

# Imaging payload performance considerations for on-orbit servicing and active debris removal

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## ABSTRACT

The prospects of on-orbit satellite servicing and active debris removal (ADR) missions have been accelerating. Long-term orbital debris growth projections, coupled with decreasing launch costs and proposed “mega” constellations of small satellites has prompted the exploration and maturation of satellite designs which enable on-orbit servicing and orbital debris removal. The majority of these satellite design concepts employ an optical imaging payload. Imaging payloads and their associated machine vision processing may be used to accurately determine object dynamics which are necessary to assess suitable candidate objects for ADR and understand ingress conditions.

Imaging spatial resolution is often the key payload performance parameter to establish the minimum range at which features of interest may be determined given an optical aperture size. Ideal imaging conditions are obtained by matching the orbital planes of candidate objects, thus minimizing the relative angular motion. Upon matching the orbital plane, minimal fuel may be expended to achieve the required range to assess the suitability of ADR candidates. However, the initial orbital plane alignment is expensive due to the high relative velocity change required and the depletion of propellant, often the limiting factor for such missions. The ability to image objects orbiting out-of-plane dramatically improves the overall mission effectiveness by expanding the number of candidate survey objects.

This work explores the design trade space to discover the optimal spatial imaging resolution performance from a small satellite while maximizing the number of targeted objects and minimizing fuel expenditures. This work also demonstrates that spatial imaging resolution is a function of the aperture size, range, angular slew rate of the imaging satellite, and relative angular rate of the targeted object. In particular, improved satellite attitude control technologies enable higher performance imaging from smaller aperture sizes. Smaller aperture sizes, in turn, translate to overall lower satellite and mission costs. Quantifying the relationships among these variables enables optimization of imaging performance at the satellite system level for any given requirement set for ADR missions as well as on-orbit servicing missions.

## 1. INTRODUCTION

Numerous studies have concluded the low earth orbit (LEO) orbital debris population will continue to grow even if all future missions are fully compliant with orbital debris mitigation standards [1]. In the geosynchronous orbit (GEO) region, there are many massive abandoned objects which fully or partially reside within the GEO Protected Region [2]. As such, approaches to enable Active Debris Removal (ADR) have been extensively explored, along with the closely related mission of on-orbit servicing [3]. The long-term environmental benefits may be maximized by targeting the removal of massive objects in orbits with higher debris spatial densities. Specific candidate ADR objects identified include Envisat and “clusters” of derelict objects often dominated by rocket bodies [4]. Many ADR concepts require physical contact or capture, thus necessitating an understanding of the object rotational state and resulting moments of inertia [5]. Ground-based temporal photometry provides a means to understand the rotational period, but the more complex rotational state of objects are more readily determined via direct spatial imaging. The rapid growth in small satellites and the increasing sophistication of their commoditized subsystems has enabled smallsats to provide significant imaging capabilities as well as the potential means to implement ADR solutions [6].

Maximizing ADR survey mission effectiveness involves several key considerations. Imaging is most easily conducted when the relative motion between the objects is minimized, resulting in coplanar conditions such as that experienced during rendezvous and proximity operations (RPO). Obtaining RPO conditions for multiple objects in varying orbital planes requires significant fuel expenditures, with the total delta velocity being a key design

parameter and constraint for small satellites. However, advances in small satellite attitude determination and control subsystems has enabled significant angular slew rates which may be leveraged to image out-of-plane objects subject to an angular rate constraint. Finally, the aperture size of the optical payload dictates the best-case spatial resolution achievable assuming all other imaging conditions are satisfied. Each of these key variables is examined independently. Section 2 quantifies the relative angular rates resulting from orbital dynamics. Spatial imaging resolution is addressed in Section 3. Finally, Section 4 consolidates the equations into a single framework providing a means to quantify the interdependencies and the design trade space.

## 2. RELATIVE ANGULAR RATES

Imaging operations conducted under conditions without RPO or orbit matching require an examination of the relative velocities between the objects. The velocity of the object to be imaged is considered relative to the imaging satellite. Given the relative ranges of interest, Cartesian coordinates provide a sufficient approximation. The geometrical conditions and variables are shown in Figure 1. Point P is the location of the imaging payload while the object to be imaged is indicated by point O which has a velocity vector relative to the imaging payload along  $R_v$  with point C representing the location of closest approach resulting in a range orthogonal to the velocity vector,  $R_o$ . The angle  $\theta$  is defined as that between the orthogonal velocity vector and the target position. Successful imaging is possible when the payload can acquire and track the target. This highlights that the angular slew rate capabilities of the payload host become a key driver in determining what the minimum distance may be for a given relative velocity between the two objects.

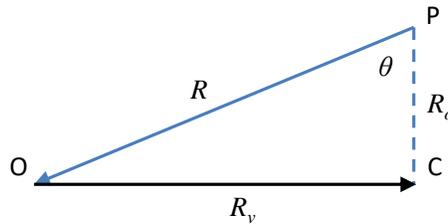


Figure 1. Geometry of a satellite payload P imaging a space object O approaching with a relative velocity along  $R_v$ .

The base of the triangle,  $R_v$ , is the range to the point of closest approach and coincides with the velocity vector of the target object. We will only be examining the relative velocity magnitude, and as such,  $R_v$  is simply the product of velocity and time,  $vt$ . Geometrically, we see that  $\theta$  may be defined as

$$\theta = \text{atan} \left[ \frac{vt}{R_o} \right]$$

The relative angular rate between the target and payload is the time derivative of  $\theta$  or

$$\dot{\theta} = \frac{d}{dt} \left\{ \text{atan} \left[ \frac{vt}{R_o} \right] \right\}$$

$$\dot{\theta} = \frac{v/R_o}{1 + \left( \frac{vt}{R_o} \right)^2}$$

As anticipated, the maximum angular rate of  $v/R_o$  occurs at  $t = 0$  or that corresponding to the point of closest approach for the target,  $R_o$ . If the maximum imaging payload slew rate,  $\omega_{max}$ , is greater than  $v/R_o$ , then imaging can occur at the minimum range, offering the best resolution. However, if  $\omega_{max}$  is exceeded, then the imaging range must be increased such that the object angular rate is within the slew rate of the payload. It is perhaps not at first intuitive, but the angular rate of the approaching object can be minimized by reducing  $R_o$ . In the extreme case of  $R_o$  being zero, or that of a collision path, there is minimal apparent motion of the approaching object. The net result

is that the imaging range may be minimized by setting up an approach orbit in which imaging occurs while the object is approaching the payload (but not at the point of closest approach). This is further developed below.

### 3. IMAGING PAYLOAD PERFORMANCE

The overall imaging performance of the satellite is determined by two primary considerations. First is the angular slew rate capability of the payload, which is usually dictated by the spacecraft, and second is the optical payload aperture size.

#### 3.1 Satellite Angular Slew Rate

What are reasonable values of  $\omega_{max}$  for small satellites? Capabilities of 10 °/s are possible with 3U CubeSats,<sup>1</sup> however the additional sophistication necessary to enable object acquisition such as a wider field of view optical payload and the associated processing likely require a larger form factor. Some 12U designs accommodate ~3 deg/s while larger 250 km class small sats can achieve 5 deg/s. Angular rates between 1-5 deg/s are considered an optimal design point and it is around this range that performance will be examined.

Given the scenario that the point of closest approach ( $R_o$ ) results in an angular rate which exceeds the satellite slew rate capability,  $\omega_{max}$ , what is the minimum range,  $R_{min}$ , at which the object may be imaged? We answer this by finding where  $R_v$ , the range along the object velocity vector from the point of closest approach, results in a relative angular rate  $\dot{\theta}$  which is equal to  $\omega_{max}$ .

$$\omega_{max} = \frac{v/R_o}{1 + \left(\frac{R_v}{R_o}\right)^2}$$

Solving for  $R_v$  results in

$$R_v = \sqrt{\frac{v R_o}{\omega_{max}} - R_o^2} \quad (1)$$

Having found  $R_v$ , the minimum imaging range possible  $R_{min}$  may be determined (ref Figure 1).

$$R_{min} = \sqrt{R_v^2 + R_o^2}$$

Substituting  $R_v$  from equation (1) results in

$$R_{min} = \sqrt{\frac{v R_o}{\omega_{max}}} \quad (2)$$

It is recognized that  $R_{min}$  cannot physically be less than  $R_o$ , meaning  $v/\omega_{max}$  must be greater than or equal to  $R_o$ . As a matter of mission planning, imaging satellites can consider lower delta velocity orbit phasing which results in a point of closest approach ( $R_o$ ) while maintaining favorable lighting conditions. Safety of flight considerations to avoid an unintended conjunction may also be a factor to consider in targeting a minimum  $R_o$  value.

<sup>1</sup> For example, the Blue Canyon Technologies' XB3 3U cubesat (<http://bluecanyontech.com/buses/>, accessed August 2018). See also "Small Spacecraft Technology State of the Art," NASA/TP-2015-216648/REV1, December 2015. (<https://go.nasa.gov/2PPZowd> accessed August 2018).

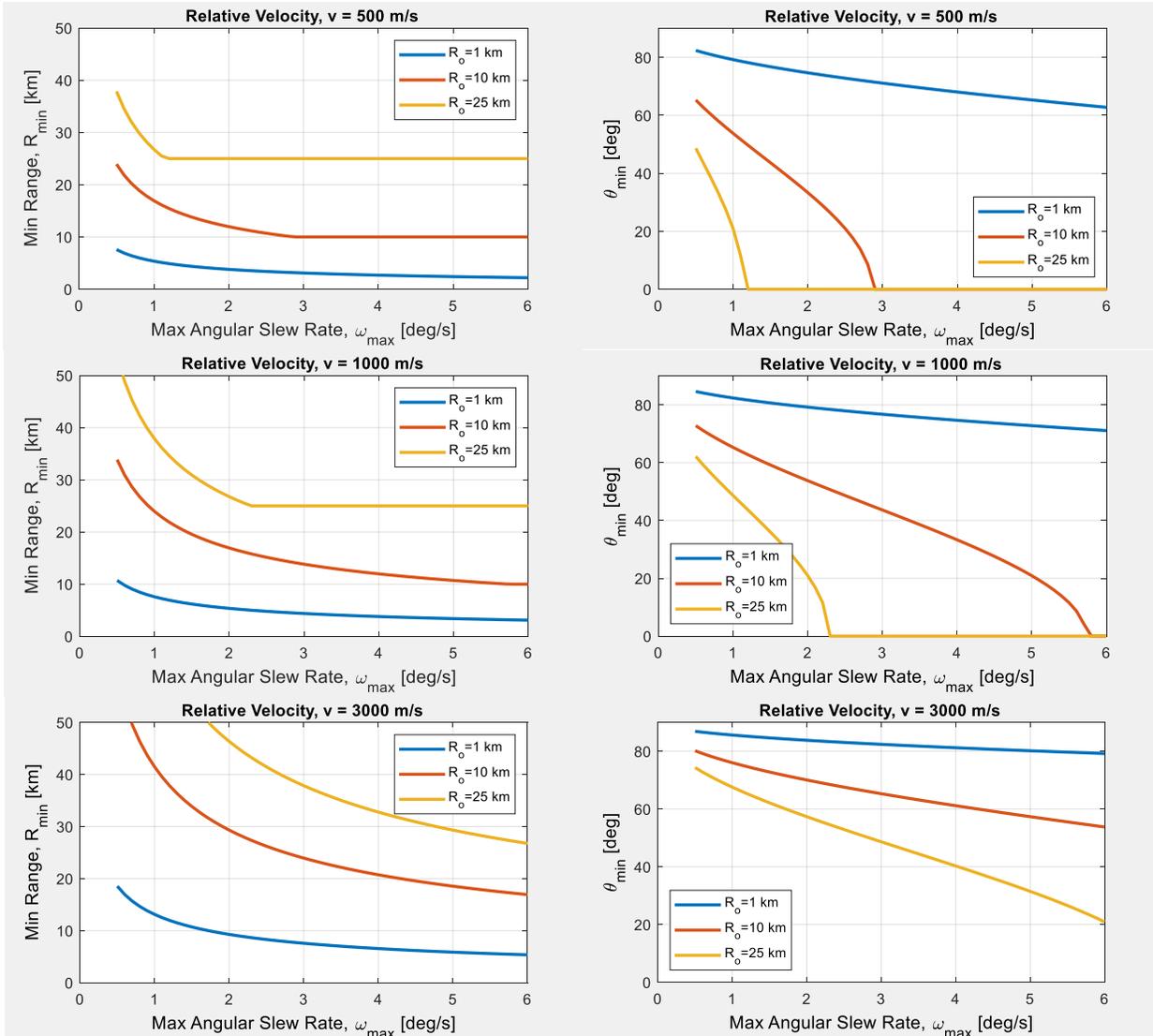


Figure 2. The minimum imaging range ( $R_{min}$ ) (left) and minimum imaging angle ( $\theta_{min}$ ) (right) for relative velocities of 500 m/s (top), 1000 m/s (middle) and 3000 m/s (bottom) as a function of the maximum payload angular slew rate ( $\omega_{max}$ ) for three different close approach distances,  $R_o$ . Inflection points where  $R_{min} = R_o$  can be seen when  $\omega_{max}$  accommodates the maximum object angular rate at the point of closest approach. Similarly, the minimum angle of zero is reached when  $R_{min} = R_o$  or when the imaging payload has sufficient slew capability to image at the point of closest approach.

The corresponding imaging angle relative to the orthogonal velocity direction,  $R_o$  is therefore

$$\theta_{min} = \text{acos} \left[ \frac{R_o}{R_{min}} \right]$$

Figure 2 illustrates the behavior of the minimum range and angle possible across a range of  $\omega_{max}$  and relative velocities. It is critical to note that imaging during the approach of an object enables a closer range than establishing an orbit where the relative angular rate at  $R_o$  matches the capability of the imaging spacecraft.

A helpful intuitive way to understand these geometric values is to place oneself beside the track of a speeding train at a distance  $R_o$  away from the tracks. As the train approaches, at some point you may no longer be able to sufficiently follow the train with your eyes and see details due to the high angular rate. You can only make out

details of the train at a point down the track as it is approaching you, or at the equivalent point as it races away from you. The closest point at which you can make out details corresponds to  $R_{min}$ , and the associated angle away from the track as  $\theta_{min}$ . While there is geometric symmetry for both the approach and recession of the object, satellite imaging during the approach may be the only practical geometry considering that the object must be acquired and tracked through the maximum angular rate possible.

### 3.2 Optical Payload

The ability for an optical system to spatially resolve features of a target is limited by diffraction imposed by the telescope aperture size. We consider the basic resolution of a circular aperture and the associated minimum resolvable angle ( $\varphi$ ) with the Rayleigh resolution criterion of

$$\varphi = \frac{1.22 \lambda}{d}$$

where  $\lambda$  is the wavelength of light and  $d$  is the diameter of the telescope. For simplicity, a wavelength of 600 nm will be used as this approximates the peak spectral performance for a typical silicon-based detector with solar illumination conditions. Converting the Rayleigh criterion from an angle to a length,  $x$ , is then the product of the angular resolution with the range,  $R$ , to the object.

$$x = \varphi R \tag{3}$$

As a single point example, a 10 cm aperture ( $d = 10$  cm) imaging an object at a range of 10 km ( $R = 10$  km) is theoretically capable of providing a spatial resolution,  $x$ , of 7 cm.

The object must first be acquired and tracked prior to imaging. Low cost small satellite optical payloads will typically be limited to those fixed to the body foregoing more complex gimballed designs. With this consideration in mind, and ability of the satellite to acquire, track, and image objects depends on the relative velocities between the two objects. The best imaging resolution is obtained at the closest range, but that also coincides with the highest angular rate and the most challenging condition for the host satellite.

### 3.3 Imaging Payload Figure of Merit

Having explored both the angular rate and the inherent spatial imaging performance limits of an optical payload, it can now be appreciated how each are key performance drivers for enabling resolved imaging in other than co-orbital or RPO conditions. Consider a 20 cm optical payload which can slew at 1 deg/s to that of a 10 cm payload which can slew at 2 deg/s. Due to the higher slew rate, the 10 cm payload could obtain the same resolution as the 20 cm payload.

To capture this performance, an imaging payload figure of merit is proposed which is the product of the aperture size,  $d$ , and the host slew rate capability  $\omega_{max}$  while imaging.

$$\beta = d \omega_{max}$$

Units of cm are suggested for  $d$ , while deg/s are used for  $\omega_{max}$ . Using the preceding example, both the 20 cm payload with 1 deg/s of slew capability and the 10 cm payload with 2 deg/s of slew capability have an identical figure of merit of  $\beta = 0.2$ . Units are not carried, as there is minimal intuitive value.

## 4. IMAGING PAYLOAD VERSUS SPACECRAFT TRADES

We now explore the design space and the potential imaging performance. The key variables to consider for optimization include

- Imaging resolution of the target,  $x$
- Duration of imaging required
- Number of objects to be imaged

To this point the *duration* of imaging has not been addressed. If the objective is determine the complex rotational condition of a candidate object for ADR, then it is desired to observe some fraction of the rotation period with a minimum resolution. Ground-based photometric measurements indicate the majority of larger rocket bodies have rotational periods greater than one minute [7].

The primary relevant satellite design parameters to enable this performance include:

- Payload aperture size,  $d$
- Angular slew rate capability,  $\omega_{max}$
- Total delta velocity for the satellite

It is possible to combine the minimum range equation (Eq 2) with the resolution equation (Eq 3) to produce an overall performance assessment.

$$x = \phi R_{min} = \frac{1.22 \lambda}{d} \sqrt{\frac{v R_o}{\omega_{max}}} \quad (4)$$

We now examine the relative velocity,  $v$ , in more detail. The velocity must be placed in the context of the various orbit conditions which may be used for imaging operations. LEO and GEO provide significantly different circumstances for the imaging payload. In general, candidate objects in GEO have a much lower diversity of orbital planes but overall larger distances. In LEO, there is significant variation in the orbital planes but with opportunities for shorter ranges, but typically at much higher relative velocities than GEO (Figure 3).

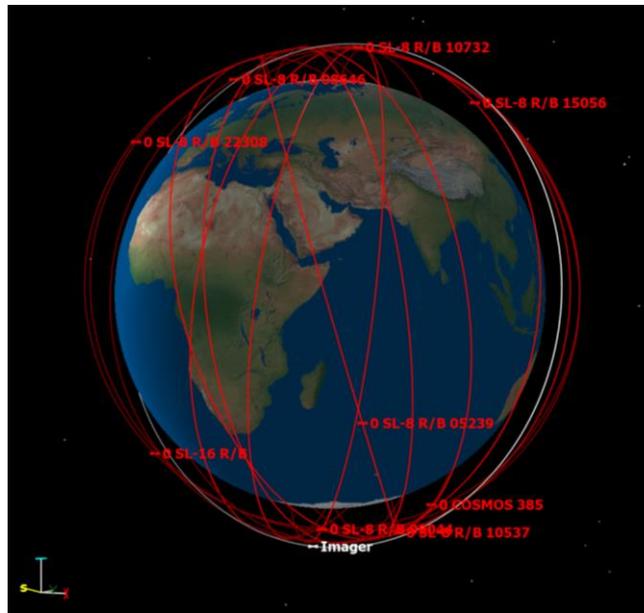


Figure 3. The twelve highest-risk conjunction candidates in the 975 km altitude “cluster” of objects (CC975) [8].

In GEO the natural cycle of orbit perturbations results in a maximum inclination of 15 deg for objects with normal area to mass ratios. This inclination results in a relative “north-south” velocity of ~800 m/s when passing through the node relative to an earth fixed reference.

The spatial resolution provided from Equation 4 is illustrated in Figure 4 for a 20 cm optical payload ( $d = 0.2$  m) across a range of point of closest approach distances ( $R_o$ ) and maximum spacecraft angular rates,  $\omega_{max}$ .

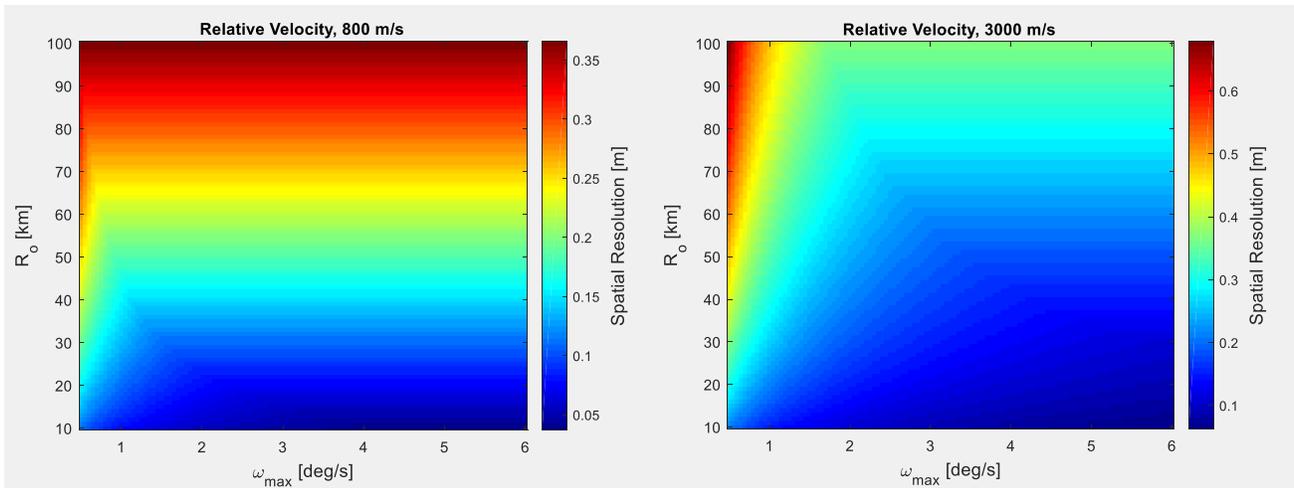


Figure 4. Imaging spatial resolution possible for an optical payload with a 20 cm aperture ( $d = 0.2$  m) as a function of the point of closest approach,  $R_o$  ( $y$ -axis) and maximum angular rate,  $\omega_{max}$  ( $x$ -axis) for relative velocity conditions typical of those which may be encountered in GEO (*left*) and those more representative at LEO (*right*).

## 5. SUMMARY AND FUTURE STUDY

The growing interest in satellite servicing and active debris removal will continue to drive the need for on-orbit imaging. Enabling imaging operations without orbit-matching or RPO conditions greatly expands the mission utility of a satellite by minimizing the required fuel expenditures. Geometric analysis of the ranges and relative angular rates provides a framework to assess the potential performance of small satellites conducting imaging operations and provides a means to optimize mission design.

This work introduces a construct to determine the performance of spacecraft imaging systems enabled by the growing capabilities of small satellites. Further exploration should examine the angular acceleration rates as well as the duration of imaging which may be required at a minimum resolution such that complex tumble dynamics of objects can be quantified. Finally, a more robust treatment of the relative orbit velocities may be incorporated as a basis to more accurately plan the delta velocity mission budget.

## 6. REFERENCES

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