All Sky Survey Mission Observing Scenario Strategy

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This paper develops a general observing strategy for missions performing all-sky surveys, where a single spacecraft maps the celestial sphere subject to realistic constraints. The strategy is flexible such that targeted observations and variable coverage requirements can be achieved. This paper focuses on missions operating in Low Earth Orbit, where the thermal and stray-light constraints due to the Sun, Earth, and Moon result in interacting and dynamic constraints. The approach is applicable to broader mission classes, such as those that operate in different orbits or that survey the Earth. First, the instrument and spacecraft configuration is optimized to enable visibility of the targeted observations throughout the year. Second, a constraint-based high-level strategy is presented for scheduling throughout the year subject to a simplified subset of the constraints. Third, a heuristic-based scheduling algorithm is developed to assign the all-sky observations over short planning horizons. The constraint-based approach guarantees solution feasibility. The approach is applied to the proposed SPHEREx mission, which includes coverage of the North and South Celestial Poles, Galactic plane, and a uniform coverage all-sky survey, and the ability to achieve science requirements demonstrated and visualized. Visualizations demonstrate the how the all-sky survey achieves its objectives.

I. Introduction

A. Observing Scenario Overview

This paper develops an general observing strategy approach for accomplishing an all-sky survey, which could be applied to both mapping the celestial sphere (zenith-pointing) or mapping the Earth (nadir-pointing). The approach is flexible such that it is applicable to missions with focused observations and those that may have variable coverage requirements. The approach focuses on missions in a Low Earth Orbit (LEO), although the constraints can be modified or relaxed and applied to a broader range of orbit scenarios. The observing problem is dynamic throughout the year as the orbit evolve relative to the Sun, Moon, celestial sphere, and other potential targets (e.g. Galactic plane). The problem formulation considers the interacting and dynamic constraints related to thermal and stray-light avoidance relative to the Sun, Earth, and Moon for a mission operating in LEO. These combined constraints limit the zone where the spacecraft and instrument can point, which varies throughout the year. Decisions related to both to the spacecraft configuration and observing strategy, which must be robust throughout the full year, are addressed. System-level issues related to the spacecraft configuration, the telecommunication system, the attitude control system, and the thermal control system, are considered in the strategy.

B. Literature Review

There is a large body of related research on spacecraft operations and scheduling. Most of the scheduling approaches described in the literature involve a nadir-pointing spacecraft, however the formulations in the literature share similar dynamics, constraints, and objectives with the observing problem addressed in this paper. We review the historic space-based all-sky survey observatories and scheduling work on pointed observations and discuss their similarities and differences relative to the problem addressed in this paper.

Several space-based observatory missions that performed or proposed to perform all-sky surveys. The Infrared Astronomical Satellite (IRAS) was the first space-based observatory to perform a survey of the entire sky at infrared wavelengths from LEO, and it mapped 96% of the sky four times, each time at a different wavelength [1]. The IRAS

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satellite design and survey strategy were optimized to maximize the detection of point sources[1], and consisted of mapping out "lunes" bounded by ecliptic meridians 30° apart[2]. The Akari infrared astronomy satellite surveyed the entire sky in the near-, mid-, and far-infrared from LEO [2]. This mission achieved continuous coverage by pointing in the zenith direction and scanning the sky continuously, while pointed observations are constrained by Sun and Earth constraints[3]. Akari scanned 94% of the sky twice and performed 5,000 pointed observations approximately 1.5 years following launch. Wide-field Infrared Survey Explorer (WISE) performed an all-sky survey from LEO, imaging every part of the sky at least 8 times in ten months [3]. WISE's observing scenario consisted of continuously pointing in the zenith direction and taking a 47-arcminute field of view image every 11 seconds [4]. TBD- mention COBE, WMAP, and Planck. The ROSAT All Sky Survey operated in LEO and consisted of 1378 distinct fields, where each scanning-mode observation covers 6.4 x 6.4° of sky [5]. The TESS mission will perform a a step and stare approach to monitor the full celestial sphere in a two-year mission by stepping the FOV 27° east every 27 days from a High Earth Orbit in 2:1 resonant orbit with the Moon [4]. Most of these observing strategies consisted of a step-and-stare approach with a zenith-pointed instrument to accomplish an all-sky survey, and most did not also consider pointed observations.

There has been considerable scheduling work focusing on pointed observations that is informative in the development of scheduling algorithms. The Hubble Space Telescope (HST), launched in 1990, was one of the largest and most complex scheduling problems because 10,000 to 30,000 observations must be scheduled annually and operated in the challenging LEO environment and was subject to a large number of operational and scientific constraints [5]. HST scheduling problems were formulated as constraint satisfaction problems and solved with search approaches that include multi-start stochastic repair strategies. The James Webb Space Telescope (JWST), HST's predecessor to be launched in 2018, will operate from Earth-Sun L2 is also a complex multi-objective scheduling problem. JWST scheduling problems consist of three three objectives: to minimize schedule gaps, minimize the number of observations that miss their last scheduling opportunity, and minimize momentum build-up. These scheduling problems are solved using evolutionary algorithms [6, 7].

This paper develops a general approach to scheduling all-sky strategies that can accommodate diverse survey requirements and goals for the first time. Most observing problems in the literature consist of a zenith-pointing spacecraft that scans the sky quickly and it is not clear how they extend to accommodate additional surveys. Furthermore, many are not restricted by dynamic thermal and stray-light constraints, nor do they consider instrument and spacecraft configuration decisions. In general, the formulations and approaches in the literature (Refs. [1, 2, 3, 4, 5, 6, 7]) have a different set of problem objectives, decisions, and constraints relative to the all-sky survey considered in this paper. This paper develops a general approach for accomplishing an all-sky survey, which is flexible and can accommodate diverse objective goals and constraints. Much of the observatory scheduling literature is informative in developing these models and algorithms.

C. Paper Overview

The observing scenario problem constraints and objectives are described in detail in Section II. Capturing this problem as a single global problem would be complex and may be difficult to generate solutions guaranteed optimal solutions. To overcome this challenge, this paper separates and solves these problems in series, passing a simplified set of constraints between sub-problems. Thus, although solutions may not be guaranteed optimal, they are guaranteed to be feasible. First, a feasible instrument configuration is established that satisfies the Sun-avoidance constraint and observability requirements throughout the year. Second, the configuration and Earth-avoidance (thermal) constraints are combined and yield maximum observation time constraints that depend on the angle of the orbital plane relative to the Sun. These first two steps are described in Section III.A. Third, a high-level scheduling strategy and a resultant constraint-based heuristic algorithm is developed in Section III.B. This constraint-based approach guarantees solution feasibility. Extensions to the special case focusing on the Galactic plane is described in Section III.C. Section IV applies the general approach to the SPHEREx mission, an astrophysics LEO mission which includes three district surveys, including an all-sky survey with specific coverage requirements. The survey goals are achieved in both idealized and realistic cases, and demonstrated with coverage visualizations. The paper contributions and results are summarized and insights into how the step-wise approach presented in this paper can be applied to other observing scenarios are described in Section V.

[1] http://www.ipac.caltech.edu/project/15
[2] http://irsa.ipac.caltech.edu/IRASdocs
[3] http://www.ir.isas.jaxa.jp/ASTRO-F
[4] http://wise.ssl.berkeley.edu/documents/FactSheet.2010.1.4.pdf
[5] http://heasarc.gsfc.nasa.gov/docs/rosat/rass.html

II. Problem Description

This section describes the generic all-sky scheduling problem, by defining vectors, angles, constraints, and then defining scheduling terms used throughout the paper. It is assumed that the spacecraft is in a Sun synchronous LEO, as typically selected for all-sky surveys, such as IRAS, Akari, and WISE. Missions with different orbits may still benefit from the algorithms in Section III, but may require alternative formations of the constraints presented in this section (in many cases most of these constraints can be relaxed or ignored for orbits other than LEOs, which tend to be particularly constraining). In Sun synchronous orbits, every rotation about the Earth provides visibility to all declinations. By definition, Sun synchronous orbits precess at a rate of approximately one degree a day, thus the instrument can access the entire celestial sphere in approximately six months.

The overall goal of the scheduling problem is to efficiently observe the celestial sphere. The approach presented in this paper can be applied to pointed observations distributed across the celestial sphere or the case where the entire celestial sphere must be observed. The decision variables are where and when to point the instrument on the celestial sphere as a function of time. The dynamics include the orbit motion relative to the Earth, Sun, Moon, celestial sphere, and other targets (e.g. Galactic plane). There are constraints related to the thermal and stray-light avoidance from the Earth, Sun, and Moon. There may also be constraints that the mission must accomplish targeted observations or observe certain areas of the celestial sphere more often.

To scan the celestial sphere, the spacecraft points roughly in the zenith direction, and the instrument is fixed at an offset angle, see Fig. 1. Prior to describing the constraints, several vectors and angles are defined:

- Spacecraft +Z axis: Symmetry axis of the spacecraft.
- Instrument boresight: Vector aligned with the center of the telescope field of view (FOV).
- Beta angle (β): The angle between the orbital plane and vector to the Sun.
- Tilt angle (θ): The angle between the orbital plane and the spacecraft +Z axis in the orbit cross-track direction.
- Cant angle (ϕ): The angle between the spacecraft +Z axis and the instrument boresight.
- Nod angle (δ): The angle between the spacecraft +Z axis and the local zenith in the orbital plane.

The scheduling problem is also subject to the following spacecraft and instrument constraints (where the angles are shown in Fig. 1):

- Sun-avoidance criteria: Spacecraft +Z axis cannot be pointed within Ω of line-of-sight to the Sun due to thermal constraints,
$$\theta \geq \Omega - \beta. \tag{1}$$
- Earth-avoidance criteria: Spacecraft +Z axis cannot be pointed more than α from the local zenith due to thermal constraints. The spacecraft is rotated both in the cross-track direction by θ and the in-track direction by δ, thus the constraint on the resulting total angle is:
$$\cos(\alpha) = \cos(\theta)\cos(\delta), \tag{2}$$
- Moon-avoidance criteria: Instrument boresight cannot point within ζ of line-of-sight to the Moon due to stray-light constraints.

These combined constraints result in visibility restrictions for where spacecraft and instrument can point as a function of time. In particular, the spacecraft boresight must point to the right of the Sun Avoidance Line (where the Ω Sun-constraint is satisfied) and within the Earth Zone to satisfy the combination of constraints in Fig. 2.
The scheduling terms used in this paper are defined as:

- Pointing: Period of time focused on a region of the sky, comprised of steps.
- Step: Subset of a pointing pointing focused on one target in the sky. A pointing is composed of a fixed number of steps.
- Large Slew: A maneuver to transition between pointings.
- Small Slew: A maneuver to transition between steps.

- Redundancy: Number of times the same region of the sky is observed by the desired part of the instrument FOV appropriate for that survey (i.e. if a region of the sky is observed once by every wavelength, the redundancy is one).

Throughout the remainder of the paper the observing scenario is described in terms of the number of pointings per orbit and number of steps per pointing.

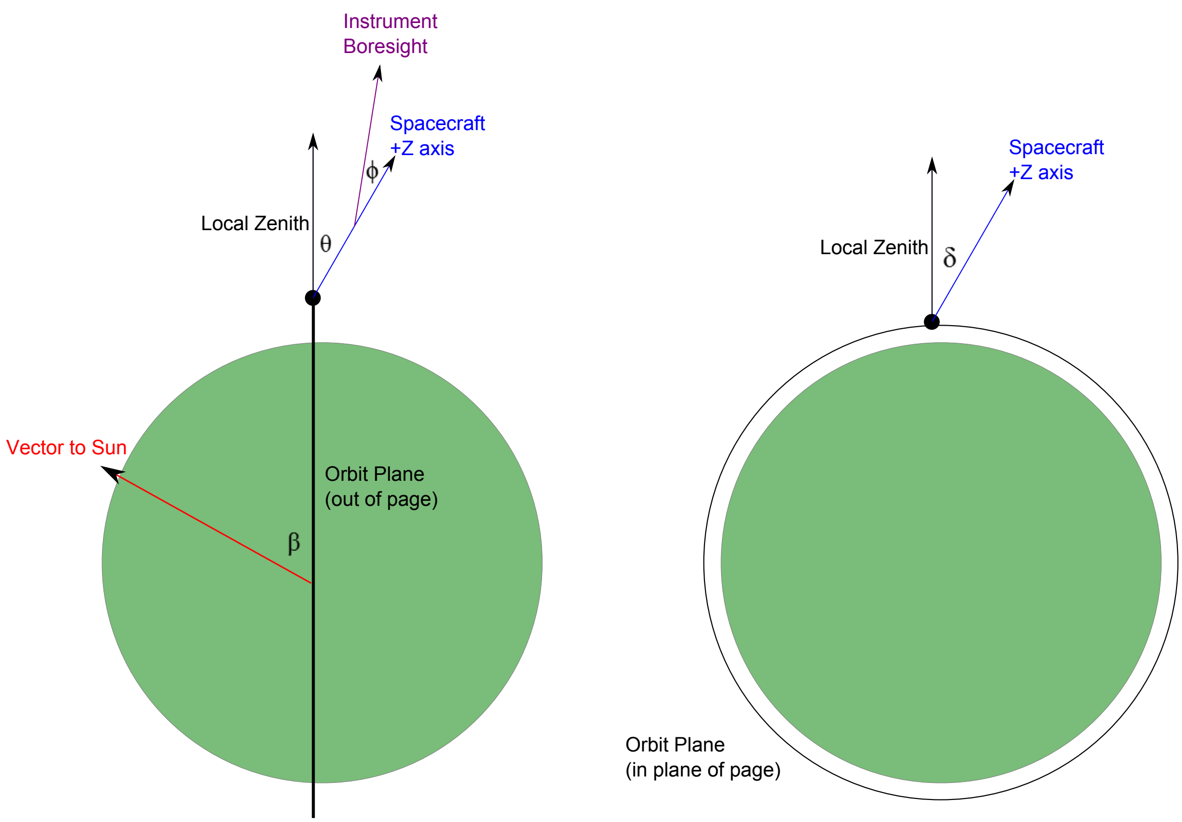
III. Observing Scenario Strategy

The general all-sky observing strategy is to point the spacecraft roughly in the zenith direction in the orbit plane throughout every orbit. Both the ascending and descending portions of the orbit are utilized equally for observing. First, this enables mapping of the entire celestial sphere because the orbital plane naturally precesses at a rate of one degree per day, enabling coverage of the entire celestial sphere in six months. Second, this maximizes the time before the Earth-avoidance constraints will be violated by minimizing the number of pointings and thus number of slews (i.e. the instrument can point at a target in the sky for a long time).

A. Spacecraft and Instrument Configuration

To satisfy the Sun-avoidance constraint, the general strategy is to tilt the spacecraft according to $\theta = \Omega - \beta$ as in Eq. 1. To satisfy the Earth-avoidance criteria in Eq. 2, the nod in the in cross-track direction, δ, is constrained,

$$\delta_{max} \leq \cos^{-1}\left(\frac{\cos(\alpha)}{\cos(\theta)}\right) \tag{3}$$



a) View Orthogonal to Orbital Plane **b) View in Orbital Plane**

Figure 1. Angle Definitions

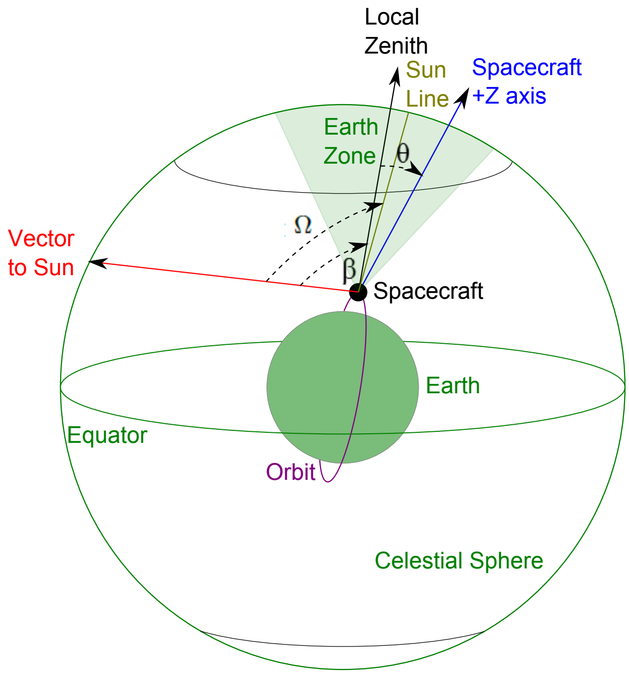


Figure 2. Constraints on spacecraft orientation. The spacecraft must point to the right of the Sun Avoidance Line and within the Earth Zone.

This restricts the time the instrument can focus at a single target, where the maximum time is a function of two times the half angle and the orbital period (where the following equation accounts for the conversion from degrees to radians),

$$T_{max} = \frac{\delta_{max} P}{\pi}, \tag{4}$$

where P is the orbital period and δ_{max} is given in radians. The maximum pointing times vary as a function of β throughout the year. This places dynamic constraints on the problem, where T_{max} varies throughout the year, and as a result, the minimum number of pointings per orbit is higher for lower β values. An example is given in Fig. 7b for the SPHEREx mission described in the next section.

B. Scheduling Algorithm

The general scheduling approach is to prioritize the most constrained pointings and steps and schedule these first, while satisfying the dynamic constraints such as the β and position of the targets (e.g. Galactic Plane). Second, the all-sky algorithm generates a schedule that maps the complete celestial with the desired redundancy in the time of interest while satisfying all constraints. The approach is constraint-based, so by construction yields feasible solutions. Solutions are not guaranteed to be globally optimal; however they do provide good initial guesses for further optimization.

First, the targeted pointings are scheduled according to the desired cadence and when the target regions are accessible, which depends on the time of the year. The cadence for the these observations is selected to achieve the required total number of steps per time that satisfies coverage requirements and is feasible with the rest of the survey. Second, the all-sky pointings are scheduled, which is more complex and described in greater detail next.

To achieve complete coverage of the all-sky survey, pointings are dedicated to certain declinations, and successive steps at that declination are taken varying the RA (where the step size is equal to the desired FOV step size). Over time, the individual images will stack up and achieve full coverage of each declination ring, as in Fig. 3. The all-sky pointings are scheduled according to a heuristic-based scheduling approach, which can be applied to any time horizon. The number of total required steps at each declination is a function of this time horizon. The strategy is to first identify the times that are not already scheduled by targeted pointings and the required slew times between pointings. Second,

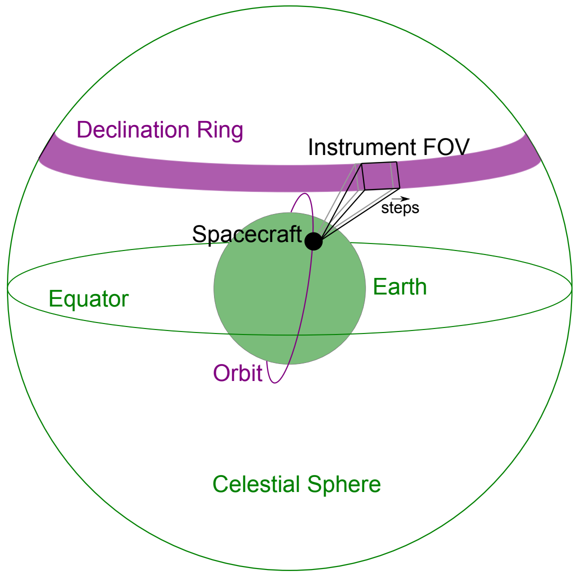


Figure 3. All-sky survey strategy where the purple ring shows coverage along a ring of constant declination, where on successive pointings, the FOV is stepped along this ring.

the algorithm schedules each pointing by determining the maximum feasible observing time for that pointing (given a starting time), which is the minimum of the time until the next scheduled pointing and T_{max} as constrained by β. Third, the declinations are identified that can be feasibly viewed for this maximum time (i.e. do not violate the Earth constraint at the start or end of the time interval). Fourth, the feasible all-sky declination with the maximum number of remaining required steps is selected. This prioritization enables all the all-sky declinations to be covered with the required number of steps in the given time horizon. Fifth, the starting and ending times of this pointing are assigned, all counters are updated, and the start time of the next pointing is assigned. This process is repeated until every block of unassigned time is scheduled with all-sky pointings.

The following definitions are necessary to understand the algorithm pseudo-code,

- T_s: Vector of chronologically sorted starting times of all scheduled pointings.
- T_e: Vector of chronologically sorted ending times of all scheduled pointings.
- $d(t)$: Vector of spacecraft declination, which is a function of time, t.
- D: Vector of required declinations for the all-sky survey.
- RD: Vector of required number of steps to cover every declination in D, which depends on the duration of time being scheduled. The number of steps to be scheduled for one day is a function of declination.
- SD: Vector of the already scheduled number of steps for every declination in D.
- PD: Vector of chronologically sorted declination index for scheduled pointings, corresponding to the times in T_e and T_s with indices referring to the declinations in D.
- $n = |T_s| = |T_e| = |PD|$: Number of scheduled pointings.
- s: Temporary variable indicating the number of steps in that pointing.
- t_{sp}: Duration of large slew between successive pointings.
- t_{ss}: Duration of small slew between successive steps.

- t_{st}: Duration of small step.
- τ: Temporary time variable representing the start of the next pointing.
- $T_{max}(\beta)$: the maximum pointing duration, which depends on β, as in Fig. 7b.
- $\delta_{max}(\beta)$: the maximum tilt in the cross-track direction, which depends on β, as in Eq. 3.
- $F \subset D$: Vector of feasible declinations for a given scheduling instance.

Prior to starting the all-sky scheduling algorithm, the scheduled targeted observations captured in T_s, T_e, and PD, and the pointing counter is initialized to $j = n$. The algorithm for assigning the all-sky survey pointings is as follows:

for i=1 **to** i = n-1 **do**

  if $T_s(i+1) - T_e(i) \geq t_{sp} + t_{st}$ **then**
    $\tau = T_e(i) + t_{sp}$
    while $\tau \leq T_s(i+1) - t_{sp} - t_{st}$ **do**
      $j \rightarrow j + 1$
      $\Delta t \rightarrow \min(T_{max}(\beta), T_s(i+1) - \tau - t_{sp})$
      $F \rightarrow intersect(find(|d(\tau) - D| < \delta_{max}), find(|d(\tau + \Delta t) - D| < \delta_{max}))$
      $j \rightarrow \max(RD(F) - SD(F))$
      $s \rightarrow ceiling((\Delta t + t_{ss})/(t_{st} + t_{ss}))$
      $SD(F(j)) \rightarrow SD(F(j)) + s$
      $PD(j) \rightarrow D(j)$
      $T_s(j) \rightarrow \tau$
      $T_e(j) \rightarrow \tau + \Delta t$
      $\tau \rightarrow \tau + \Delta t + t_{sp}$
    end while
  end if
end for

The all-sky algorithm above will append vectors T_s, T_e, PD, which will no longer be ordered chronologically because the algorithm fills in time periods without scheduled pointings (however they can be easily sorted). This scheduling approach, including selection of the cadence and distribution of the targeted observations, as well as integration times for all surveys, should be iterative until the appropriate parameters are determined to achieve the scheduling goals. In particular, they should be selected such that all required all-sky pointings are accomplished (i.e. $SD = RD$), and that the desired trade-off between scheduling efficiency and maximizing the deep survey redundancy is achieved. After the algorithm has been completed, the resulting schedule can also be improved, for example short periods of time that are not scheduled can be scheduled by increasing the number of steps (adding redundancy) or scheduling other spacecraft operations (e.g. downloads, reaction wheel de-saturation).

Completing the all-sky survey can be visualized as imaging a grid of the celestial sphere, with vertical bands with height equal to the instrument's FOV and within each band scanning at angular steps equal to the angular wavelength steps (s_{AS}). When projected as an equal-area Mollweide map, as in Fig. 12, the circumference at declinations is different- maximum at the equator and minimum at the poles due to the equal-area projection. To achieve global coverage with a redundancy of one in 6 months, a circumference of $c = 360° \cos(d)$ must be covered for each declination, d. Thus, fewer steps are required near the poles relative to near the equator. The total number of steps to cover this area depends on the FOV size and number of required steps across the detector.

C. Special Case: Galactic Plane Survey

To demonstrate how a targeted observation can be accommodated in the observing strategy and due to the scientific interest in the Galactic plane, we address the special case where in addition to the all-sky survey, the mission must include coverage of the Galactic plane with higher spatial resolution or redundancy than the rest of the survey. In a LEO, the RA where the spacecraft crosses the Galactic plane varies throughout the year, so the orbit declination where the orbit crosses the Galactic plane will be dynamic. The spacecraft has two opportunities to image every part of the Galactic plane every year due to the orbit precession, which provides some flexibility on when Galactic plane pointings are scheduled to satisfy its redundancy requirements.

The Galactic plane runs at an angle relative to the orthogonal lines of RA and declination. To efficiently cover this area, the proposed strategy is to rotate the spacecraft such that the long end of the FOV is parallel to the Galactic plane and the FOV is centered over the Galactic plane. Thus, successive steps along the Galactic plane with step size to achieve the specific survey coverage goals, as in Fig. 4. The number of steps required to cover the Galactic plane depends on the FOV and redundancy requirements. Note the ability to rotate the spacecraft may be constrained by solar panel or star tracker angles, or thermal limitations.

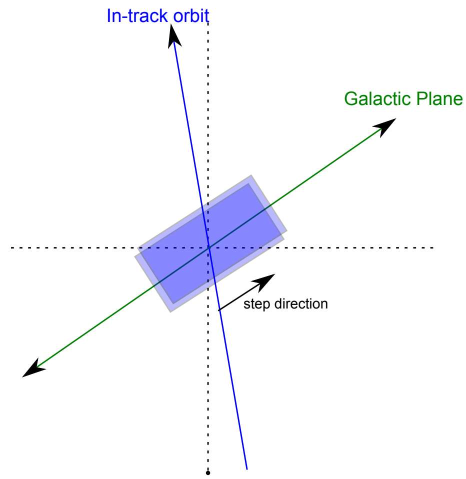


Figure 4. Steps along Galactic plane to achieve complete coverage

IV. Application to the SPHEREx Mission

This section applies the scheduling strategy and algorithm to the SPHEREx mission, proposed by California Institute of Technology (Caltech) and Jet Propulsion Laboratory (JPL). The SPHEREx is an astrophysics mission performing an all-sky spectroscopic survey, studying inflationary cosmology, the history of galaxy formation, and Galactic ices. The SPHEREx spacecraft will be in launched into a 500 km altitude sun-synchronous (inclination=$97.4°$) nearly terminator orbit (18 hr orbit) with a period of 94.6 minutes, selected to minimize thermal concerns and maximize power collection with the ability to view the entire celestial sphere. This two year mission has requirements to cover the entire celestial sphere once every six months, the Galactic plane once every six months, and maximize coverage of the North Celestial Pole (NCP) and South Celestial Pole (SCP) regions.

In a nearly-terminator Sun synchronous orbit, the β angle varies between $60° - 90°$ throughout the year, see Fig. 7a. The SPHEREx pointing constraints are: $\alpha \leq 35°$, $\zeta \leq 35°$, $\Omega = 90°$ thus T_{max} varies from 9 to 19 minutes throughout the year, see Fig. 7b. For the SPHEREx spacecraft, ϕ is a fixed angle that must be determined before the spacecraft is developed (and impacts other subsystems such as thermal and attitude determination and control), while θ is a free decision variable in the scheduling problem that can be dynamic over time.

A. Survey Overview

The three surveys focus on different areas of the celestial sky and have different integration and redundancy requirements. The deep survey consists of surveying 100^o both around the NCP and SCP, respectively (which can be expressed as all declinations $\leq 83.5°$ and $\geq 83.5°$), as in Fig. 5. The NCP and SCP are selected as the regions where deep surveys are done because the poles are the natural rotation axis for the SPHEREx orbit and the instrument can access these regions throughout the year. The Galactic plane survey requires coverage of approximately one degree above and below the Galactic plane. The all-sky survey consists of the remaining celestial sphere and the full data set will use data from the Deep and Galactic surveys to achieve full celestial sphere coverage.

The SPHEREx instrument has a field of view (FOV) that is 7.04^o by 3.52^o, which consists of two size-by-side detectors that are each 3.52^o square, see Fig. 6. There are also two detectors stacked behind the two detectors in the image for a total of four detectors. The detectors are Linear Variable Filters (LVFs), which are wedge filters, where the thickness and thus wavelength varies continuously along one dimension, the scan direction [8].

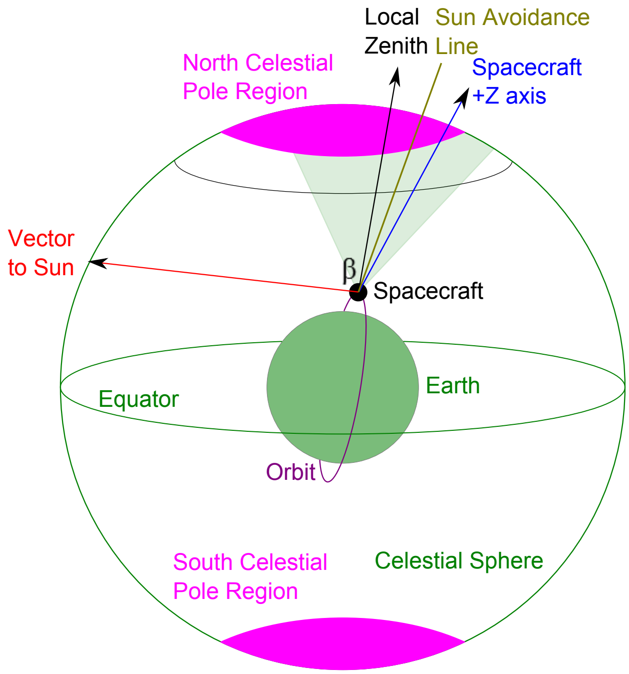


Figure 5. Constraints on spacecraft orientation for the SPHEREx mission.

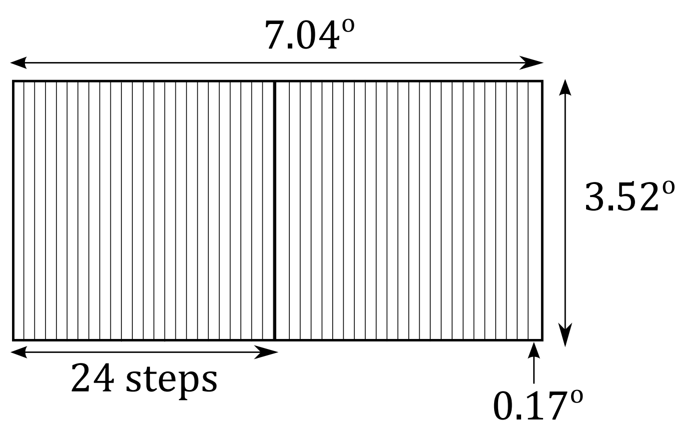


Figure 6. Field of view (FOV) with 24 steps across each detector (as used for the all-sky and Galactic plane surveys

The surveys have different wavelength and spatial resolution requirements, summarized in Table 1. Every survey needs to have complete wavelength coverage, meaning every wavelength (long rectangles in Fig. 6) FOV covers every area in the survey. Wavelength coverage is achieved by stepping the detector by the step required to achieve the required spectral resolution. In this mission application, redundancy is defined as the number of times a given area of sky is covered by every wavelength band applicable for that survey. The Galactic and all-sky surveys require a redundancy of once per six months, meaning each half of the orbit (ascending and descending) covers the entire celestial sphere in view as it precesses. The scheduling objective is to maximize the redundancy of the Deep surveys, i.e. uniformly sample the NCP and SCP and surrounding areas the maximum number of times, subject to the requirements of all surveys.

The SPHEREx scheduling parameters are in Table 2, which are a function of the orbit altitude and inclination, FOV, and preliminary science, scheduling, and attitude control calculations. Telecommunication operations requires

Table 1. SPHEREx Survey Overview

Survey	Deep (NCP/ SCP)	Galactic Plane	All-Sky
Parts of celestial sphere	NCP/ SCP (100°)	1° of Galactic plane	All remaining sky
Spectral Resolution	40	40	40
Steps Across the Detector	21	21	21
Integration Time (per step)	185 secs	95.7 secs	95.7 secs
Redundancy Requirements	Maximized	once per 6 months	once per 6 months

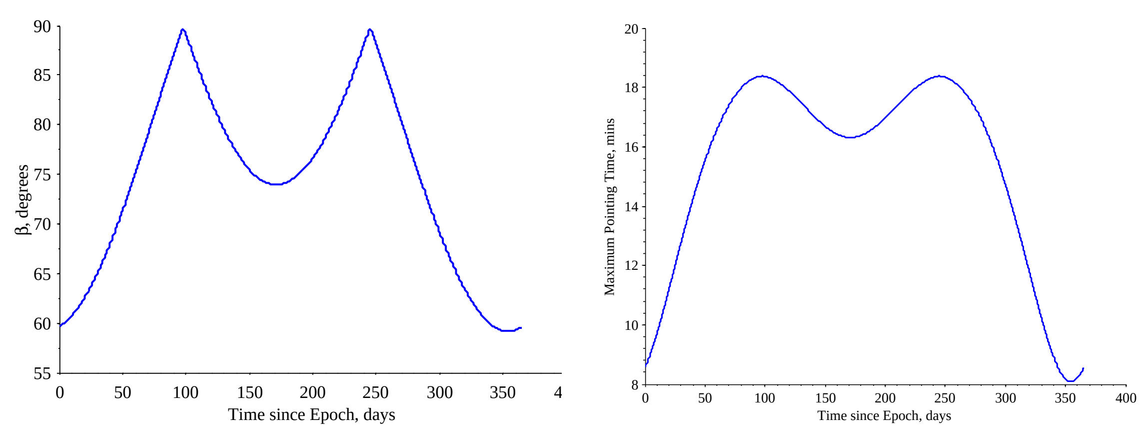
Table 2. SPHEREx Schedule Parameters

Parameter	Values	Units
Orbits per day	15.2	orbits/day
Orbits per year	5552	orbits
Orbit Period	94.7	mins
Orbit Precession	1	deg/day
FOV half width	3.52	deg
all-sky/ Galactic Integration Time	95.7	sec
Deep (NCP/SCP) Integration Time	185	sec
Small Slew Duration (between steps)	10	sec
Large Slew Duration (between pointings)	90	sec
Telecom Time	1.6	min/orbit

an average of 1.6 minutes per orbit, which is scheduled for about seven minutes every three to four orbits. This telecommunication time is accounted for in the overall scheduling.

B. Spacecraft Configuration

The instrument is at a fixed cant angle, ϕ, relative to the spacecraft (i.e. it cannot move dynamically throughout the orbit or year), which is a design variable that interacts with the observing scenario. In order for the instrument to have the NCP and SCP in view throughout the entire year which is necessary to maximize the Deep survey redundancy, and considering the tilt angle for solar avoidance (θ), $\phi = 21°$ was selected. There is one limiting case throughout the year where either the NCP or SCP is on the edge of the FOV (i.e. a single wavelength range can image the NCP or SCP). A Sun-synchronous orbit with a longitude of descending node is 18 hours is selected such that the limiting case is during the winter solstice for the SCP ($\beta = 60°$), because the NCP is higher priority. In the worst case for the NCP, the FOV is 2.4° from the NCP center, which occurs during the Summer Solstice ($\beta = 74°$).



a) Solar β Angle

b) Maximum Pointing Time, T_{max} in Orbital Plane

Figure 7. The maximum pointing time is a function of the solar β angle as in Eq. 4.

For the $\beta = 90°$ case, generally the angular difference between successive slews is about $60°$ ($360°/6$ pointings). Differences in successive pointing angles of up to approximately $80°$ can be tolerated (depending on the declinations), which exceeds the $75°$ that may be expected due to tilting from the local Zenith by $35°$ in each direction because of the motion of the spacecraft during the slew (about 90 seconds).

C. Strategy Overview

The SPHEREx mission is considered an "engineered" survey because the three survey goals are a natural synergy enabled by its polar orbit. Removing one of the surveys would not directly impact the other surveys, and in fact, as a result, the spacecraft may be idle for portions of the orbit. On every orbit the instrument can access the NCP and SCP (enabled by the selection of appropriate cant angle ϕ), the Galactic plane, and a band of the celestial sphere at constant right ascension (RA) for all-sky survey coverage. In general the surveys do not directly conflict because they target different areas of the celestial sphere, however there are trade-offs between the various surveys.

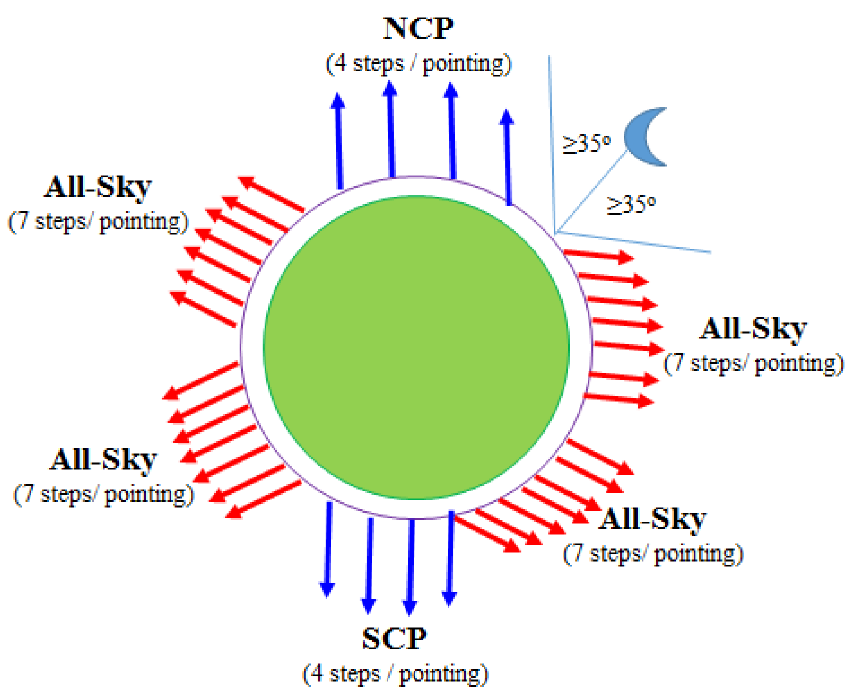


Figure 8. General observing scenario for $\beta = 90°$ case where there are 6 pointings per orbit.

The general strategy to maximize science time is to minimize the number of pointings because the large slew durations are longer than the small slew durations, see Table 2. However; the pointing durations must never exceed T_{max}, see Fig. 7b, so when $\beta = 60°$ at least 8 pointings are required, and when $\beta = 90°$, at least 6 pointings are required. Fig. 8 shows a representative distribution of pointings throughout an orbit for the $\beta = 90°$, where there is one NCP, one SCP, and 4 all-sky pointings (which also cover the Galactic plane) per orbit. In this example, the number of arrows represents the number of steps per orbit, and an example is given to satisfy the Moon avoidance constraint. Every pointing consists of several small steps, where the step direction depends on the survey type. The distribution of number and location of pointings and steps will vary depending on β, location of Galactic plane, and specific orbit.

To achieve full wavelength coverage of the all-sky survey, successive pointings will pick up where the last pointing left off such that the individual images stack and achieve full wavelength coverage, as in Fig. 3. A total of 367 All Sky steps must be accomplished per day, or approximately 24 steps per orbit to account for covering both the ascending and descending sides of the orbit. The constraint of achieving global coverage does not introduce any more constraints on the scheduling problem. This is because the constraints are satisfied in both extreme cases, when $\beta = 60°$ (with at least 8 pointings per orbit and 4 steps/pointing) and when $\beta = 90°$ (with at least 6 pointings per orbit and 6 steps/pointing). However; if the redundancy requirement increases or the number of steps/ pointing changes dramatically, this may introduce new constraints. The Galactic and all-sky surveys have the same wavelength and redundancy requirements, as in Table 1, thus the Galactic science is accomplished as part of the all-sky survey. In the case that the Galactic survey requirements differ, an alternative approach may be required to satisfy its requirements, as discussed in Section III.C.

To maximize the Deep Survey observations, there is an NCP and SCP pointing on a large number of orbits. Deep survey observations are not feasible on every orbit because of the need to cover high-declination all-sky areas. For example see the fractions in Table 3 for the $\beta = 90°$ case. Efficient coverage of the polar caps is achieved by sliding the FOV along lines of constant RA for a given number of days, and repeating the pattern at the next RA once the orbit has processed. To achieve uniform coverage over the deep region, the number of steps at each declination will not be exactly even. There will be incomplete wavelength overhang on to the all-sky survey that will augment its coverage but will not be part of the Deep survey. Note the band of constant RA is not the orbital plane because the instrument is offset from the local zenith by the combination of the static ϕ and dynamic θ.

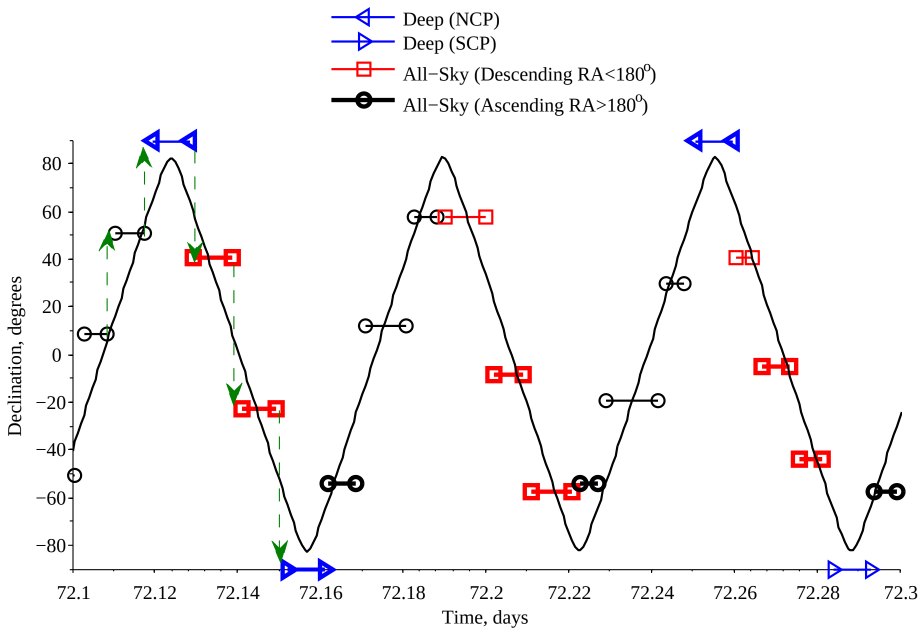
Table 3 provides an idealized summary of the breakdown for the three surveys, pointings, and steps the representative $\beta = 90°$ scenario, which is shown in Fig. 10a. This case assumes perfect scheduling (i.e. every second is scheduled perfectly) and overall average number of pointings and steps (which is why there are fractional values). Overall, 84.7% of the time is dedicated to science observations, with the largest fraction of other time dedicated to large slews (five 90 second slews).

Table 3. Representative ideal schedule overview for $\beta = 90°$ with the scenario parameter in Table 2.

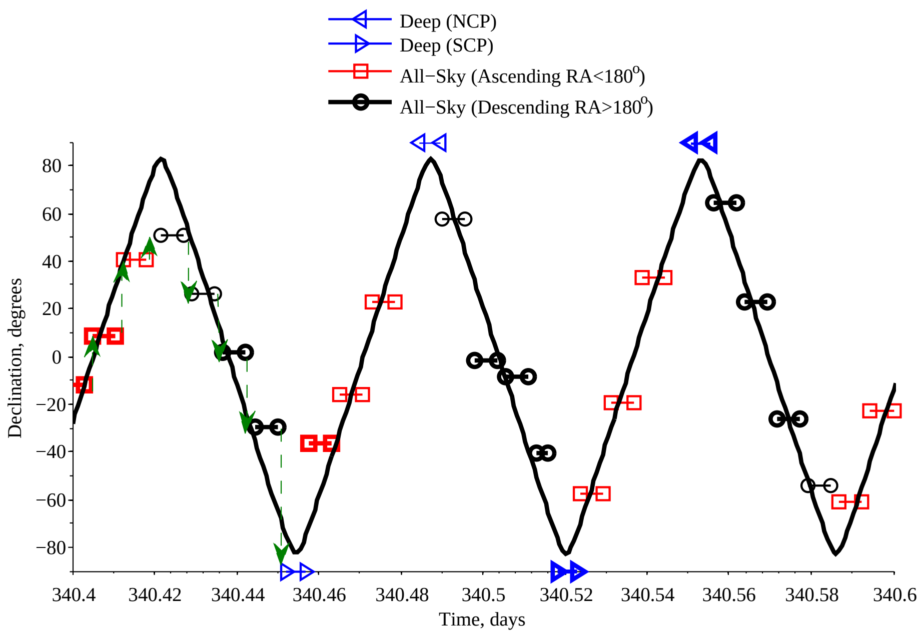
Parameter	Deep (NCP/SCP) Survey	All-Sky Survey	Total	Units
Pointings per orbit (average)	2	4	6	pointings
Pointings per year (average)	11104	22207	33311	pointings
Steps per pointing (average)	4	7		steps
Steps per orbit (images per orbit)	8	28	36	steps
Steps per year	44414	15545	199865	steps
Integration time per step	185	99		secs
Science time	1660	3156	4816	secs
Percentage of science time	34.5	65.5	100	%
Total time (including small slews)	28.7	56.6	85.3	mins
Large Slews			7.5	mins
Telecom			1.6	mins
Total scheduled time (including small slews)			93.6	mins
Science efficiency			84.7	%

D. Scheduling Algorithm Implementation

The algorithm described in section IIIB is applied to the SPHEREx mission, where the targeted observations focus on the Deep and Galactic plane surveys. Scheduling the NCP/SCP pointings (each with four steps) with a cadence of three quarters of orbits when $\beta = 90°$, and scheduling NCP/SCP pointings for two thirds the orbits when $\beta = 60°$) provided good science efficiency and enabled us to achieve the all-sky survey requirements. The survey is implemented in MATLAB®with orbital information generated with Systems Tool Kit (STK)®. The algorithm was applied to realistic SPHEREx scenarios and the resulting schedules are shown in Figs. 9-10. The schedule is applied to two-day planning windows, and the steps fully cover two degrees in RA (as the orbit precesses at one degree per day). The binned number of steps per day at each declination is shown in Fig. 11, which is essentially the steps collapsed from Fig. 10. As the orbit precesses, a similar schedule is repeated at different RAs to cover the available celestial sphere. As expected, the results show 6 pointings/orbit for the $\beta = 90°$ case and 8 pointings/orbit for the $\beta = 60°$, which emerged naturally from the algorithm (i.e. it was not constrained). The telecommunication operations (downloading and uploading from Earth ground stations) is not shown in Figs. 10-9 because it only occurs a few times a week, however appropriate time is allocated to these operations on average, see Table 3.



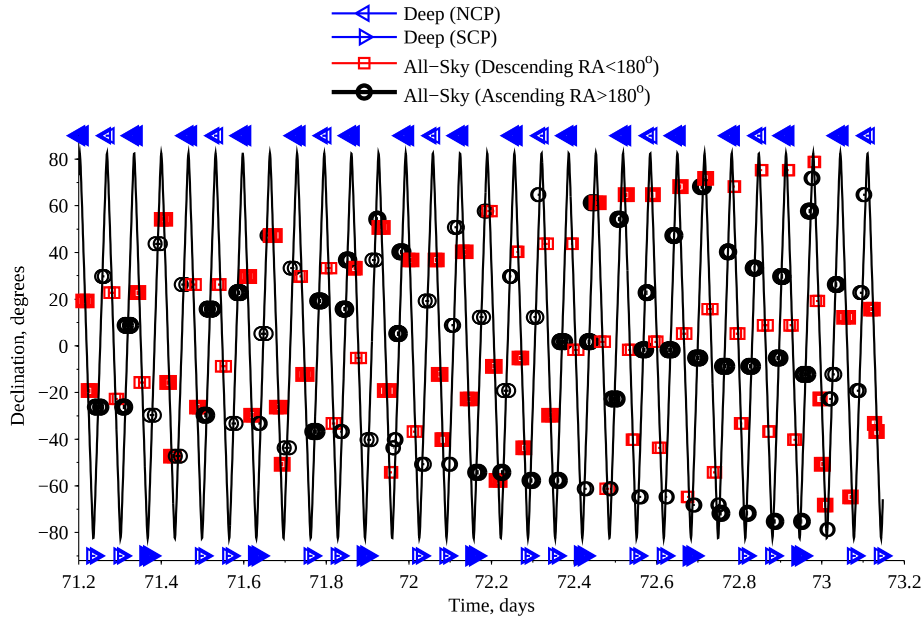
a) $\beta = 90°$ **with deep (NCP/SCP) pointings, skipping every fourth orbit with 4 steps/ pointing. There are usually 6 pointings per orbit due to** $T_{max} = 19$ **mins.**



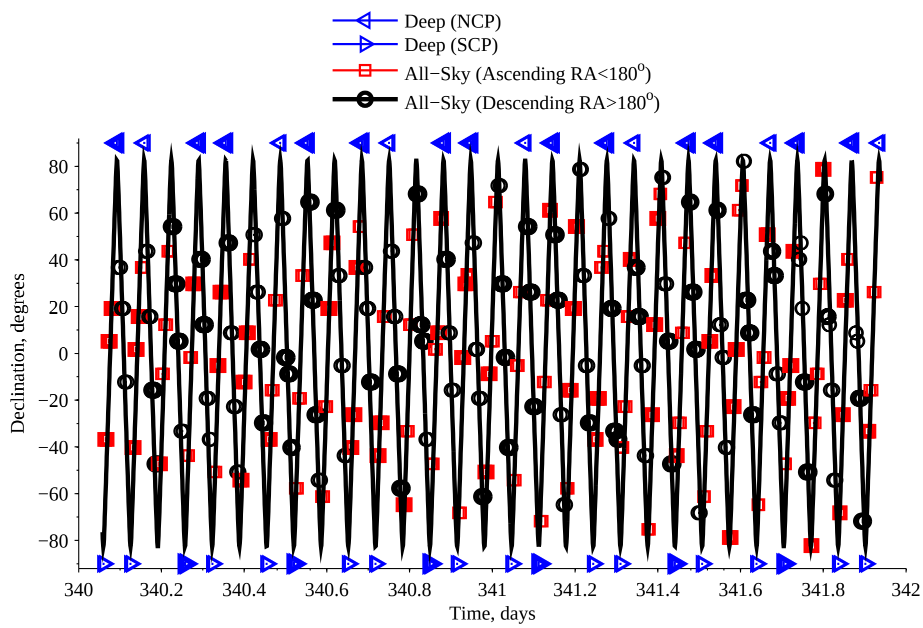
b) $\beta = 60°$ **with Ddeep (NCP/SCP) pointings every second orbit, with 3 steps/ pointing. There are usually 8 pointings per orbit due to** $T_{max} = 9$ **mins.**

Figure 9. Representative schedules for three orbits (detailed view of the schedules in Fig. 10). The black solid lines denote the orbit track on the celestial sphere, which establishes the available declinations as a function of time. The green dotted lines with arrows denote the large slews between successive pointings. The symbols denote the survey pointings, which are chosen to satisfy the constraints, where each pointing is comprised of 4-9 steps where the step duration depends on the survey type. There are large slews (90 sec) between successive pointings are shown in green dotted lines and small slews (10 sec) between successive steps (in a single pointing) not shown here.

Implementing the schedule for the $\beta = 90°$ case, as in Figs. 10-9, results in a science efficiency of 78%. This science efficiency can be further improved to approach the optimized efficiency by using the generated schedules as



a) $\beta = 90°$ **with deep (NCP/SCP) pointings, skipping every fourth orbit with 4 steps/ pointing. There are usually 6 pointings per orbit due to** $T_{max} = 19$ **mins.**



b) $\beta = 60°$ **with deep (NCP/SCP) pointings every second orbit, with 3 steps/ pointing. There are usually 8 pointings per orbit due to** $T_{max} = 9$ **mins.**

Figure 10. Representative schedules for a two day planning horizon. The black solid lines denote the orbit track on the celestial sphere, which establishes the available declinations as a function of time. The symbols denote the survey pointings, which are chosen to satisfy the constraints, where each pointing is comprised of 4-9 steps where the step duration depends on the survey type. There are large slews (90 sec) between successive pointings and small slews (10 sec) between successive steps (in a single pointing) not shown here.

initial guesses in a global optimization problem to maximize overall science time with the decision variable and model improvements discussed next. The NCP/SCP pointing cadence, placement in the schedule, and/or total number of pointings could also be decision variables, providing improved flexibility in overall scheduling towards improving efficiency. The slew times could also be modeled more accurately based on actual slew angles for both short and long slews and the problem should be constrained to prevent any down time between science observations and slews, which will reduce overall slew times and improve efficiency.

Representative coverage results of the all-sky survey over long-duration planning horizons are shown in Fig. 12. These visualizations demonstrate that the observing scenario strategy achieves the required redundancy requirements for the all-sky survey, where uniform coverage with a redundancy of one in six months is achieved in the all-sky survey, and redundancy scales linearly with time.

V. Conclusion

This paper presented a general approach for scheduling all-sky surveys that accommodates targeted observations subject to dynamic constraints in the LEO environment. The approach includes spacecraft and instrument constraints related to dynamic and interacting thermal and stray-light environments, which vary as a function of the orbit position relative to the Sun, Earth, and Moon. The instrument and spacecraft configuration problem is solved to satisfy the Sun-avoidance criteria, which combined with the Earth-avoidance criteria leads to dynamic maximum observation time constraints throughout the year. Targeted observations constrain the time available to schedule all-sky observations. A heuristic-based all-sky scheduling algorithm is presented that is designed to generate guaranteed-feasible solutions that achieve the all-sky redundancy requirements. The approach is applied to the proposed SPHEREx mission, which consists of a deep survey focusing on the celestial poles and an all-sky survey including a Galactic plane survey, where each survey has specific requirements and objectives. Representative solutions are presented that achieve the survey goals for nominal and worst cases. The scheduling efficiency of the all-sky survey is approximately 78%, while idealized schedules are approximately 85% ($\beta = 90°$ case), where further optimization can be performed to approach the idealized efficiencies.

Beyond the general approach for efficiently accomplishing all-sky surveys, this paper presents insights for operating a spacecraft in the challenging LEO environment, where there may be Sun, Earth, and Moon avoidance constraints. Furthermore, this approach could be utilized to map the Earth with nadir-pointing spacecraft instead of the celestial sphere with a zenith-pointing spacecraft. The general step-wise approach of solving several sub-problems presented in this paper has significantly reduced the number of constraints, variables, and objectives. This approach is applicable to a larger class of spacecraft scheduling problems; however requires a solid understanding of the interactions of the problem objectives and constraints.

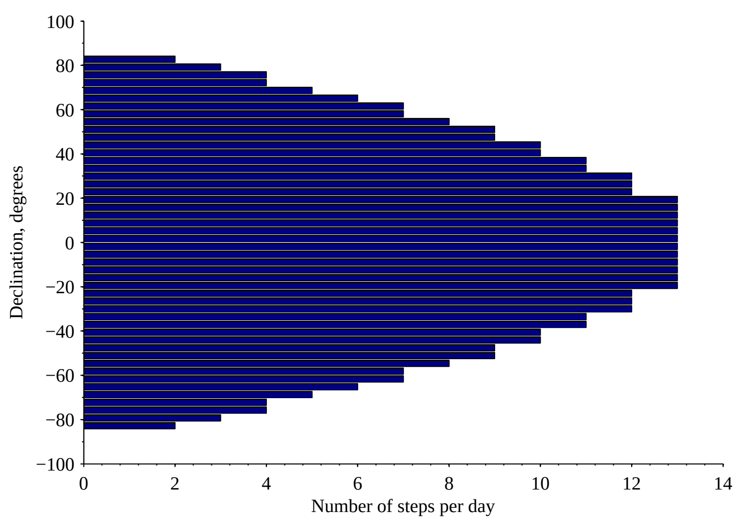
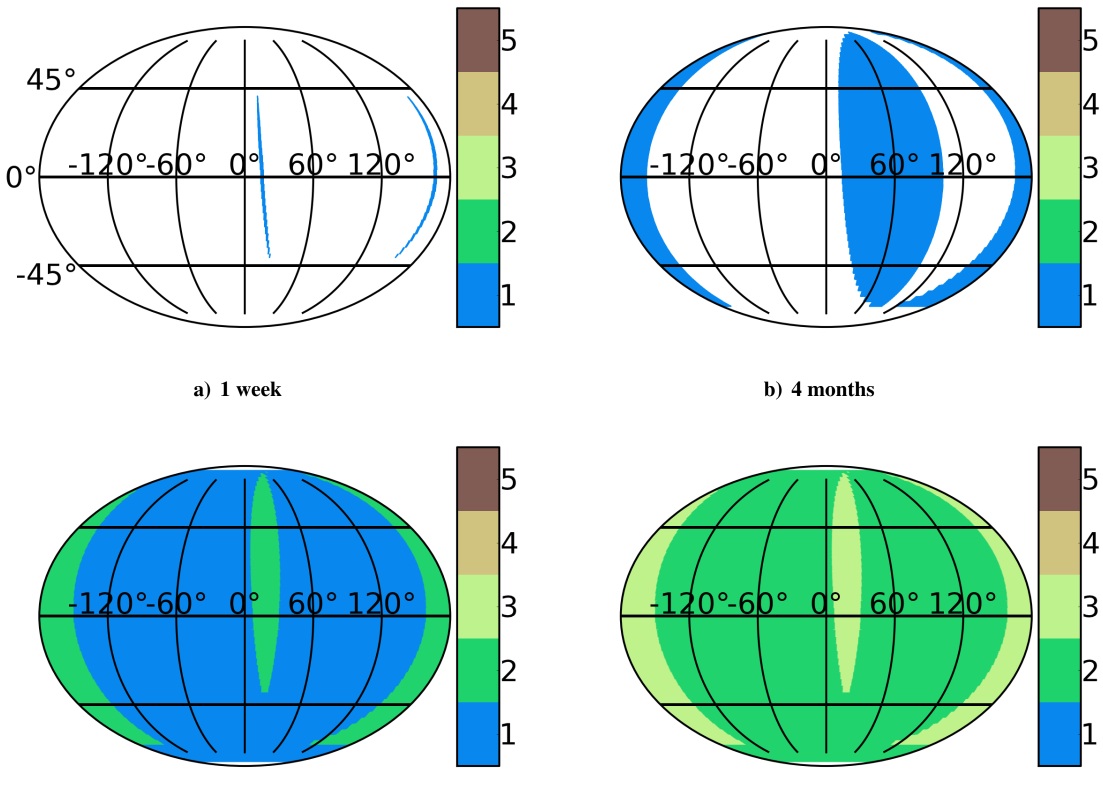


Figure 11. Histogram of idealized number of steps per day to achieve redundancy requirements for all-sky survey. This distribution in declination is readily implemented by the scenario illustrated in Fig. 10.



a) 1 week
b) 4 months
c) 7 months
d) 13 months

Figure 12. Progressive coverage for all-sky survey, where the color shows the minimum wavelength coverage of every area of the sky. The approach achieves an overall efficiency of one in six months.

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