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Advantages of small satellite carrier concepts for LEO/GEO inspection and debris removal missions

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Abstract: This work focuses on two important types of space missions: close-in satellite inspection of LEO/GEO high-value assets to detect and/or resolve anomalies, and LEO/GEO debris disposal missions to reduce space hazards. To demonstrate the efficiency of using reusable SmallSats, two mission architectures are analysed: 1) a SmallSat carrier-based system with an in-space refuelling capability; 2) a traditional carrier-less SmallSat. For each architecture the number of potential SmallSat satellite inspection and debris disposal mission sorties is determined as a function of the required initial launch mass. The analysis shows that reusable SmallSats can efficiently conduct multiple satellite inspection and debris removal sorties. For LEO missions, the carrier-based architecture enables a significantly lower launch mass than the carrier-less system. For GEO missions, the advantages of a carrier-based system are less clear and more mission specific. To accomplish these missions, key enabling SmallSat technologies are identified.

Keywords: satellite inspection; space debris; mission design; trajectory design.

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1 Introduction

The geostationary orbit (GEO) belt contains many valuable assets for communications, Earth monitoring, and national security. The ability to periodically inspect these satellites to assess anomalies or detect potential problems is important to the aerospace community. The presence of GEO debris, including large dead GEO satellites, represents a hazard to these assets and future GEO assets. As such, NASA, AFRL, DARPA, and the aerospace community at large have significant interest in GEO satellite inspection and debris removal.

Unfortunately, the capability to inspect GEO satellites or remove debris from GEO is limited. Remote inspection from the largest ground-based telescopes is of very low resolution (Mozurkewich et al., 2011). Active propulsive de-orbit options for debris removal are costly, and passive orbital decay options are not realistic (Committee on Space Debris, 1995; Kaplan et al., 2010). This paper provides a realistic approach to solving the GEO debris removal problem using SmallSat systems.

A similar situation exists in the low earth orbit (LEO) environment. Inspection of valuable LEO assets using ground-based telescopes is limited, and the presence of LEO debris presents an even more dangerous situation owing to the possibility of unexpected high-velocity collisions and LEO object fragmentation (Kaplan et al., 2010; Liou, 2011). By recognising that LEO objects are generally concentrated in one of several inclination bands, this paper is able to define a SmallSat system that can address this problem as well.

The purpose of this paper is to

1. define LEO and GEO satellite inspection and debris disposal missions that can be achieved with SmallSats
2. compare the required launch mass of a SmallSat carrier system, to a stand-alone carrier-less SmallSat concept
3. identify key enabling SmallSat technologies that are required to achieve these missions.

As will be seen, these technologies are applicable to other SmallSat space missions that require rendezvous and proximity operations.

Section 2 of this paper defines GEO satellite inspection and debris disposal missions for a carrier-based SmallSat and a carrier-less SmallSat, and reports the results of a preliminary mission analysis, including trajectory design, delta-v analysis, and an assessment of overall launch mass.

Section 3 presents a similar analysis for LEO satellite inspection and debris disposal missions; however, the uniqueness of the LEO environment is clearly exposed by the uniqueness of the mission design and the associated SmallSat performance.

Section 4 provides a list of important issues that need to be considered for future satellite inspection and debris removal missions, and Section 5 summarises the results of the analysis conducted for this paper.

2 Mission analysis I: GEO inspection and debris disposal

A review of the GEO space object (GSO) population data (STRATCOM, http://www.space-track.org) shows a high density of objects with inclinations less than 0.1 degrees. Within this small inclination band there are over 250 catalogued objects with semi-major axes ranging from 42,163 km to 42,167. The ascending nodes of these objects range from 0–360 degrees.

Using this GSO population as a guide, two key mission requirements are assumed:

1. a responsiveness requirement – the SmallSat shall have the capability to inspect and revisit any GSO with an inclination less than 0.1 degrees, within any 90 day period, or transport any GSO with a mass up to 5,000 kg and inclination less than 0.1 degrees to a GEO graveyard orbit, within any 90 day period

2. a communications requirement – the SmallSat must have a direct link to the ground for monitoring and control.

Based on these requirements, a preliminary mission design and analysis is presented, including trajectory design, delta-v analysis, and an assessment of overall launch mass requirements for multiple GEO inspection and debris disposal sorties.

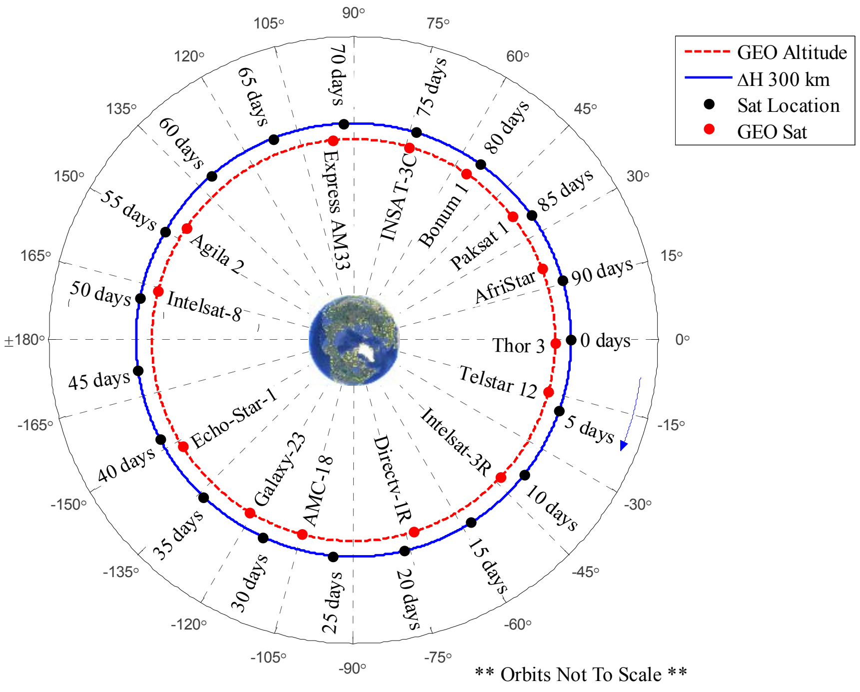
The GEO SmallSat carrier concept consists of one SmallSat attached to a carrier in a near GEO. When a SmallSat is deployed, it transfers to a GSO of interest, conducts an inspection or disposes the GSO in a graveyard orbit, returns to the carrier, docks, and makes preparations (e.g., refuelling) for another sortie. The GEO carrier-less concept is similar, but in this case the SmallSat returns to a nominal parking orbit instead of returning to the carrier for refuelling.

Additionally, it is assumed that the SmallSat has a ‘capable’ mass of 100 kg, and the carrier has a capable mass between 100 kg and 300 kg, where the capable mass is defined to be the mass required for all vehicle subsystems (e.g., GN&C, C&D, docking/birthing mechanisms, power, propulsion, thermal, etc.) excluding structure and propellant. In the absence of an extensive system design, these capable masses seemed reasonable and in line with recent rendezvous missions (XSS-11 < 145 kg, Orbital Express, < 900 kg, PRISMA/TANGO, < 40 kg). In all cases, the carrier-less SmallSat has the same capabilities as the carrier SmallSat, but without a refuelling and cooperative docking capability.

2.1 Carrier orbit and capabilities

To accommodate the responsiveness requirement, the carrier is placed in either a circular orbit 300 km above (or below) GEO or in a cycloid orbit with the same 90-day synodic period. Figure 1 illustrates how these orbits return to the same geocentric longitude every 90 days. The advantage of the cycloid is its proximity to GEO during perigee passes (if the carrier is above GEO) which may enable additional reconnaissance and/or inspection.

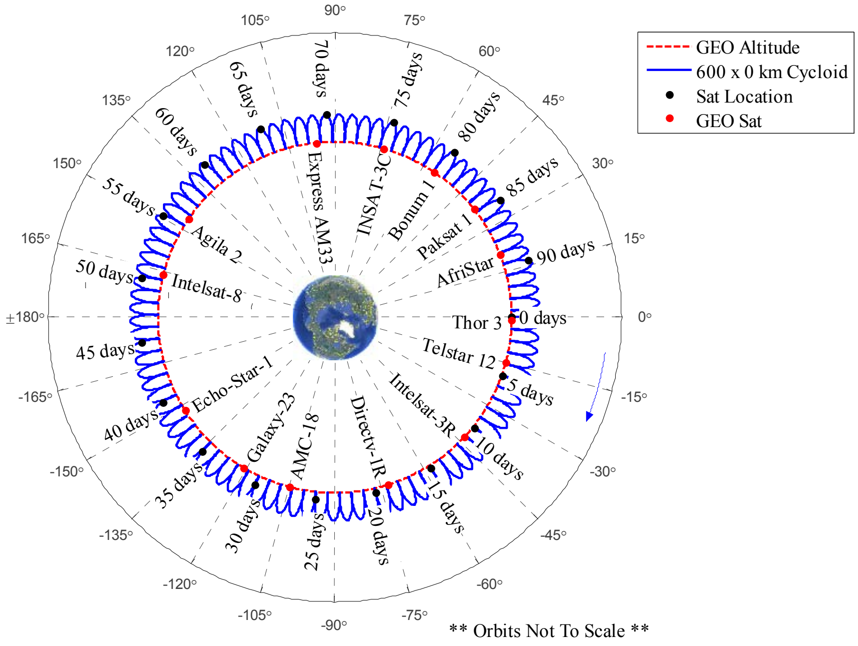
Figure 1 Carrier and GSO orbits in an Earth centred Earth fixed (ECEF) reference frame, (a) carrier orbit in a co-planer, co-circular orbit, 300 km above GEO (b) carrier in a cycloid orbit with apogee 600 km above GEO and perigee at GEO altitude (see online version for colours)



(a)

Notes: The black dots represent the position of the carrier satellite as a function of time. The red dots are fixed GSO locations. The red dotted line is the geostationary orbit. The blue line is the orbit of the carrier in an ECEF (non-inertial) reference frame. The figure shows that it takes about 94 days for the carrier to return to the same GEO longitude.

Figure 1 Carrier and GSO orbits in an Earth centred Earth fixed (ECEF) reference frame, (a) carrier orbit in a co-planer, co-circular orbit, 300 km above GEO (b) carrier in a cycloid orbit with apogee 600 km above GEO and perigee at GEO altitude (continued) (see online version for colours)



** Orbits Not To Scale **

Notes: The black dots represent the position of the carrier satellite as a function of time. The red dots are fixed GSO locations. The red dotted line is the geostationary orbit. The blue line is the orbit of the carrier in an ECEF (non-inertial) reference frame. The figure shows that it takes about 94 days for the carrier to return to the same GEO longitude.

The carrier vehicle is designed to serve primarily as an active docking and refuelling station for the SmallSat. It maintains a full set of basic GN&C functions, a communications link with the ground, a minimal propulsion capability, a short-range inter-satellite communications link with the SmallSat, and serves optionally as a high-speed data link to the ground.

The single, carrier-less SmallSat concept is similar, but does not have a refuelling or cooperative docking capability. For this concept, the 90 day responsiveness requirement is met by requiring the single SmallSat to return to a circular orbit 300 km above (or below) GEO or similar orbit with a 90 day synodic period.

2.2 *SmallSat capabilities*

The SmallSat vehicle is designed to provide a GSO inspection capability or a GSO disposal capability. The SmallSat maintains a full set of basic GN&C functions, a communications link with the ground, a propulsion capability, and a short-range inter-satellite communications link with the carrier (for the carrier concept). Inertial navigation is nominally achieved by ground tracking and optionally supported by the carrier inter-satellite communications link. Each SmallSat maintains an optical camera for long-range relative optical navigation (1 km–100 km), inspection imagery, and close-in (< 100 m) six-dof relative (pose) navigation. An optional artificial illumination device is also maintained. A flash Lidar is also considered for robust, close-in (< 100 m), six-dof relative (pose) navigation.

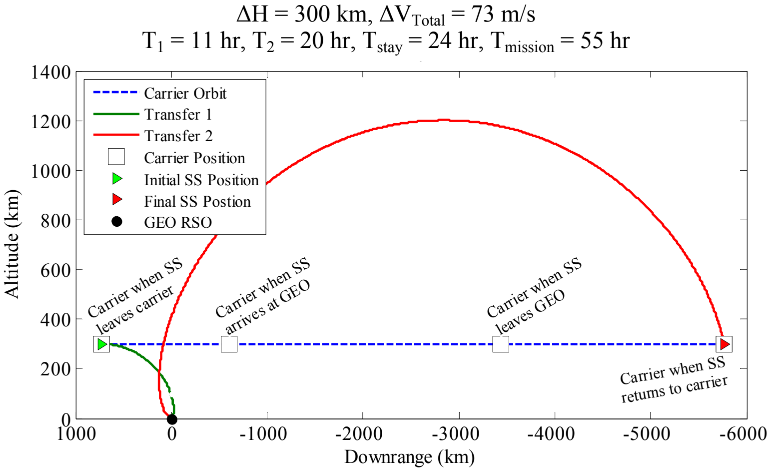
For debris disposal missions, the SmallSat is equipped with a small lightweight towing boom. The towing boom consists of a deployable 3–10 m boom with a set of electro- or gecko-adhesive pads mounted on rocker-arms at the end of the boom. To accommodate centre-of-mass offsets, a mechanical ball-joint is optionally located near the debris attach point. Preliminary estimates indicate that the entire towing boom package will provide 10 pounds of tension and shear force, weight less than 10 kg, require less than 5 W of power, and have a volume less than 6 in × 6 in × 12 in.

2.3 *SmallSat inspection sortie and trajectory design*

For inspection missions, a sequence of pre-planned or autonomous manoeuvres are required to transfer to the GSO of interest, conduct the inspection, and transfer back to an orbit with a synodic period of 90 days, in this case a circular orbit 300 km above (or below) GEO, to meet the responsiveness requirement. In the carrier concept the SmallSat is also required to rendezvous and dock with the carrier.

To transfer to the GSO, the SmallSat first executes a manoeuvre at the GSO node location to match the GSO inclination. A two-manoeuvre Hohmann transfer sequence is then executed at the proper time/phasing to affect a rendezvous with the GSO. Trajectory correction manoeuvres are executed to null eccentricity differences and position the SmallSat in the vicinity of the GSO at a range of 100 m–1 km in front or behind the GSO where the inspection begins. A full 4π steradian survey will generally require some form of artificial lighting.

Figure 2 Example carrier SmallSat (SS) rendezvous trajectory for a short 55 hour sortie (see online version for colours)



Notes: The dashed blue line is the position of the carrier relative to the GSO (black dot) at the origin. The white squares are the position of the carrier at different times in the mission. The green curve is the transfer from the carrier to the GSO. The red curve is the transfer of the SS from the GSO to the carrier.

When the inspection is complete, the carrier SmallSat executes a two-manoeuvre Hohmann-transfer sequence at the proper phase angle and an inclination change at the GSO node to return and rendezvous with the carrier. The carrier-less SmallSat returns to any orbit with a synodic period of 90 days.

Non-optimal/non-Hohmann short duration inspection missions (e.g., < 7 days) are also considered for situations where there is a need for a fast return to the carrier. Figure 2 shows an example of an optimal carrier SmallSat rendezvous trajectory for a short 55 hour sortie mission. The total delta-v (ΔV_{total}) for this sortie is 73 m/s. The time of flight to GEO (T1) is 11 hours, the time in GEO is 24 hours, and the time-of-flight to return to the carrier (T2) is 20 hours.

2.4 SmallSat debris disposal sortie

For GSO debris disposal sorties, the SmallSat transfers to GSO debris in the same manner as an inspection mission. A set of pre-planned or autonomous manoeuvres are executed to place the SmallSat in a position (< 10 m) where it can attach a towing boom to the debris object.

When the SmallSat, towing boom, and debris object are aligned with the inertial velocity vector, the SmallSat begins to propulsively tow the object to a graveyard orbit. Orbital manoeuvres may require either a very long, low-thrust, multi-day spiral out of the GEO, or a relatively fast, high-thrust, 24 hour Hohmann transfer to the graveyard orbit. The SmallSat may be disposable and remain with the debris in the graveyard orbit, return to the carrier to prepare for another debris disposal mission, or, in the case of a carrier-less SmallSat, returns to an orbit with a synodic period of 90 days.

2.5 Δv requirements for individual sorties

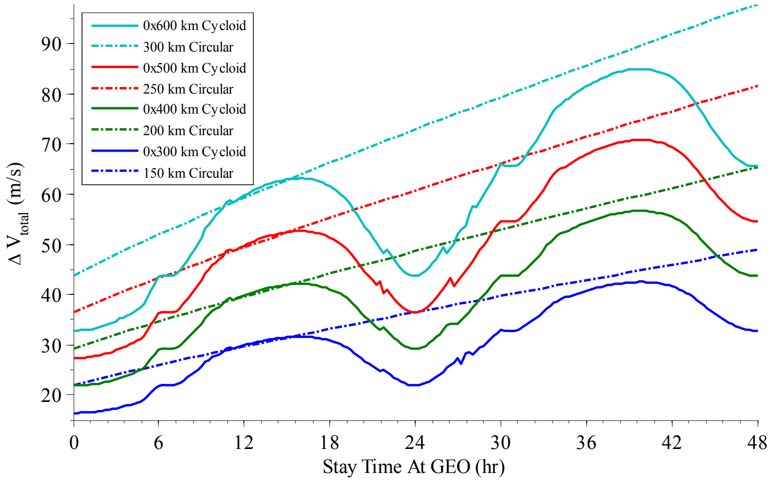
To determine the launch mass of a SmallSat designed to conduct many inspection or debris disposal sorties, estimates of the delta-v requirements for each individual inspection or debris disposal sortie must be determined.

The analysis presented below is ideal in the sense that it does not take into account the delta-v required for midcourse corrections, and proximity operations, i.e., only the major manoeuvres are considered. When launch mass estimates are determined, additional delta-v will be added to results of this section later to account for the relatively smaller correction manoeuvres.

For GSO inspection sorties, the optimal delta-v for a roundtrip SmallSat sortie from a 300 km orbit above GEO (i.e., from an orbit a 90 day synodic period) is approximately 22 m/s without a plane change and 32 m/s with a plane change of 0.1 degrees. This minimum delta-v is achievable with the carrier-less SmallSat since there are no requirements to rendezvous with a carrier.

A carrier SmallSat however must return to the carrier to prepare for the next sortie, and if the return time is unconstrained (i.e., if the carrier SmallSat can wait one synodic period in GEO for an optimal return), the optimal delta-v's above are applicable. This is reasonable since both the carrier-less SmallSat and the carrier SmallSat are assumed to have the same capabilities (i.e., they can both function without carrier support for long periods of time).

Figure 3 Optimal roundtrip in-plane delta-v requirements for a carrier SmallSat inspection sortie as a function of GEO stay-time/inspection-time (see online version for colours)



Notes: The dash-dot curves show delta-v requirements for different circular carrier orbits with synodic periods ranging from three months to six months. The solid curves show delta-v requirements for different cycloid orbits with the same range of synodic periods.

However, it may be beneficial to return to the carrier in just a few days to prepare for the next sortie. Figure 3 shows the optimal roundtrip in-plane delta-v requirements for a carrier SmallSat inspection sortie as a function of GEO stay-time/inspection-time. In all cases, the inspection sortie duration is less than 3.3 days. A maximum inclination change of 0.1 degrees can be accounted for by adding a 10 m/s to the data presented. The sensitivity to different carrier circular and cycloid orbits (with different synodic periods) is shown.

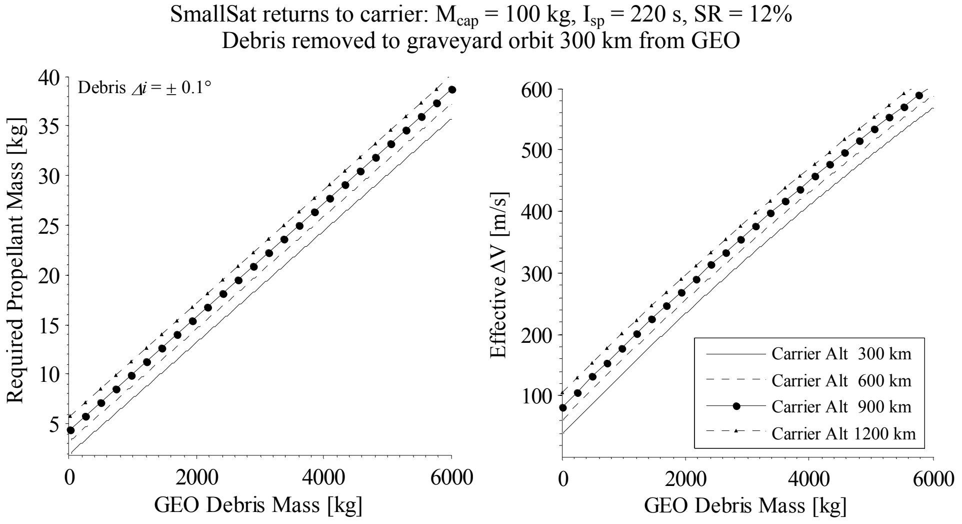
Because the phasing of the cycloid apogee relative to the GSO is variable, the optimal delta-v is a function of orbit phasing as well. The cycloid data presented in Figure 3 shows only the worst case delta-v (i.e., worst case phasing) for each GEO stay time.

For individual GEO debris disposal sorties, it is not possible to compute the roundtrip delta-v directly because the SmallSat mass during the debris disposal phase of the sortie (SmallSat plus the attached debris object) is different than the SmallSat mass during the transit to and from GEO (SmallSat only). Instead, the total required *propellant mass* for an individual sortie must be computed first. Then, the total *effective* delta-v can be computed from the initial/final mass ratio.

To determine an estimate of the required propellant mass, it is assumed that the SmallSat transfers from a 300 km circular orbit above GEO to the debris object using a Hohmann transfer and a 0.1 degree inclination change. Then, the SmallSat transfers the debris object to a graveyard orbit 300 km above GEO using a Hohmann transfer (no inclination change is required for debris disposal). After disposal, the SmallSat returns to the carrier using small phasing manoeuvres and a 0.1 degree inclination change, or, in the case of a carrier-less SmallSat, the SmallSat returns to an orbit with a 90-day synodic period using small phasing manoeuvres to meet the 90-day responsiveness requirement.

The propellant requirements shown in Figure 4 were generated assuming a SmallSat with 100 kg of capable mass, 12% structural mass (STRATCOM, http://www.space-track.org), 10% additional delta-v for midcourse corrections, 0.1 degree inclination change, and a SmallSat propulsion system Isp equal to 220 s (monopropellant hydrazine). The effective delta-v on the right-hand side of the figure is calculated from the required propellant mass results using the initial mass/propellant mass ratio. The sensitivity to different carrier orbits (with different synodic periods) is shown.

Figure 4 (a) Required SmallSat propellant mass and (b) effective delta-v as a function of GEO debris object mass and carrier altitudes ranging from 300 km to 1,200 km (and synodic periods ranging from one week to three months)



(a) (b)

2.6 Launch mass comparison

A key metric in assessing GEO inspection and debris disposal missions is the total carrier-less SmallSat mass and the total carrier plus SmallSat mass required to conduct N inspections or N debris disposal sorties. In either case, the initial required on-orbit mass is referred to simply as *launch mass*. The objective of this section is to use the delta-v information for the individual sorties presented above to determine the total initial carrier-less SmallSat mass and the total initial carrier plus SmallSat mass required to conduct N inspection or debris disposal sorties.

In all cases, the rocket equation is employed using the following assumptions: 100 kg SmallSat capable mass, 12% structural mass (STRATCOM, http://www.space-track.org), 10% delta-v penalty for trajectory corrections, a maximum 0.1 degree inclination change, and 10 m/s for proximity operations.

The 90-day responsiveness requirement is enforced by requiring the carrier-less SmallSat to return to a 300 km orbit above GEO after each inspection sortie and by requiring the carrier SmallSat to return to its carrier in a similar orbit. An engine Isp of 220 s is assumed.

Figure 5 Launch mass as a function of the number of GEO inspection missions for both a carrier concept and carrier-less concept (see online version for colours)

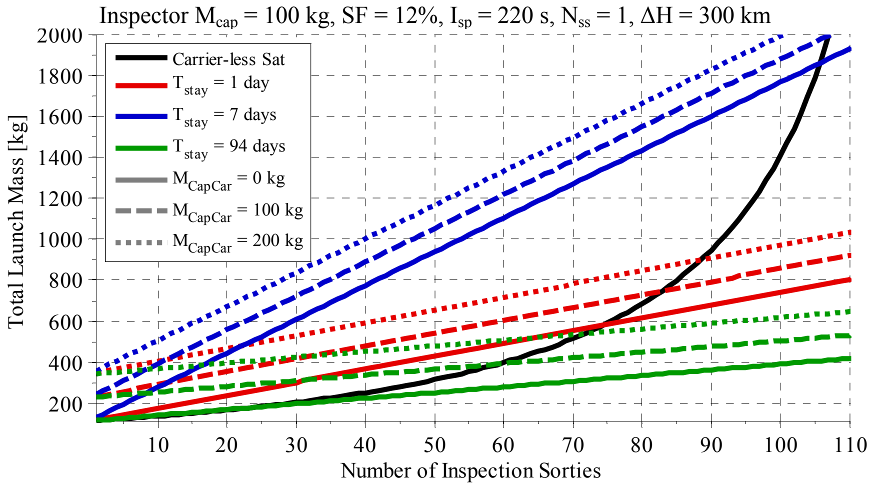


Figure 5 shows the required launch mass as a function of the number of required inspection sorties. The black curve shows the launch mass required for a single carrier-less SmallSat to complete N inspection sorties. The coloured curves show the launch mass required for a SmallSat carrier concept (i.e., SmallSat mass plus carrier mass). The different colours show the sensitivity to time in GEO, and the line styles show the sensitivity to carrier capable mass.

For multiple debris disposal sorties, the rocket equation is again employed using the *effective* delta-v computed for debris disposal sorties in the previous section. A 94-day GEO stay-time is assumed for the carrier SmallSat.

Figure 6 Launch mass as a function of the number of GEO debris disposal sorties for both a SmallSat carrier concept and a carrier-less SmallSat concept (see online version for colours)

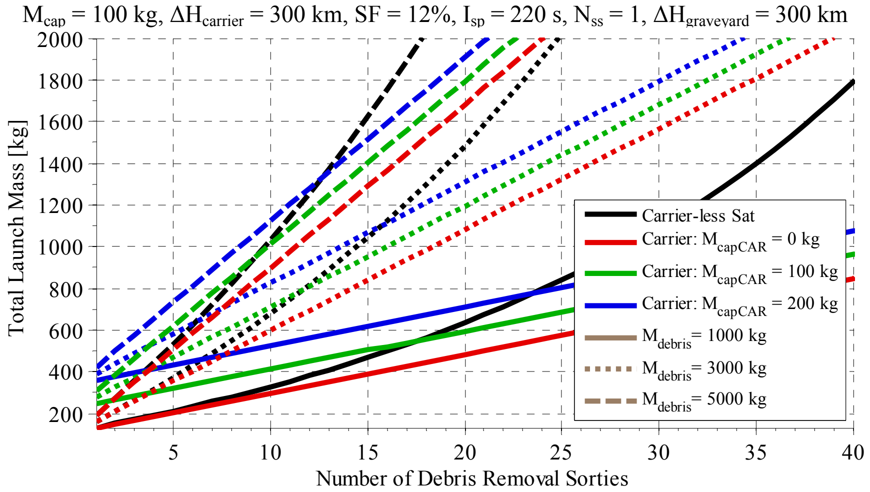


Figure 6 shows the required launch mass as a function of the number of required debris disposal sorties. The black curves show the launch mass required for a single carrier-less SmallSat to complete N debris disposal sorties. The coloured curves show the launch mass required for a SmallSat carrier concept (i.e., SmallSat mass plus carrier mass). The different colours show the sensitivity to carrier capable mass, and the different line styles show the sensitivity to GSO debris mass.

The data in Figure 5 and Figure 6 neglect the additional mass that would be required for packaging the SmallSat system into the payload fairing of the launch vehicle. The volume of the payload fairing is also not taken into account. The results are thus optimistic, but clearly show the differences between a carrier-based system and a carrier-less system.

2.7 Discussion

The above results show that for a limited number of missions, e.g., < 10, a single carrier-less SmallSat has a clear launch mass advantage of over the carrier concept. In this regime of sorties, the benefit of using a reusable/refuelable carrier-based SmallSat is not strong enough to overcome the penalty associated with the carrier mass. The primary reason for this is the relatively small delta-v required for each individual sortie. The compounding effect of small delta-v's for multiple sorties on a single carrier-less SmallSat mass (via the rocket equation) is nearly linear in this regime and does not offset the additional mass required for a carrier.

However, for hundreds of sorties the compounding effect of many small delta-v's on the single SmallSat mass becomes exponential and eventually exceeds the required mass for the carrier concept. While hundreds of inspection and debris disposal sorties may not be required in the foreseeable future, the carrier does have a clear mass advantage over the single SmallSat concept in this regime.

This conclusion, however, may not be universal. An alternative strategy is to consider the deployment of multiple carrier-less SmallSats, each capable of conducting multiple sorties without a carrier or refuelling. In this case, the overall launch mass required to conduct hundreds of missions may in fact be less than a SmallSat carrier concept. On the other hand, if a fleet of carrier-less SmallSats can be optimised such that each SmallSat is capable of conducting multiple sorties, a carrier concept can also be optimised such that each carrier-based SmallSat is capable of conducting multiple sorties before returning to the carrier.

It should also be noted that if a more responsive system is required, e.g., a system that must conduct an inspection within 1 week after a request is made, the required parking orbit for the carrier or the carrier-less SmallSat must be raised (or lowered) to approximately 4,000 km. This will increase the delta-v associated with individual sorties and will favor the SmallSat carrier concept.

3 Mission analysis II: LEO inspection and debris disposal

The LEO space object (LSO) population differs significantly from the GSO population in that the LSOs span a wide range of altitudes and inclinations. However, a review of the LSO population (STRATCOM, http://www.space-track.org) shows distinct bands of high-density populations at various inclination and altitudes. One particular high-density region, a 1 degree band centred at 74 degrees, contains over 2,000 LSOs ranging in altitude from 400 km to 1,600 km. The ascending nodes of these objects range from 0–360 degrees, and at 74 degrees inclination, the relative precession of the ascending node can provide access to these objects over a five year period.

Using this LSO population as a guide, two key mission requirements were assumed:

1. a responsiveness requirement – the SmallSat shall have the capability to inspect or dispose of any LSO debris object with a mass up to 5,000 kg with an inclination between 73.5 degrees and 74.5 degrees, and an altitude between 400 km and 1,600 km, within a five-year period after initial deployment
2. a communications requirement – the SmallSat must have a direct link to the ground for monitoring and control
3. an orbital lifetime requirement for debris disposal sorties – debris must be transferred to an orbit with an orbital lifetime of less than three years.

The LEO SmallSat carrier concept consists of one SmallSat attached to a carrier in a LEO orbit. When a SmallSat is deployed, it transfers to a LSO object of interest, conducts an inspection or propulsively transfers LSO debris to a lower orbit that meets the orbital lifetime requirement of < 3 years. The carrier SmallSat then returns to the carrier, docks, and prepares (e.g., refuelling) for another sortie. The LEO carrier-less SmallSat concept is similar, but in this case the SmallSat returns to a desired parking orbit instead of returning to a carrier for refueling.

It is recognised that the requirements for a debris disposal mission will be based not only upon LSO population densities, but also on those LSO populations that have higher probability of collision and fragmentation. Thus, the space object populations of interest for disposal missions may be different than the space object populations for inspection missions.

As in the GEO mission analysis, it is assumed that the SmallSat has a ‘capable’ mass of 100 kg, and the carrier has a capable mass between 100 kg and 300 kg, where the capable mass is defined to be the mass required for all the vehicle subsystems (e.g., GN&C, C&D, docking/birthing mechanisms, power, propulsion, thermal, etc.) excluding structure and propellant. In all cases, the carrier-less SmallSat again has the same capabilities as the carrier SmallSat, but without a refuelling and cooperative docking capability.

3.1 Carrier orbit and capabilities

The carrier vehicle is designed to serve primarily as an active docking and refuelling station for the SmallSat and maintains all the of the same basic GN&C functions as the GEO SmallSat carrier with the addition of GPS for absolute navigation.

To accommodate inspection or debris disposal of LSOs in this inclination/altitude band, a SmallSat carrier is initially deployed to a circular orbit at the centre of the band, i.e., a 74 degree inclination, 1,100 km altitude orbit. From this staging point, individual inspection and debris disposal sorties will require a mean altitude change of 400 km and a mean inclination change of 0.25 degrees. Over a five-year period, the differential precession of the carrier ascending node will provide access to all the objects in this band that are more than 300 km below or above the carrier. Hence, the altitude of the carrier orbit is located in the middle of two high LSO density populations, one below at 500–800 km altitude, and the other above at 1,400–1,600 km altitude.

The single carrier-less SmallSat concept is similar, but does not have a refuelling/cooperative docking capability. In this case, the responsiveness requirement is met by requiring the single SmallSat to return to an orbit with an 1,100 km semi-major axis to ensure the differential precession rate will enable access to a full 360 degrees of ascending node over a five-year period.

3.2 SmallSat capabilities

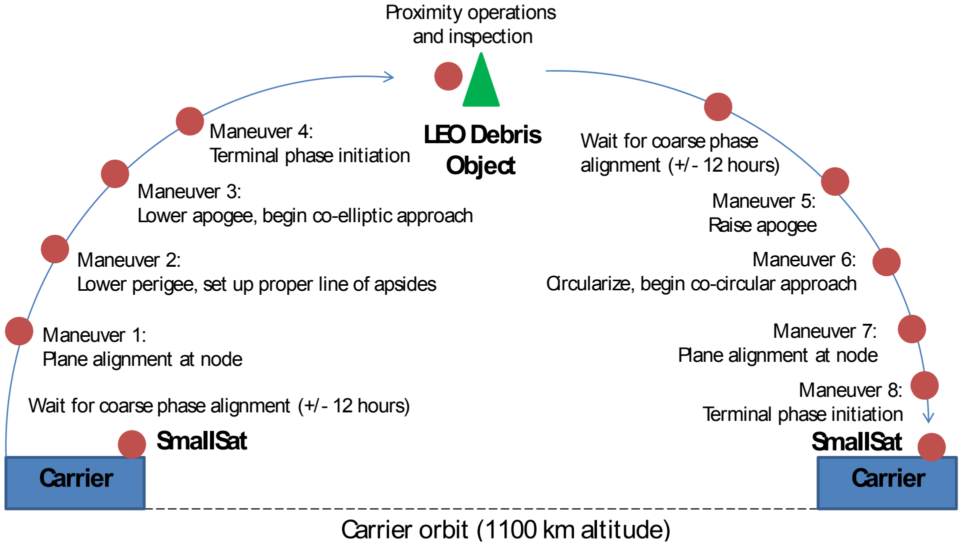
With the addition of GPS for absolute navigation, the LEO SmallSat capabilities are identical to the GEO SmallSat capabilities given in Section 2.2.

3.3 SmallSat inspection sortie and trajectory design

For inspection sorties, a sequence of pre-planned or autonomous manoeuvres are required to transfer to the LSO of interest, conduct the inspection, and transfer back to the required LEO parking orbit to meet the responsiveness requirement. In the carrier concept the SmallSat is also required to rendezvous and dock with the carrier.

To transfer to the LSO, the SmallSat first executes a small plane change at the LSO/SmallSat line-of-nodes to accommodate small LSO inclination and ascending node differences, taking into account a small amount of differential nodal precession that will occur during the sortie. Proper phasing is achieved by adjusting the departure time up to ±12 hours. The SmallSat then transfers into a co-elliptic orbit by executing two Hohmann-like transfer manoeuvres at the points where the LSO line-of-apsides intersects the SmallSat orbit. The altitude of the co-elliptic orbit is chosen to ensure final phasing for rendezvous. A more optimal sequence of manoeuvres can be considered.

Figure 7 Example of carrier SmallSat rendezvous manoeuvre sequence for a LEO inspection sortie (see online version for colours)



As the SmallSat approaches the LSO from above or below on the co-elliptic trajectory, it executes a manoeuvre to transfer directly to the LSO. Trajectory correction manoeuvres are executed to position the SmallSat in the vicinity of the LSO at a range of 100 m–1 km in front of or behind the LSO where the inspection begins. Optional co-elliptic flyby inspections and circumnavigating orbit inspections are also possible.

When the inspection is complete, the carrier SmallSat executes a similar set of manoeuvres to return and rendezvous with the carrier. The carrier-less SmallSat returns to any orbit with a nodal precession that meets the responsiveness requirement, i.e., the carrier-less SmallSat only needs to adjust its semi-major axis and does not need to make any plane changes after the inspection. An example of a carrier SmallSat manoeuvre sequence for a LEO inspection sortie is shown in Figure 7.

3.4 SmallSat debris disposal sortie

For LSO debris disposal sorties, the SmallSat transfers to the LEO debris object in the same manner as an inspection sortie, and a set of pre-planned or autonomous manoeuvres are executed to place the SmallSat in a position less than 10 m from the debris object where it can attach a towing boom.

When the SmallSat and towing boom are connected to the LEO debris object, the system is aligned with the object's inertial velocity vector, and the SmallSat propulsively tows the debris to a lower orbit that meets the orbital lifetime requirement of < 3 years. Orbital manoeuvres may require a very low-thrust, multi-orbit spiral to a lower orbit or two relatively high-thrust Hohmann transfer manoeuvres (< 15 minutes each). The exact final orbit will depend on the area-to-mass ratio of the object as well as the phase of the solar cycle. Once the final orbit is achieved, the SmallSat may be disposable and remain with the debris, return to the carrier to prepare for another debris disposal mission, or, in the case of the carrier-less SmallSat, return to an orbit with the required nodal precession to wait for another disposal mission.

Drag augmentation devices and other non-propulsive approaches can be effective in reducing the lifetime of particular LEO debris objects for certain LEO orbits. However, the simplicity and effectiveness of propulsive devices may outweigh the relatively low effectiveness and complexity of non-propulsive approaches. A more detailed trade study will be needed in the future.

3.5 Δv requirements for individual sorties

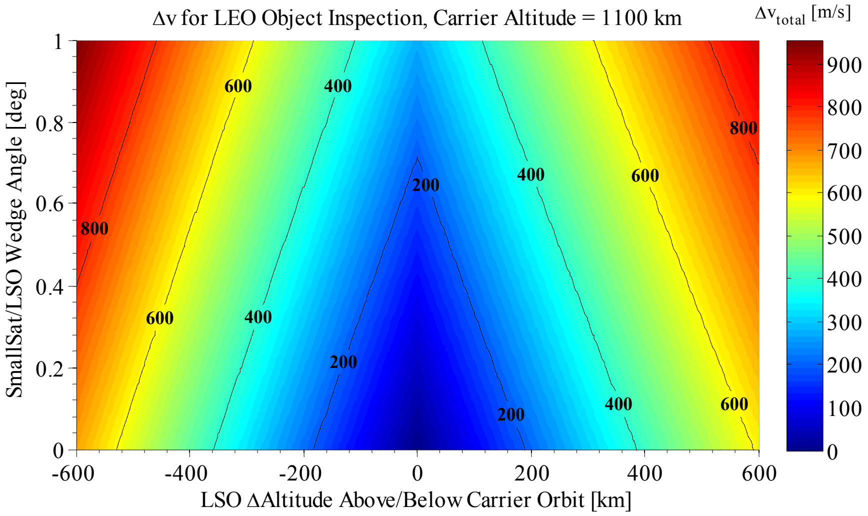
To determine the launch mass for a LEO SmallSat inspection or LEO debris disposal system, estimates of the delta-v requirements for individual inspection and debris disposal sorties must be determined.

The analysis presented below is ideal in the sense that it does not take into account the delta-v required for midcourse corrections, and proximity operations, i.e., only the major manoeuvres are considered. When launch mass estimates are determined, additional delta-v will be added to results of this section to account for smaller, relatively minor manoeuvres.

There are other simplifying assumptions to be considered. The LSO population at 74 degrees inclination lies within a ±0.5 degree inclination band. At any given time there is also a small ascending node difference. In the analysis that follows, it is assumed that the maximum difference between the SmallSat orbit plane and the LSO orbit plane (commonly referred to as the wedge angle) is 1.0 degree. Thus every inspection or debris disposal sortie is assumed to require a plane change of up to 1.0 degrees. Additionally, the eccentricities of 93% of LSO population at 74 degrees inclination span a small but non-trivial range of 0.0–0.02 (STRATCOM, http://www.space-track.org). For this analysis it is assumed that all LSOs are in circular orbits at varying altitudes. Since most of the eccentricities are small, this assumption is not overly restrictive.

Using these assumptions, Figure 8 shows the delta-v required for a roundtrip inspection sortie as function of the LSO altitude and wedge angle. The manoeuvres for changing the SmallSat orbit altitude and nulling the wedge angle are made separately. All in-plane manoeuvres are assumed to be optimal Hohmann transfer manoeuvres. Smaller manoeuvres for orbit phasing, proximity operations, and rendezvous are neglected in this data, but will be considered later when launch mass estimates are determined.

Figure 8 Required carrier SmallSat delta-v for a roundtrip inspection sortie as a function of key LEO space object orbital parameters (wedge angle and altitude) (see online version for colours)



Note: Results will be similar for a carrier-less SmallSat.

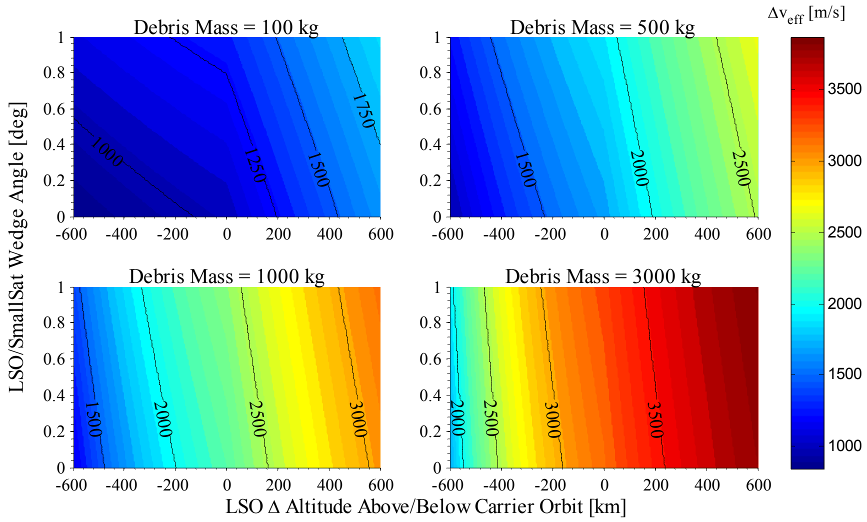
While the results in Figure 8 are based on a carrier SmallSat sortie, they are also valid for the carrier-less SmallSat sortie. First, to meet the responsiveness requirement, the carrier-less SmallSat must return to an orbit with the same semi-major axis as the carrier. Thus the delta-v required for altitude changes will be similar. Second, while the carrier-less SmallSat is not required to return to the original orbit plane via a second plane change, subsequent plane changes may be as high as 2 degrees to accommodate the entire LSO population inclination band. Thus, overall, the total inspection sortie delta-v will be similar.

For individual LEO debris disposal sorties, it is not possible to compute the roundtrip delta-v directly because the SmallSat mass during the debris disposal phase of the sortie (SmallSat mass plus debris mass) is different than the SmallSat mass during the transit to and from the debris object (i.e., only the SmallSat mass). Instead, the required *propellant* *mass* for an individual sortie must be computed first. Then, an *effective* delta-v can be computed from the initial/final mass ratio.

To determine an estimate of the required propellant mass, it is assumed that the SmallSat first transfers to the LEO debris object in the same manner as an inspection mission. Then, the SmallSat transfers the debris to a circular 400 km disposal orbit using a Hohmann transfer with no plane change. After disposal, the carrier SmallSat returns to the carrier by executing a plane change and another two-burn Hohmann transfer sequence, or, in the case of a carrier-less SmallSat, a two-burn Hohmann transfer sequence without a plane change. It is recognised that a more efficient disposal orbit may be an elliptical orbit with a low perigee.

Figure 9 shows the required effective delta-v for a single disposal sortie based on the required propellant mass using the initial mass/propellant mass ratio. The effective delta-v assumes a SmallSat with 100 kg of capable mass, 12% structural mass, 10% additional delta-v for midcourse corrections, 1.0 degree inclination change, and a SmallSat propulsion system Isp equal to 220 s (monopropellant hydrazine).

Figure 9 Required carrier SmallSat effective delta-v for a debris disposal sortie as a function of key LEO debris object mass (100 kg, 1,000 kg, 500 kg, 3,000 kg), and orbit wedge angle and altitude (see online version for colours)



3.6 Launch mass comparison

A key metric in assessing LEO inspection or LEO debris disposal missions is the initial total carrier-less SmallSat mass and the initial total carrier plus SmallSat mass required to conduct N inspections or N debris disposal sorties. Again, the initial mass at deployment is referred to simply as *launch mass*. The objective here is to use the delta-v information for the individual LEO-based sorties presented above to determine the total carrier-less SmallSat mass and the total carrier plus SmallSat mass required to conduct N inspection or N debris disposal sorties.

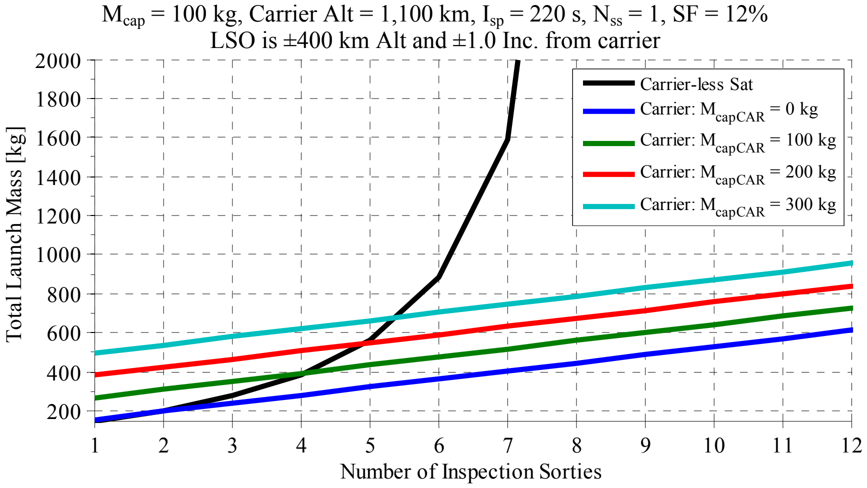
In all cases, the following assumptions apply: 100 kg SmallSat capable mass, 12% structural mass, 10% delta-v penalty for trajectory corrections, 10 m/s for proximity operations, a 400 km mean altitude change, two 0.5 degree mean plane changes for carrier SmallSat sorties, and one 0.667 mean plane change for carrier-less sorties.

While using a mean altitude and inclination changes is reasonable for estimating the total propellant load for N sorties, it does not take into account that propellant tanks will need to be sized for worst case individual sorties. However, the additional mass associated with potentially larger propellant tanks is offset by the rather conservative 12% structural mass.

In all cases, the responsiveness requirement is enforced by requiring the carrier-less SmallSat to return to a an orbit with a 1,100 km semi-major axis after each inspection sortie and by requiring the carrier SmallSat to return to a carrier in a 1,100 km circular orbit. An engine Isp of 220 s is assumed.

Figure 10 shows the required launch mass as a function of the number of required inspection sorties. The black curve shows the launch mass required for a single carrier-less SmallSat to complete N inspection sorties. The coloured curves show the launch mass required for a SmallSat carrier concept (i.e., SmallSat plus carrier mass). The different colours show the sensitivity to carrier capable mass.

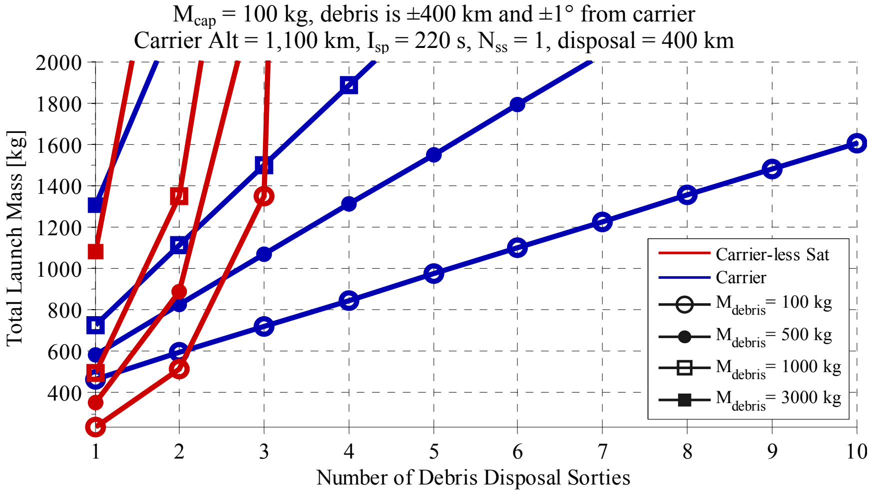
Figure 10 Launch mass as a function of the number of LEO inspection sorties for a SmallSat carrier concept and a carrier-less SmallSat concept (see online version for colours)



For multiple debris disposal sorties, the rocket equation is again employed using the *effective* delta-v computed for the individual LEO debris disposal sorties presented in the previous section. Since the delta-v for debris disposal above the nominal carrier orbit is greater than the delta-v required for debris disposal below the carrier orbit, an average value of the two cases was used to estimate launch mass.

Figure 11 shows the required launch mass as a function of the number of required debris disposal sorties. The red curves show the launch mass required for a single carrier-less SmallSat to complete N debris disposal sorties. The blue curves show the launch mass required for a SmallSat carrier concept (i.e., SmallSat plus carrier mass). The different symbols show the sensitivity to LDO mass.

Figure 11 Launch mass as a function of the number of LEO debris sorties for a SmallSat carrier concept and a carrier-less SmallSat concept (see online version for colours)



The data in Figure 10 and Figure 11 neglect the additional mass that would be required for packaging the SmallSat system into the payload fairing of the launch vehicle. The volume of the payload fairing is also not taken into account. The results are thus optimistic, but clearly show the differences between a carrier-based system and a carrier-less system.

3.7 *Discussion*

The above results indicate an advantage in using a SmallSat carrier when more than eight LEO inspection sorties are required or when more than only four LEO debris disposal sorties are required. These results stand in stark contrast to the GEO inspection and debris disposal results. The key difference is in the significantly larger delta-v requirements for individual sorties, e.g., 32 m/s–100 m/s for GEO inspection sorties, and 400 m/s–900 m/s for LEO inspection sorties. The compounding effect of large sortie delta-v on the carrier-less SmallSat via the rocket equation produces an exponential growth in launch mass versus a near linear growth for the SmallSat carrier concept.

When the number of required LEO sorties is small, e.g., less than 5 or 4, the carrier-less SmallSat can be competitive and in some cases has an obvious advantage. In this regime, the benefit of using a reusable/refuelable carrier-based SmallSat is not strong enough to overcome the penalty associated with the carrier mass. The carrier-less SmallSat wins out primarily due to the relatively low delta-v required for a small number of sorties.

While these conclusions may be true for the two scenarios that were considered (i.e., a carrier-based SmallSat and a single carrier-less SmallSat), an alternative strategy to consider is the deployment of multiple carrier-less SmallSats, each capable of conducting multiple sorties without a carrier or refuelling. For example, the launch mass for a single carrier-less SmallSat capable of conducting four inspection sorties is approximately 450 kg. Five of these SmallSats would be capably of conducting 20 inspection sorties, and the total launch mass would be only 2,250 kg. While this strategy does not outperform the SmallSat carrier concept, it is much more competitive in terms of launch mass. A similar trend exists for debris removal missions, though the carrier concept is highly favoured.

4 Additional considerations

In addition to launch mass, there are other important considerations that will affect the overall design and cost of a particular mission concept. For example, some level of fault tolerance and redundancy will be required. The additional dry mass for a backup carrier SmallSat (dry mass only) must be traded against a backup carrier-less SmallSat, fully loaded with propellant.

Another example is if near-simultaneous GSO inspections. A carrier concept may be beneficial when more than one inspection per month or simultaneous GSO inspections are required, i.e., a single carrier-less SmallSat can be in only one place at a time. On the other hand, multiple carrier-less SmallSats may have the advantage of re-deployment or re-assignment to another asset without the need to return to a carrier for refuelling, thereby providing additional flexibility and responsiveness. A carrier SmallSat will always be required to return to the carrier for refuelling.

In terms of cost, multiple carrier-less SmallSats may benefit from economies of scale, while a SmallSat carrier concept will require the development of a carrier vehicle, propellant transfer/replacement devices, and docking devices. Multiple carrier-less SmallSats will need to be tracked and monitored separately on the ground, requiring greater operational costs. A carrier concept may require less ground support.

The carrier concept offers features that may be value to particular missions: navigation support via a radio navigation beacon, high powered optics for SmallSat support and remote inspection, safe port for SmallSats during periods of inactivity, and a high-speed communications relay station for high-speed data and transfer. All of these features come with additional carrier subsystem development, carrier mass, and additional cost.

Until a particular mission is clearly defined, it is difficult to accurately assess all of the advantages and disadvantages of these mission concepts.

5 Conclusions

As SmallSat capabilities improve, the complexity of SmallSat missions will continue to increase. The development of new technologies such as low-power, low-mass, Lidar-based or optical-based navigation subsystems for close-in (< 100 m) proximity operations will enable close-in inspection, anomaly assessment, and health monitoring of high-value assets. The development of a lightweight towing boom with an electro-gecko-adhesive attachment mechanism will enable orbital debris disposal missions that can significantly be used to systematically reduce space hazards.

This paper has shown that for LEO inspection and debris disposal missions, the carrier-based system enables a significantly lower launch mass due to the relatively high delta-v requirements for each individual sortie. For GEO missions, the advantages are less clear. However, as individual GEO sortie delta-v becomes large, e.g., for inspection missions requiring faster response time, the carrier system will outperform the carrier-less system.

For multiple inspection or debris removal missions, the solution to the minimal launch mass problem can be determined only when a detailed set of mission requirements is specified. Once these requirements are known, an optimal GEO SmallSat carrier concept can be designed and compared to an optimal fleet of single carrier-less SmallSats. And while there may theoretically be a mass advantage to in-space refuelling, the additional mass required for a carrier-based refuelling concept – the carrier mass, docking equipment and propellant transfer/replacement devices – must be properly assessed and traded against the additional capable mass that will be required for multiple carrier-less SmallSats.

Independent of the mission approach, new SmallSat technologies need to be developed to accomplish LEO/GEO close-in inspections and orbital debris removal missions. These technologies have been identified and include:

- Lidar-based relative navigation (< 100 m) with an uncooperative object
- optical-based relative navigation (< 100 m) with an uncooperative object
- deployable towing boom with adhesive pads for removing orbital debris
- artificial illumination device for proximity operations (< 100 m)
- light modulated flash Lidar for proximity operations (< 100 m)
- dynamics and control of a multi-body space system
- on-orbit propellant storage and transfer devices
- on-orbit cooperative docking devices.

SDL and USU researchers are working at various levels in many these areas knowing that the advancement of these technologies will enable future SmallSats to carry out critical satellite inspection and debris disposal missions.

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