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Orbit Control Considerations for a Bistatic SAR Formation Flying Mission

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Abstract

This paper describes the orbital aspects of a bistatic SAR formation-flying mission. The NASDA ALOS satellite, schedule for launch in 2004, is used as a reference. The concept proposed is to fly a small SAR satellite in formation with ALOS to perform SAR interferometry (Figure 1).

The first half of the paper describes a preliminary design concept for the ALOS-SSS formation and presents an orbit insertion scenario to bring SSS into formation with ALOS. One of the challenges is to plan and maintain the formation within the desired constraints while minimizing the fuel consumption required. The formulation of a relationship for which the relative path of the satellites repeats itself over time is presented. Special attention is needed to this problem with regards to orbit perturbations since it affects the relative geometry of the formation and thus, the success of the mission.

The second aspect treated concerns the control system of the orbit. It is practically impossible to account for all perturbations and to maintain both satellites in formation is a complex procedure. A study of the relative drift between the satellites is included for the configuration proposed. Orbit correction maneuvers are necessary to maintain the relative orbit of the small satellite. Considering the complexity of these orbits and the frequency at which orbit corrections may be needed, autonomous orbit control is preferred. A ground based command and control system would be heavily over-burdened and not sufficiently rapid [1]. Ideally, the navigation software relies on precise data for relative positioning such as GPS or an inter-satellite ranging system. The autonomous navigation makes continuous measurements between the satellites to maintain the existing configuration with ALOS. Aspects of relative orbit determination for the orbit control of SSS are discussed.

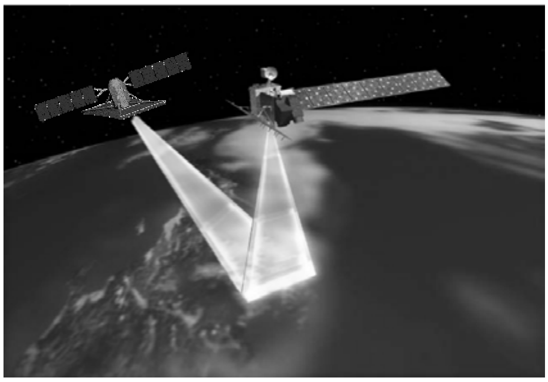

Figure 1: Artist Conception of the ALOS-SSS Interferometric SAR Formation

1 Introduction

Formation flying satellites are progressively becoming a reality as new missions are under way and several others currently investigated. One possible use is to combine two or more Synthetic Aperture Radar (SAR) signal of the same area to generate elevation maps and surface change maps with unprecedented precision and resolution. This technique is called SAR interferometry and its geometric representation is shown in Figure 2. In a joint effort with the National Space Development Agency of Japan (NASDA), the Canadian Space Agency (CSA) is currently studying the feasibility of a two-satellite formation using the PALSAR antenna of Japan's Advanced Land Observing Satellite (ALOS) in bistatic mode. A proposal was put forward in late 2002 to launch a Small Satellite SAR (SSS) in formation with ALOS to provide interferometric capabilities to the system.

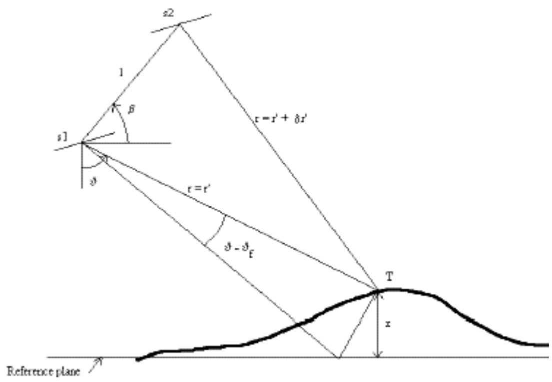

Figure 2: SAR Interferometry

2 Orbital Configuration

Before the aspects of formation control and autonomy are discussed, it is important to define a suitable formation flying configuration that meets the SAR interferometric needs. Indeed, the orbit control depends on the formation geometry because the relative motion of the satellites is affected differently. Since ALOS and SSS will orbit the Earth at very close distances, maintaining the formation is not trivial and there is always the risk of collision present. The approach sequence from the post-launch orbit of SSS for final rendezvous with ALOS is also a subject of high precision spacecraft control. This section intends to discuss these aspects and to summarize the latest design.

2.1 Formation Geometry

The critical parameter in SAR interferometry is the baseline perpendicular to the SAR slant-range direction. This parameter is denoted B_{perp}.

To perform proper interferometry, the nominal baseline length must be selected upon a certain number of factors. Without entering the details of radar engineering, lets say that this distance is a function of the operating mode of the SAR. As such, an L-band SAR such as ALOS's PALSAR will require a longer baseline than a C-band SAR. Thus, the relative distance between the satellites must be maintained between a minimum and a maximum value to provide accurate interferometric data while ensuring safe operation.

The perpendicular baseline can be achieved in two different ways. The satellites can be separated across-track (side by side), or radially (one above each other), or by a combination of both, as shown in Figure 3.

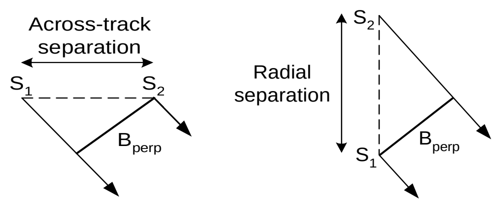

Figure 3: Perpendicular Baseline

A cross-track separation is achieved when choosing slightly different orbit planes for each satellite. This can be done using orbits with either a different inclination (i) or a different right ascension (Ω). A difference in the inclination will cause a cross-track separation at the poles, while a different Ω will cause the separation at the equator. Since the polar region mapping is an objective of the mission, the inclination offset is favored. However, this concept is not viable as perturbations from the Earth's oblateness (J2) produces a drift, thus causing the baseline separation to accentuate over time and the spacecrafts to drift apart. This would require a high fuel consumption, mainly because inclination change maneuvers are costly.

The possibility of using a radial separation is more appealing since both satellites remain in the same plane. To achieve the radial separation at the poles (for $\omega = 90^o$; $\nu = 0^o$ or 180^o), the eccentricity can be adjusted following the relationship $B = a\delta e$, where B is the baseline separation, a is the semi-major axis of the orbit and δe is the eccentricity difference between the satellites. For a baseline separation of 5-km radial, a δe of 0.0007 is needed. This relatively simple scenario is therefore proposed since the relative movements due to the J2 perturbation are doused. It also has the particularity of being stable to higher order perturbations when frozen orbit characteristics are taken into account, which will be discussed later.

The next figure illustrates the proposed orbit configuration in a reference frame relative to ALOS. In the plot, ALOS is at (0,0) and the horizontal and vertical axes are along ALOS's velocity vector (v-bar) and its radial position vector (anti r-bar), respectively. There is no nominal cross-track separation.

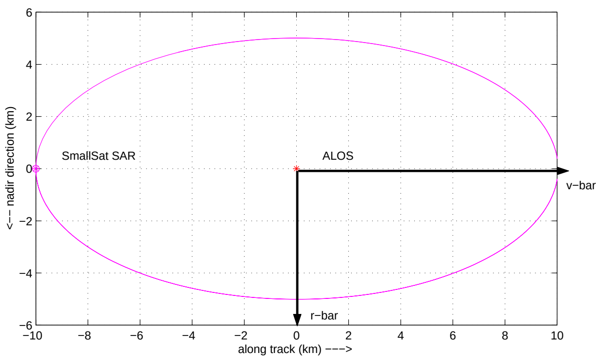

Figure 4: Relative Orbit Configuration

2.2 Frozen Orbit

Frozen orbits are specialized orbits that try to fix one or more orbital elements in the presence of perturbations. This is never an exact process because other forces, such as drag, tend to disrupt the frozen geometry. However, these disruptions can be compensated by small periodic corrections to maintain the desired frozen orbit. Reducing the size of station-keeping maneuvers has an important impact in the fuel budget. It is thus important to consider minimizing as much perturbation as possible.

Frozen eccentricity orbits are used to design orbits that minimize global variations in altitude by nulling the long-periodic variations eccentricity and argument of perigee. It can be demonstrated that the argument of perigee rate vanishes for given values of $\omega = \omega_0$ and $e = e_f$. However, a non-vanishing eccentricity rate will cause the eccentricity value e_f, and thus the argument of perigee, to change. The eccentricity rate will vanish if the argument of perigee is set to 90^o or 270^o. In a formation flying situation, however, the required δe will prevent having perfectly frozen orbits. However, further analysis of the eccentricity and the argument of perigee demonstrate a suitable scenario [2]. As mentioned above, the two elements are tied together, and a configuration is possible for which the periodic variations are averaged out between the two satellites. Assuming a frozen eccentricity $e_f = 0.00115$, the long-term periodic variations of the two elements are shown in Figure 5 when near-frozen eccentricities ($e_f \pm 0.00035$) are selected.

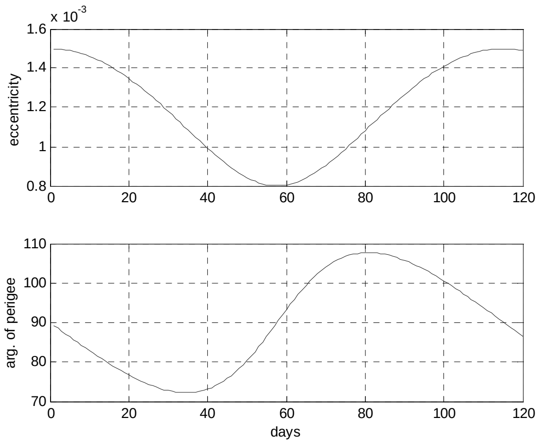

Figure 5: Eccentricity and Argument of Perigee Long Term Periodic Variations

Finally, Figure 6 shows the variation of the orbit eccentricity as a function of the argument of perigee. The point $[e(t), \omega(t)]$ moves with time counter-clockwise along the curve. The period is about 120 days. Selecting eccentricities 0.0007-apart for SSS and ALOS on both sides of the frozen eccentricity creates equal and opposite variations of both the eccentricity and the argument of perigee. It results in a stable, repeating formation.

As a consequence of the drift in the argument of perigee, the radial baseline location will gradually shift from the poles towards the equator, as

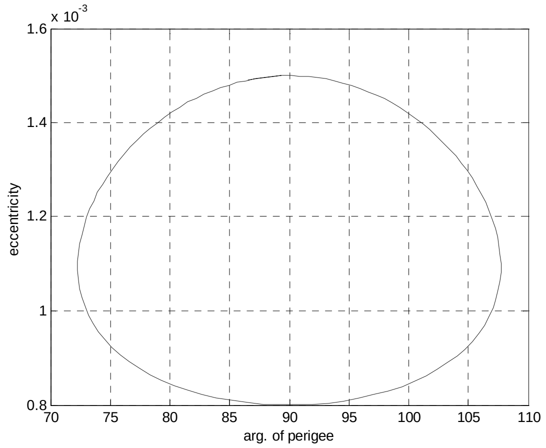

Figure 6: Variation of Eccentricity with Argument of Perigee

shown below in Figure 7. This will allow imaging of different regions on the globe.

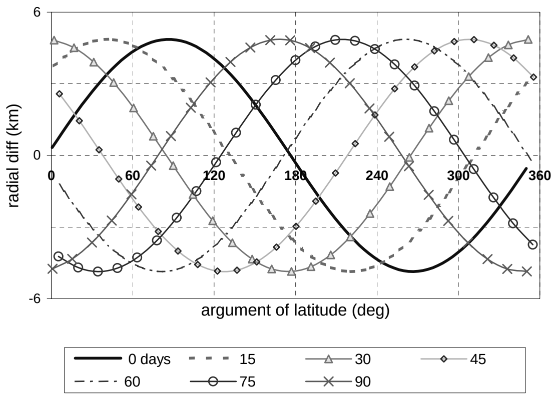

Figure 7: Radial Differences with Respect to the Argument of Latitude

2.3 Orbit Insertion

The SSS will most likely be launched as a secondary payload on board a rocket such as the Japanese HII-A. The rocket can deliver the spacecraft into the near-polar orbit plane of ALOS with a similar altitude and period. Once the communication between the SSS satellite and the ground control is established, a series of orbital maneuvers are executed to bring the satellite closer to ALOS. Hohmann transfers are used to gradually reduce the separation between the two satellites. By either increasing or decreasing the semi-major axis, depending on the initial configuration, SSS will close up on ALOS after each revolution. In order to minimize the fuel consumption and because getting to ALOS rapidly is not crucial, this sequence can take up to several weeks.

An in-track limit of approximately 100 km is proposed for the initial rendezvous sequence before the final approach. SSS would then enter a station-keeping phase to assess the hardware and software's functionality and to ensure both SSS and ALOS's safety. A series of slow, targeted approaches follows, alternating station-keeping phases and rendezvous burns, leaving time for ground control to perform orbit determination, to assess the results and to reevaluate the sequence if needed. The final configuration is obtained when the thrusters are fired from the last station keeping point, when the SSS trails ALOS by 10 km. This point is comprised in the final formation configuration proposed, as described in the next section. This rendezvous sequence along the velocity vector (v-bar) from the first 100 km station-keeping stage up to the final formation is depicted in the Figure 8.

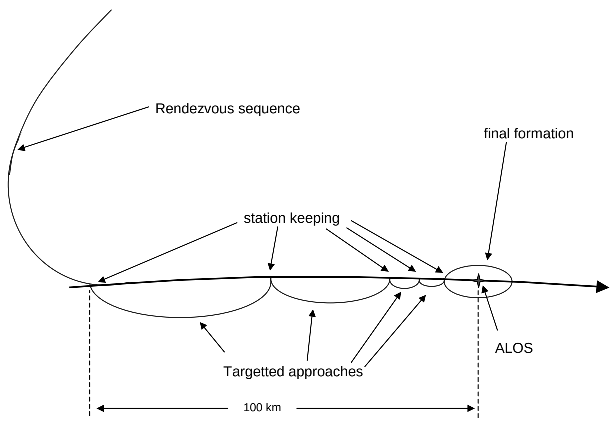

Figure 8: V-bar Approach

Different alternative exist for spacecraft rendezvous, such as a co-elliptic approach from an orbit with a slightly lower altitude. This method would cause SSS to naturally approach ALOS from below, since the orbital velocity is inversely proportional to the altitude. From an operational point of view the v-bar approach is preferred. Nonetheless, the co-elliptic option is interesting, as it offers zero probability of collision should something go wrong. Further stud-

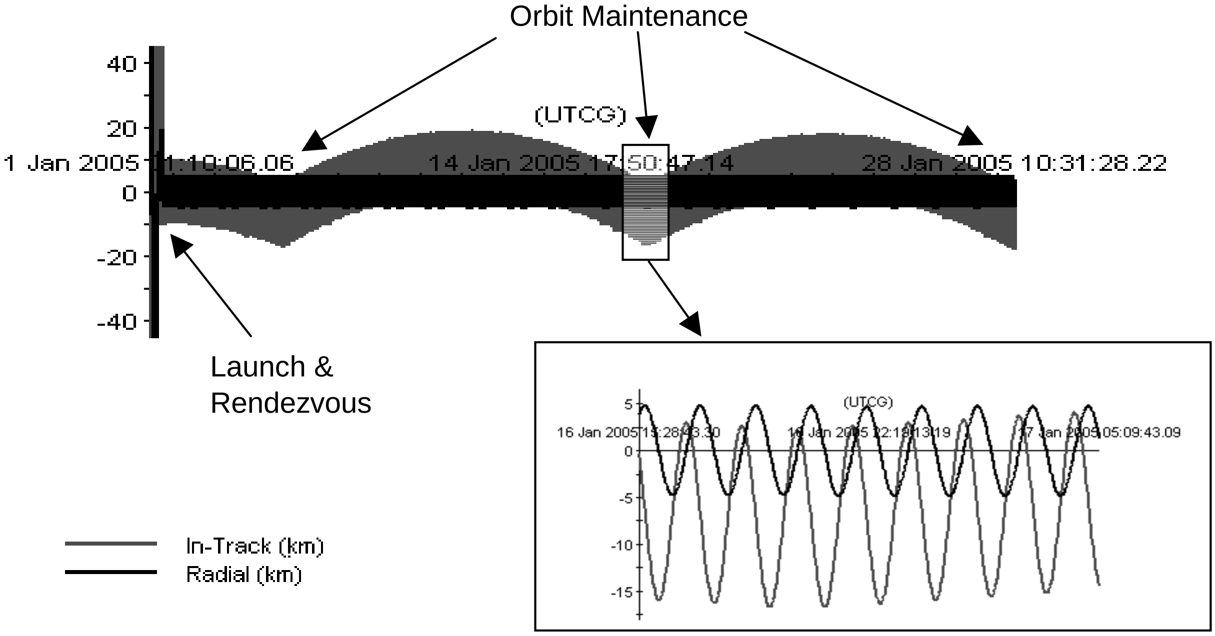

Figure 9: Effect of Drag and Orbit maintenance

ies shall demonstrate which is best. It should be noted that both method are used today in Space Shuttle rendezvous with other spacecrafts [3].

3 Orbit Control

The formation configuration described above was designed to minimize the effect of natural perturbations from the gravity geopotential. It is important to realize that any scenario adopted will undergo alterations over time due to unaccounted perturbations. The most important is due to atmospheric drag, since both satellites are flying at relatively low altitudes (less than 700 km above sea level) and most importantly because ALOS and SSS will have different ballistic coefficients. ALOS is a rather large satellite, about 10 times bigger than the current design of SSS. Therefore, it is expected that drag will influence the formation, calling for periodic orbit maintenance. For this proposal, the following spacecraft characteristics are assumed:

Table 1: Spacecraft Configuration

	ALOS	SSS
Mass (kg)	4000	400
Cross Sectional Area (m^2)	80	14
Area to Mass Ratio (m^2/kg)	0.02	0.035
Coefficient of drag	2.3	2.3

3.1 Orbit Maintenance and Safety

A simulation was setup to observe the long-term effect of drag on the overall ALOS-SSS formation. Jacchia-Roberts atmospheric density model was used. It should be mentioned that solar radiation pressure modeling was included in the simulation at the same time. Using the ballistic coefficients tabulated above, it was observed that the SSS elliptical-like path tends to drift away from ALOS. To maintain the formation in a suitable configuration, orbital maneuvers should be executed approximately twice a month, as shown in Figure 9.

The figure shows the radial and in-track separations between ALOS and SSS. Maneuvers are indicated where the ellipse gets to a 2.5-km in-track distance to ALOS. At this point, the velocity of SSS is boosted up in a manner that causes the ellipse to move the other way. Such maneuvers have to be executed when SSS is at the same radial altitude than ALOS to avoid altering the up-and-down radial pattern. Eventually, the effect of drag brings the ellipse back, where another maintenance maneuver is required. Upon revision of the size and mass of SSS, the maneuver recurrence can be elongated.

3.2 Autonomous GN&C

Undoubtedly, the orbit maintenance plan described in the previous section will undergo many revisions. In fact, interferometric SAR imaging might require much tighter constraints on the formation to maintain a proper perpendicular baseline. Smaller orbital maneuvers may be required at a much higher frequency. The situation would then require a more complex formation flying control scheme for the small SSS then what is usually done for a single satellite. These factors would make the traditional ground-based control system more difficult, very demanding and maybe not sufficient enough. To enhance the precision and to accelerate the maneuvers computation and execution time, autonomous navigation becomes a necessity.

The critical aspect of spacecraft navigation in formation flying is relative motion. To keep the formation in a suitable configuration for both spacecrafts' safety and to achieve the science objectives, the formation flight control system does not rely on a precise knowledge of the inertial position of the satellites, but rather on their relative position with respect to each other. Therefore, relative navigation, or relative orbit determination, becomes more important than absolute navigation. The simplest way to determine the relative state of two satellites is to estimate their absolute position and take the difference between the two. The other possibility is to explicitly estimate the relative state, a method for which better results can be expected [4].

It may be necessary to have a high fidelity orbit propagator to properly estimate the relative state. However, preliminary studies that uses Hill's proximity equations, a.k.a. the Clohessy-Wiltshire equations, for circular orbits can be conducted in order to simplify the SSS flight code. Future studies shall demonstrate if those equations are sufficient to provide a navigation solution and to what extend.

Tied to the orbit determination problem is the type of data used. Traditionaly, ground based tracking is required to ensure proper spacecraft navigation. In the case of relative navigation, an inter-satellite link might be preferred, such as radar, laser or visual ranging devices. Another possibility is to use GPS data. Studies that used differential GPS have been conducted in the past and suggest promising results [4, 5, 6]. It is believed at this point that single difference GPS observations, which provide direct relative positioning, should be used.

It is important to note that if autonomous on-board navigation is desired, these methods require some communication between the two satellites to pass the information from one satellite to the other. It may be dificult to achieve this since ALOS has not been designed for an inter-satellite link. However, it would be possible for SSS to pick up the telemetry signal from ALOS and thus gather the appropriate GPS data. A radio ranging device might also be installed on SSS to detect ALOS and thus provide a alternate mean for relative state estimation. It can also be used to refine the GPS solution. In any case, an autonomous GN&C system is clearly considered to be advantageous for the reasons highlighted above. The implementation of an inter-satellite communication link for the SSS mission is therefore recommended. Future missions should also be designed in that respect and the technology development implied in this paper will follow this idea.

The Canadian Space Agency is currently developing a formation flying simulator to study the aspects of Guidance, Navigation and Control (GN&C). The plan is to develop an Extended Kalman Filter (EKF) based on GPS tracking to provide autonomous GN&C capabilities to a spacecraft such as the Small Satellite SAR. A measurement model for differential GPS pseudoranges has to be developed. Inherent to spacecraft orbit determination with GPS data is the knowledge of the GPS space vehicles (SV) ephemerides. This information would come from the broadcasted GPS signal. To allow the relative propagation model to work, the state of one of the satellite is needed. It will be assumed in the future ALOS-SSS simulations that ALOS's state is known to some extent and the that information is passed to the SSS flight computer.

In most studies of relative orbit determination found in the literature, this subject is treated jointly with the complex matter of precision orbit determination. Relative state estimation for SSS is addressed separately in this paper since the mission treated is not design strictly as a formation flying experiment but rather as a complement to ALOS' functionality. One can make the analogy of a fly buzzing around light bulb, where the bulb works independently from the fly.

It should be noted that this work is done in parallel to a rendezvous GN&C code development for an autonomous rendezvous in Mars orbit. As this work shares some similarities with the subject of formation flying orbit control, readers are encouraged to review the preliminary results presented in Pelletier [7].

A flowchart representation of the Autonomous GN&C system proposed for SSS is depicted in Figure 10. The GPS single differences are computed in a pre-processing phase using the pseudoranges from both GPS receivers. The EKF then estimates the relative state of SSS using all kinds of observations available. A control box evaluates if the SSS position is within safe boundaries. The guidance subsystem computes a maneuver to bring back the satellite to its nominal position if seen out-of-bounds. The maneuver is applied by the control subsystem based on inputs from the Attitude Control System (ACS). The boundary values define a fixed spheroid specified in the ALOS coordinate system, i.e. in the radial, cross-track and in-track directions.

4 Conclusions

This paper presented different aspects of orbital mechanics for formation flying satellites. The subject was treated with respect to a SAR interferometric mission. The definition of the perpendicular baseline required for this mission/formation was reviewed and a suitable configuration was proposed. The effects of the perturbations due to gravity were taken into account in the choice of the orbital parameters, leading to an analysis of frozen orbits to eliminate the long-term J3 perturbations.

A simulation of the influence of drag on both satellites was performed. The matters of formation control and autonomous navigation were discussed and a preliminary algorithm scheme was proposed.

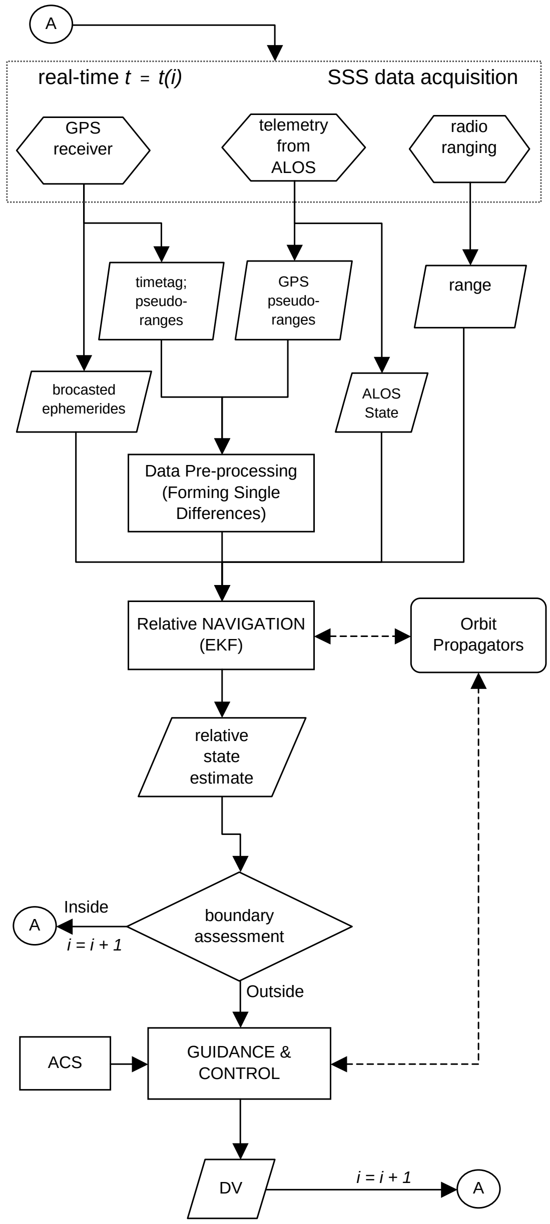

Figure 10: Autonomous GN&C Flowchart

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