PaddleSats: Attitude Control and Station-Keeping for Ultra-Low Density SSP Satellites

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***Abstract*—'PaddleSats' represent a unique class of Space Solar Power (SSP) satellites distinguished by their ultra-low area density and distinctive design, featuring two circular disks—a solar collection disk and a microwave transmission disk—connected by a cylindrical joint. This paper introduces a comprehensive framework and presents initial results for an advanced PaddleSat attitude control algorithm. The primary objective of this algorithm is to emulate the behavior of traditional geostationary satellites, particularly their station-keeping procedures while adhering to the specific requirements for efficient microwave SSP transmission. Our results show that the PaddleSat attitude control algorithm successfully achieves the desired station-keeping behavior, effectively balancing the demands of stable positioning with the unique requirements of microwave SSP transmission. These findings highlight the potential of PaddleSats as a viable and efficient means of harnessing solar power in space.**

***Index Terms*—Paddlesats, Space Solar Power, Control Algorithms, Station Keeping, Solar Radiation Pressure**

I. Introduction

Solar power is considered the most efficient source of renewable energy. While the Earth receives enough radiation in a minute to cater to the annual energy requirement of the entire population, most of the energy is lost in the atmosphere in the form of diffused radiation. An extension to this area was proposed by Peter Glazer in 1968 [1] in his key patent to use space solar power satellite (SPS) systems. The key idea is to capture the solar power in space and transmit this energy to Earth.

The SPS systems absorb the solar energy using the PV panels of the satellites and convert this energy to microwave signals. Microwave signals can be transmitted to the Earth with much better efficiency than the radiation itself. The energy conversion techniques for the SPS systems are the same as the PV panels - photovoltaic design and thermal-electric conversion. The performance of the SPS systems also depends on various other parameters other than the energy conversion. Solar radiation pressure, orbital perturbations due to the moon, Sun, and Jupiter, microwave radiation recoil pressure, the ellipticity of the Earth's equatorial plane, rotary joint friction torque, magnetic field interactions, and aerodynamic drag are some factors that may alter the orbit and hence, the absorption rate of solar energy.

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In this paper, we explore the use of Paddlesats, a class of large, thin space solar power satellites made up of two ultra-low area density disks – one for capturing solar energy and the other to transmit this captured power back to Earth. This area density can be as low as $1.5kg/m^2$ [2], [3]. This class of satellites experiences non-Keplerian astrodynamics due to significant effects of solar radiation pressure (SRP) [4] owing to their low area density. We assume the deployment of these satellites in the geostationary orbit and try to answer the question of whether these satellites can be deployed without any additional fuel required for station keeping. This can reduce the weight of the satellite in turn leading to lower launch costs, and potentially, increase the lifetime of the satellite in orbit.

Through simulations, we try to understand the impact of external forces such as solar radiation pressure (SRP) on the satellite. We started with constantly pointing the solar disk towards the sun in order to maximize the total energy captured and observed the impact of the SRP on the orbit. The satellite accelerates while it is traveling along the direction of the pressure and decelerates while traveling in the opposite direction. This helped us determine ways in which we could manipulate the effects of SRP on the orbital dynamics to provide station-keeping control authority.

We are able to show how a PaddleSat can be deployed in the geostationary orbit without the need for additional station-keeping fuel. The rest of our paper is organized as follows: In Section II we take a look into the major related works about solar radiation pressure, some of the existing techniques for station keeping, and some control mechanisms to perform station keeping with just the solar pressure. Section III explains the system model and problem formulation. We discuss the objectives and our exploration of the controller design problem in Section IV. Simulation results in Section V show the efficacy of our solution. Section VI concludes the paper with pointers to future research.

II. Related Works and Motivation

Station-keeping is a very important task that needs to be performed by satellites in order to correct the effect of various orbital perturbations. For geostationary satellites, station-keeping requirements typically place a bounding box on the satellite sub point (SSP) drift in the latitudinal (north-south) and longitudinal (east-west) directions to avoid interference or collisions with other satellites.

Traditional geostationary orbital station-keeping relies on small thrusters to correct orbital perturbations. Thrusters used for station-keeping are usually considered sources of instantaneous thrust. The force they impart on the spacecraft is a short duration in relation to the period of the orbit. Any inaccuracies in the orbital maneuver caused by misaligned thrust vectors and non-instantaneous duration are measured and corrected by subsequent station-keeping burns [5]. Station-keeping algorithms allow orbital drift within a longitude-latitude bounding box defined by regulation and mission parameters. The SSP is allowed to drift slowly between the extremes of the bounding box. Prior to violating the bounding box, the station-keeping thrusters are fired to correct the drift. This sends the SSP drifting slowly toward the other extreme. The frequency at which such station-keeping maneuvers must be performed varies based on orbital altitude, spacecraft characteristics, solar weather, and N-body perturbations. The satellites in the NASA GOES constellation perform east-west station-keeping maneuvers about once every 3 months, and north-south maneuvers about once per year [6]. This on-off thruster control is a form of bang-bang control that is optimal for geostationary station-keeping.

Most satellite systems use a thruster to control their attitude, the thrusters pose a strain on the weight and the fuel requirement of the satellite. Glaser's proposal [1] of the Solar Power satellites, which use Solar radiation pressure as a thrust force, had revolutionized the satellite control industry. In the 1970s, various designs had been proposed to harvest the power and also use it for attitude-control. One such model for spinning satellites is the design proposed by Crocker [7]. The author proposes a cylindrical arrangement of solar panels that is deployed with a spinning axis pointing toward the Sun. The SRP force acts on the solar paddles attached perpendicular to the body. These paddles, according to the author, when aligned such that angle between the plane of the spin regulator paddles and the plane of the main paddles is 35 degrees, the satellite would not require any electrical thrusters to drive the satellite in the orbit. Though the mathematical formulation of the system proves to be a feasible design, numerous assumptions are to be addressed like the movement of the Sun in an Earth-centred model, torque vectors due to the gravitational pull of the Earth, and the position of the damper in the satellite and its angular movement vector.

Some of these assumptions were addressed by Modi and Brereton [8] through their simulations of the same model using more real-time parameters. The controller design follows the same principle of altering the angle of the solar paddles to maintain the spin along the spin axis. The angular momentum of the satellite is concluded to be a variable parameter since the spin-axis is not assumed to be cyclic. The controller design has, to a great extent been successful in positioning the satellite spin-axis to the desired normal. While a large satellite system would have a better control capability, smaller satellite systems are intuitively less controllable systems. The authors claim to have addressed this challenge to a great extent using the controller design proposed. The paddles of the above two systems require the presence of solar radiation pressure for the spinning of the satellite. Most research in the 1970s had addressed the control challenge of the satellites for both spinning and non-spinning satellite systems.

Satellite systems are nonlinear systems that are associated with numerous uncertain parameters such as the pitch and yaw angles, and eccentricity in the orbit which serve as essential parameters for attitude-control and SRP counter-thrust. These parameters though crucial for controlling the satellites are less likely to be available to run control simulations. This issue was addressed by Lakshmi [9] through an estimator design for the input parameters and the output was tested using three control algorithms. The nonlinear adaptive control proposed uses the inverse control law and a high gain estimator to project a trajectory for a satellite system. While the controller gives feedback and control to the system, it is highly susceptible to noise. The uncertainty of the assumed parameters and the non-linearity of the system are cited to be the origin of the noise in the controller output. A finite time controller with estimated inputs from a differentiator and a higher-order slide mode controller gives a more practical approach to the control problem. The controller simulation for these inputs has lower noise susceptibility and thus a more efficient solution to the control design.

The development in satellite technology and the control laws has addressed both the weight constraint of solar power satellite systems and their attitude control. Low-area density satellites have been a point of research since the Glaser proposal [1] but the area density of the satellites has been reduced to the record minimum only very recently [2]. While the SPS systems are the optimal solution to the weight and volume problems, they pose a huge challenge to attitude control as they are more susceptible to perturbations due to SRP. Brunett and Schaub [10] propose an attitude controller for a single-plate satellite. The controller is designed for an SRP model with relative motion. The uncertainties in the orbital input parameters are accommodated in the controller model which led to a more comprehensive and realistic set of orbital results. This system uses a Linear Quadratic Regulator to counteract the SRP component on the satellite. But like the former controller, certain input parameters are assumed.

While the above models answer the question of optimal control for station-keeping, new designs are being proposed and simulated for better results.

III. System Model

In this paper, we consider PaddleSats with two identical circular discs deployed in the geostationary orbit. One of the discs is a solar panel whereas the other one is a high-gain antenna that is assembled with a 2-degree-of-freedom cylindrical joint (Fig 1). Since our goal for the system is to function by just using SRP, the overall weight of the system is greatly reduced.

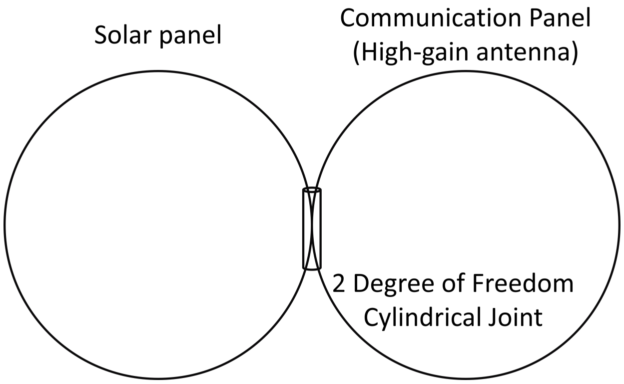


Fig. 1: A schematic of the paddlesat design consisting of the two circular panels - communication and solar connected by cylindrical hinge joint.

The solar panel has a reflectivity of 0.21 and the antenna has 0.3 [11], [12]. We consider the effects of the SRP on both the equivalently sized solar panel and communications dish with their respective reflectivity coefficients. We use the solar pressure value of 4.56 μN/m^2 [12] as observed at a distance of 1 astronomical unit (AU). We assume a geostationary satellite orbit where the orbits of the sun, earth, and satellite are coplanar. The SRP force experienced by the PaddleSat will therefore be in the orbital plane, yielding orbital perturbations that only influence the longitudinal east-west drift of the SSP.

This setup results in the forces acting on the satellite as follows:

- Gravitational Pull by the earth

$$F = -\frac{GM_E M_S}{r^2}\hat{r} \tag{1}$$

- and from [12], the Solar Pressure force is

$$F = -Pcos(\theta)A[(1-\epsilon)\hat{e} + 2\epsilon cos(\theta)\hat{n}]. \tag{2}$$

where P is the solar radiation pressure, A is the area of the panel, θ is the angle of incidence, $\hat{e}$ is the direction of the solar radiation pressure, and $\hat{n}$ is the normal direction of the panel.

With a lot of GEO satellite infrastructure already in space, the satellite service providers and engineers must abide by certain station-keeping requirements. For example, the ITU levies strict requirements on the orbital drift of satellites in the fixed-satellite service to ± 0.1 degree of east-west drift. Other geostationary satellites, such as those in the GOES constellation operated by National Oceanic and Atmospheric Administration (NOAA), maintain ± 1 degree longitude boxes [6]. PaddleSat is assumed to have strict east-west drift requirements similar to that of the fixed-satellite service due to communications design parameters and safety. Therefore, PaddleSat control algorithms assume a ± 0.1 degree east-west bounding box from nominal ground station position.

Constrained to planar motion, the solar incidence angle α, valid in the range $[-90, 90]$, is the tilt of the solar panel relative to the sun. $\alpha = 0$ indicates the panel is normal to the sun and generating max power. Conversely, $\alpha = 90.0$ or $\alpha = -90.0$ yields no power generation. The communication dish is assumed to always point nadir. The controller assumes the PaddleSat joint responds to commands instantaneously and requires no power to move.

IV. Controllers

Unlike traditional thruster-based geostationary orbit station-keeping, SRP-based station-keeping relies on a small but continuous solar pressure force applied over a large area. The design of a PaddleSat attitude controller attempts to maximize ground station received power by controlling the angle of the solar panel relative to the sun.

Ground station received power is expressed as a function of the instantaneous solar power generation efficiency s, transmission efficiency t, and satellite peak power generation P in Watts,

$$power = s * t * P \tag{3}$$

where we use the value of P 1W which allows easy comparison between controller efficiencies.

Solar power generation efficiency is a function of the commanded incidence angle of the solar panel and can be expressed as $s = cos(\alpha)$. Transmission efficiency is a function of the antenna gain pattern and the current SSP drift from the ground station. The communications dish is designed to have a parabolic fall-off to a half-power beam width equivalent to the size of the east-west bounding box. The PaddleSat is not allowed to transmit if the current SSP drift is beyond the east-west bounding box. Therefore, the transmission efficiency is a piecewise function as shown in Fig 2.

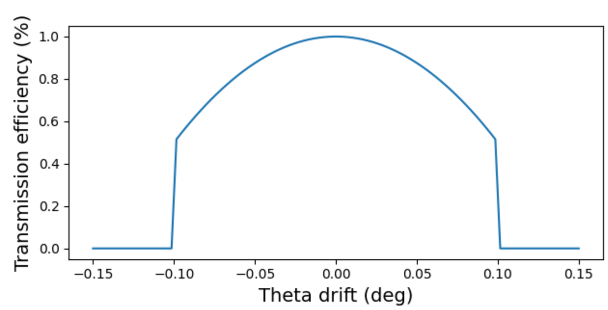


Fig. 2: Comm transmission efficiency function for max drift of ± 0.1 deg

We designed and tested a wide spectrum of controller designs. The most simple controller is the *static_incidence* that commands the solar panel to continuously track the sun at a given α offset. This controller requires active solar panel alignment throughout the orbit. The *static˙incidence(*$\alpha = 0.0$*)* controller maximizes power generation throughout the orbit. Conversely, the *static_incidence(*$\alpha = 90.0$*)* controller does not generate any power. Interestingly, the orbit of *static_incidence(*$\alpha = 90.0$*)* controller is still perturbed by the effects of the SRP on the communications dish.

The *zenith* controller varies the angle of the solar panel such that it is always pointing nadir by setting the commanded angle to equal the orbital angle. This controller requires no active solar panel alignment as it is the natural way the solar panel changes orientation throughout an orbit.

The *zenith_off_90* controller varies the angle of the solar panel offset such that it is offset 90 degrees from the current orbital angle. Conversely, the *negative˙zenith_off_90* controller performs a -90 degree phase shift. Both these controllers require active solar panel alignment throughout the orbit.

The *clipped_zenith_off_90* controller has the same operation as the *zenith_off_90* controller except the output is clipped to a specified *angle* range. The output of the controller will never exceed +*angle* and never be below -*angle*.

The *smart* controller is designed to maximize power generation while maintaining east-west station-keeping based on the results of the simulations presented in Section V.

V. Simulation Experiments and Results

A. Simulation Setup

For our simulations, we incorporate the gravitational force along with the force exerted by the solar radiation pressure. We perform our analysis in an earth-centered frame with the earth, sun, and satellite lying in the same plane. Along this plane, the earth rotates around itself whereas the satellite revolves around the earth with the time period being one sidereal day. We also move the sun around the earth with a time period of one sidereal year. For almost all our simulations, we assume the area density of the Paddlesat as $5kg/m^2$.

We run our simulations for a total period of 30 days studying a wide variety of controller scenarios. For each such scenario, we show the orbital diagram, the longitude value of the satellite sub-point, the power received by the ground station, and the power transmitted by the communication panel. For the power being transmitted, since our goal is to study the differences caused by the drift, we ignore free space path loss instead focusing on the trends observed in the absolute values of the power transmitted.

B. Analysis

The *static_incidence* controller provided insight into how the orbit of PaddleSat behaves with SRP effects on the communications dish and solar panel. *static_incidence(*$\alpha = 0.0$*)* maximizes power generation but the drift is large and will quickly push PaddleSat out of the bounding box after only 7 days as shown in Fig 3.

When we compared *static_incidence(*$\alpha = 60.0$*)* in Fig 4 and *static_incidence(*$\alpha = -60.0$*)* in Fig 5, we found that positive and negative incidence angles yield symmetrical effects with drift rates that trend in the same direction.

It is clear that *static_incidence* alone does not provide enough control authority. However, one can still characterize the optimal $alpha$ for the *static_incidence* controller given an area density. Fig 6a and Fig 6b show that the optimal angle changes for changing area densities. Lower area density ratios lead to more drift and given sufficient time the optimal

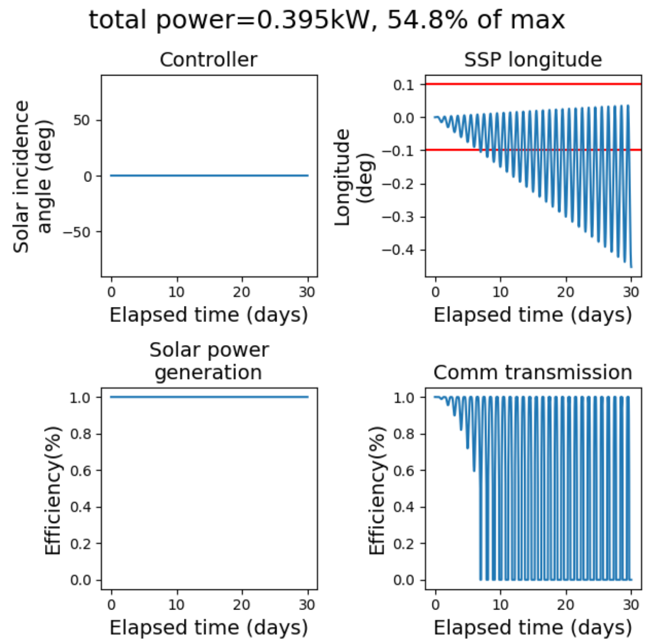


Fig. 3: 30 days of *static_incidence(*$\alpha = 0.0$*)*

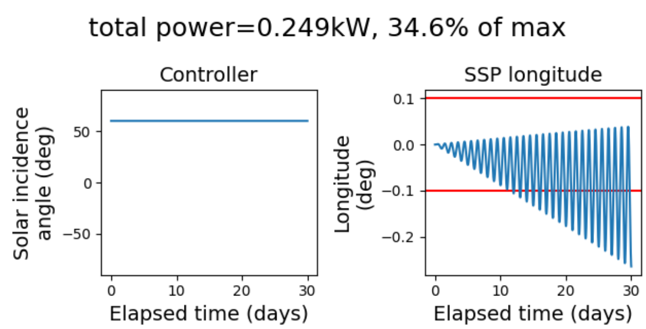


Fig. 4: 30 days of *static_incidence(*$\alpha = 60.0$*)*

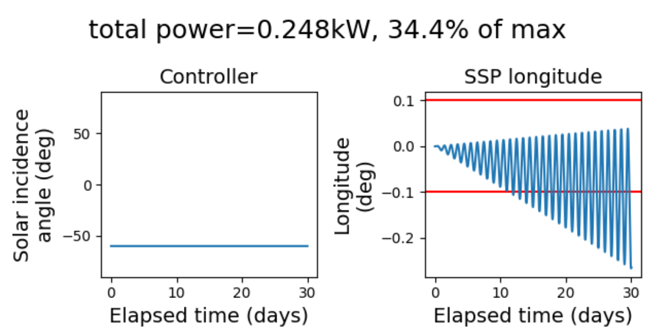
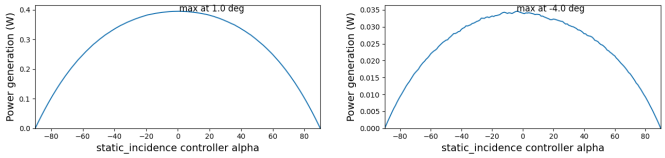


Fig. 5: 30 days of *static_incidence(*$\alpha = -60.0$*)*

static_incidence controller will not be 0 degrees because it optimizes the power generation and the time spent inside the bounding box. However, this result largely is an artifact of the time span chosen. The PaddleSat controller will make state changes on time spans far smaller than where this effect becomes pronounced.



(a) Area Density=$5kg/m^2$ (b) Area Density=$0.1kg/m^2$

Fig. 6: *static_incidence* controller at varying $alpha$ for different area densities

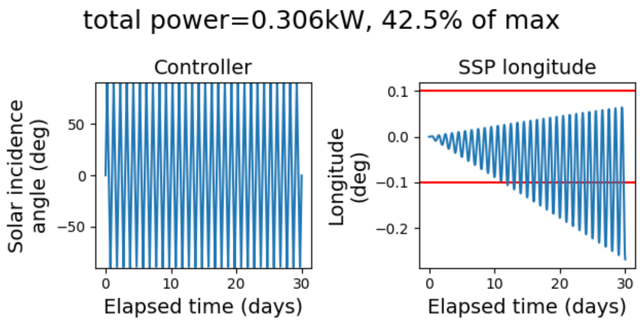


Fig. 7: 30 days of *zenith* controller

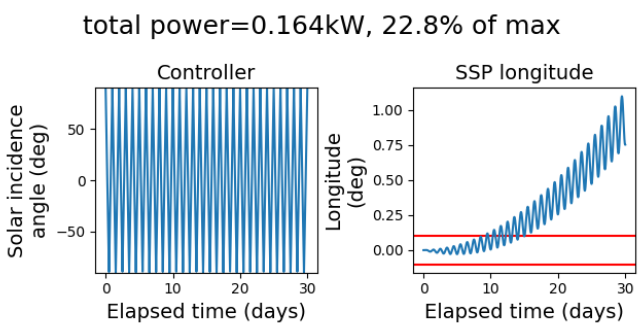


Fig. 8: 30 days of *zenith_off_90* controller

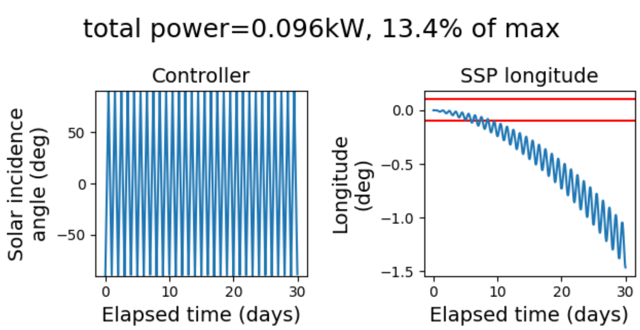


Fig. 9: 30 days of *negative_zenith_off_90* controller

We next look at the family of *zenith* controllers. While The *zenith* controller does not help reduce the orbital drift, it however shows the effect of the SRP on the communications dish exclusively. Therefore, we looked at the *zenith_off_90* and *negative_zenith_off_90* controllers that show distinctly unique behavior as seen in Fig 8 and Fig 9 respectively. This behavior

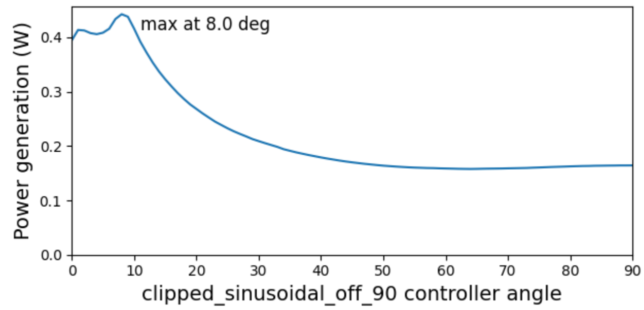


Fig. 10: Varying cutoff angles of *clipped_zenith* controller

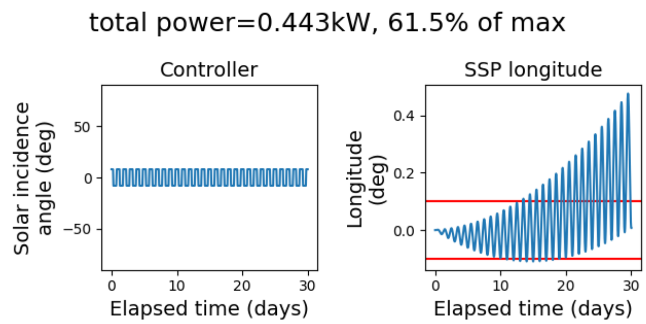


Fig. 11: 30 days of *clipped_zenith(angle=8.0)* provides desired west drift control authority

shows that a PaddleSat attitude controller can correct a drift rate occuring in either east or west directions individually. We found *zenith_off_90* to be the first controller that demonstrated a westward drift. Both controllers remain continuous such that there are no sudden jumps in commanded attitude throughout the simulation.

We then look at ways through which power generation can be maximized by looking at *clipped˙zenith* control by restricting the range of the *zenith_off_90*. The *clipped_zenith_off_90* controller allows for more optimal power generation by restricting the range the *zenith_off_90*. Fig 10 shows the optimal cutoff angle for the controller to maximize power generation, and Fig 11 shows that control authority is still sufficient at this cutoff angle to correct east-ward drift.

Using the bang-bang control mechanism to switch between the *static_incidence(*$\alpha = 0.0$*)* controller and *clipped_zenith(angle=8.0)* controller, the PaddleSat is able to control orbital drift within the east-west bounds. The bang-bang control law allows for maximum power generation and maximum negative longitude drift with *static_incidence(*$\alpha = 0.0$*)* until that drift leads to a bounding box violation, at which point the controller switches to the *clipped_zenith* to perform a period of correction (Fig 12). This behavior is analogous to the way traditional thruster-based geostationary station-keeping corrections are performed.

We observed that the orbital perturbations PaddleSat experiences cause the orbit to rotate. Over time, this rotation grows and is only compounded by the effect of regular time

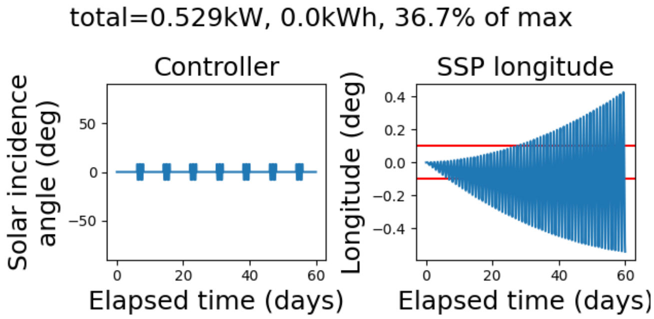


Fig. 12: 30 days of *smart* controller provides desired east and west drift control authority

interval controller actuations that do not rotate with the orbit. Similar in concept to the method used to derive the other controllers, if the *smart* controller's actuation intervals rotated with the orbit (with respect to time) the negative feedback loop may be eliminated (as in *zenith˙controller*). If the actuation intervals are rotated "beyond" the orbit (with respect to time), an improved *smart* controller may work to dampen the high-frequency oscillations.

VI. Conclusion and Future Work

In this paper, we study different classes of attitude control algorithms that can be used for Paddlesats. We are able to show that the average orbital drift rate can be corrected by using the *zenith_off_90* controller by using the bang-bang control mechanism in our *smart* controller. Despite its susceptibility to larger high-frequency oscillations compared to other controllers, this represents a significant advancement in research for PaddleSat attitude control. Our hypothesis is that these high-frequency oscillations can be dampened by identifying mechanisms to destructively interfere as part of the bang-bang control mechanism.

Furthermore, we hypothesize that these high-frequency oscillations can be mitigated by incorporating mechanisms for destructive interference within the bang-bang control mechanism. This suggests a potential avenue for future exploration in this direction.

To further advance the field, it is recommended to conduct a comprehensive analysis to determine the optimal times for activating the bang-bang controller through simulations with varying controller periodicity. Additionally, an additional layer of logic can be developed to enable automatic actuation of the controller when bounding box violations are predicted, enhancing the efficiency of PaddleSat operations. These simulations will provide valuable insights for designing a prediction algorithm aimed at maximizing power generation.

By addressing these areas of future work, we can continue to refine the attitude control algorithms for PaddleSats, paving the way for improved power generation and the realization of their full potential in space-based solar energy applications.

Acknowledgments

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