.e.* one tidal lunar day) is $T_L = 2\pi/\omega_{EM}$ = 24h 50m 8s which is slightly longer than one Earth sidereal day equal to $T_D = 2\pi/\omega_E$ = 23h 56m 4s because the Moon orbits around Earth in the same direction as Earth spins. Equation 9 also shows that the lunar repeat ratio τ_L is defined using the lunar nodal period T_L and the number of lunar revolutions N_L [11].

$$\tau_L = \frac{N_S}{N_L} = \frac{T_L}{T_S} = \frac{2\pi/(\omega_{EM}-\dot{\Omega})}{2\pi/(\dot{M}+\dot{\omega})} = \frac{\dot{M}+\dot{\omega}}{\omega_{EM}-\dot{\Omega}} \tag{9}$$

Because Earth's spin rate has been replaced with the Moon's rotation rate in this formulation, a TSO cannot have RGTs by nature. Nonetheless, one can still define a metric on how close a TSO is to an SSRGT orbit or an SSO. The node of an SSRGT orbit or an SSO drifts by 2π radians per year, so the closer a TSO's yearly nodal regression is to 2π by minimizing $\Delta\Omega_{year} = |\, 2\pi - d\Omega/dt \times T_{\mathrm{year}}|$, the more it is SSRGT-like. For example, N_L = 57 and N_S = 885 achieves a TSO whose satellite completes 885 orbits every 57 tidal cycles [12]; the satellite will return to a new location with the same tidal conditions where the new location geographically differs from the old location. The following are possible options of designing TSOs proposed here.

Quasi-SSRGT TSO

If the TSO uses an inclination of 97.6° which is the same as SSRGT with a repeat ground track ratio τ = 15, it is an SSRGT-like TSO or quasi-SSRGT TSO. The TSO have an annual nodal drift of 355°/year, differing by only 5°/year compared to an SSO. It is neither exactly an SSO nor an RGT orbit but is close enough to both orbits if we set $\Delta\Omega_{year}$=5°/year as a determinant threshold. From the other perspective, this SSRGT orbit may be said to TSO-like.

Tidal-Sun-Synchronous Orbit

If the TSO uses an inclination to 97.7°, the annual RAAN drift becomes exactly 360°/year, achieving Sun synchronism by abandoning groundtrack repetition. The groundtracks of this TSO is now far from SSRGTs, but it achieves synchronization with the Moon and the Sun at the same time. This "Tidal-Sun-synchronous" orbit (TSSO) incorporates lunar-solar dualsynchronism, which already exists in nature as spring tides and neap tides. In addition to oceanography, these orbits may be applied in quantum satellite communications in which background noises from the Sun and the Moon must be controlled.

Conclusion

This paper derived new types of Earth observation orbits based on traditional Sun-synchronous orbits with repeat ground tracks. These orbit variants can be obtained from breaking groundtrack repetition constraints or changing the reference of synchronism. The proposed classification will further be refined and be applied to case studies such as low-Earth quantum communications or Mars exploration missions [13, 14].

References

1. Short, M., et al., “The remote sensing tutorial”, NASA Goddard Space Flight Center, 2004

2. Scharroo, R., et al., “Jason continuity of services: continuing the Jason altimeter data records as Copernicus Sentinel-6”, *Ocean Science*, Vol. 12, pp. 471-479, 2016.

3. Vallado, D., *Fundamentals of Astrodynamics and Applications*, 3rd Ed., New York, 2007.

4. Paek, S. W., “Reconfigurable satellite constellations for geo-spatially adaptive Earth observation missions”, *Massachusetts Institute of Technology*, 2012.

5. Paek, S. W., Kronig, L., Ivanov, A. and de Weck, O., “Satellite constellation design for the SOLVE mission investigating diurnal cycles of vegetation phenomena”, *Advances in Space Research*, Vol. 62, No. 9, pp.2529-2550, 2018.

6. Boain, R. J., “A-B-Cs of Sun-Synchronous Orbit Mission Design”, *AAS/AIAA Space Flight Mechanics Conference Proceedings*, AAS04-108, Hawaii, USA, February 8-12, 2004.

7. Dorst, N., “What is the average forward speed of a hurricane?”, URL: http://www.aoml.noaa.gov/hrd/tcfaq/G16.html [cited 4 May 2018]

8. Bruccoleri, C., et al., “On Sun-Synchronous Orbits and Associated Constellations”, *Dynamics and Control of Systems and Structures in Space*, Riomaggiore, Italy, July, 2004.

9. Blackwell, W., et al., “MicroMAS: A first step towards a nanosatellite constellation for global storm observation”, *AIAA/USU Small Satellite Conference*, Logan, UT, USA, 2013.

10. Cahoy, K., et al., “The MicroMAS CubeSat Mission”, *AGU Fall Meeting*, CA, USA, 2012.

11. Paek, S. W. and de Weck, O., “Delta-v map of useful orbits for Earth observation missions”, *International Astronautical Congress*, Toronto, September 29-October 3, 2014.

12. Lowe, C., et al., “‘Charybdis’–The Next Generation in Ocean Colour and Biogeochemical Remote Sensing”, *AIAA/USU Conference on Small Satellites*, Logan, UT, USA, 2012.

13. Bourgoin, J.-P., et al., “A comprehensive design and performance analysis of low Earth orbit satellite quantum communication”, *New Journal of Physics*, Vol. 15, 2013.

14. Liu, X., Baoyin, H. and Ma, X., “Five Special Types of Orbits Around Mars, *Journal of Guidance, Control, and Dynamics*, Vol. 33, No. 4, pp. 1294-1301, 2010.