Future On-Orbit Spacecraft Technologies and Associated Challenges for Space Situational Awareness

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ABSTRACT

This paper reports on a set of ongoing activities conducted by the UK's Defence Science and Technology Laboratory (Dstl) to examine trends in current on-orbit technologies in order to identify future challenges for maintaining Space Situational Awareness (SSA) in the context of "Space 4.0"; particularly with regard to future propulsion systems, proximity operation capabilities and changing spacecraft design & composition. An exemplar methodology is introduced, and qualitative discussions are made regarding the influence of these developments on existing "generic" SSA functions. Possible approaches to quantitatively assess the impacts of these trends on each SSA function are presented to help scope out resiliency options for future SSA architectures.

1. INTRODUCTION

As the space industry transitions through the realm of "New Space" and beyond, market forces and technological progresses are motivating new ways to exploit the space domain. As a result, the industry is witnessing a series of rapid changes to the composition and behaviour of operational platforms; enabled by technological improvements to such factors as on-orbit propulsion capability, platform/bus designs and onboard autonomy, and driven by new mission types. From a Space Situational Awareness (SSA) perspective, these developments will provoke increasingly complex spacecraft dynamics resulting in characteristics that will diverge from assumptions made by existing target models used within SSA architectures.

Target models can be considered to comprise of dynamical models [dictating their motion through physical space] and signature models [how they are observed using different physical means]. Within existing SSA architectures (sensors & processing), dynamical models traditionally incorporate well-defined perturbations arising from natural and artificial phenomena, and assume simplified spacecraft (body) geometries which, in general, do not vary over time. Future spacecraft, missions and technologies will deliver increasing challenge for the modelling of complex manoeuvres and variable forces acting on a body; further diverging from the simplification of satellites as simply *"cannonballs in space"*. Furthermore, developments in spacecraft design will inevitably affect the physical structure and materials of future space vehicles, affecting their observable signature. These developments are likely to impact the ability to detect and track satellites using currently-fielded SSA architectures.

To enable the design of future SSA architectures that will be effective against the challenges of tomorrow, the UK Defence Science and Technology Laboratory (Dstl) have initiated a series of exercises to speculate toward a set of future spacecraft technologies in order to assess their relative performance impact on 'traditional' SSA architectures.

These topic areas include:

- Future Spacecraft Propulsion Technologies
- Emerging Proximity Missions and Associated Technologies
- Future Spacecraft Design Considerations
- Technologies Facilitating "Non-Traditional" Operations and Behaviours

These exercises have looked to characterise the trends currently witnessed in spacecraft design principles and the application of novel on-orbit technologies to derive a set of hypotheses which represent a set of possible future scenarios describing evolutionary and disruptive changes to our understanding of a "typical" satellite. To explore the resiliency of future SSA architectures, a set of generic functions have been generated based on existing SSA processes (e.g. detection, orbital estimation, etc.), against which initial trends can be mapped in a qualitative manner.

This paper summarises our current state of progress towards our overall goal of developing a method to predict the future technical demands that SSA architects will need to consider. It presents an outline methodology for pursuing a *holistic* study across the fields of space technologies and SSA, and offers some initial perspectives drawn from pursuit of this approach within two case studies associated with technologies enabling non-Keplerian dynamics and close-proximity operation of spacecraft.

2. METHODOLOGY

The overarching goal of this activity is to answer the following question: *in the future, will the (current) way that SSA architectures observe, track and catalogue space objects become redundant, and how might solutions be prepared?*

Since making detailed prediction of the future can be highly challenging[1], the activity employs a *holistic* methodology to explore future trends in spacecraft dynamics, behaviours and compositions in order to identify future challenges (and opportunities) for the surveillance of space. This methodology aims to account both for technological developments, as well as 'soft' issues such as economics and policy.

Our method comprises a series of steps as follows:

- *Step 1*: Define a set of "generic" SSA functions that we assume any/all SSA architectures need to undertake. This captures activities associated with Detection, Tracking, Identification and Characterisation (DTIC) of Resident Space Objects (RSOs)
- *Step 2:* Conduct specific technology scan(s) relating to spacecraft technologies to identify future trends and developments of relevance to "SSA"
- *Step 3*: Hypothesise exemplar future scenarios which capture general spacecraft and performance trends, whilst remaining agnostic of specific technologies/solutions
- *Step 4:* Pursue audit(s) of technologies within each scenario and qualitatively characterise technology trends in terms of their impact on the "generic" SSA architecture
- *Step 5:* Identify candidate approaches towards quantifying impact, and explore mitigations

These steps are described in more detail in **§2.1-2.5**.

2.1 Definition of "Generic" SSA Functions

To frame the problem, a functional decomposition was conducted that examined existing techniques of conducting SSA within typical architectures. In this step, the aim was to capture the higher-level functions associated with "SSA", whilst remaining agnostic of any specific architectures, methods or capabilities.

The following functions (and sub-topics) within "SSA" were defined:

- *Detection*: "Visibility" of a space object by an architecture of sensors; dependent on factors such as:
  - Sensor phenomenology (e.g. optical vs. radar, active vs. passive, etc.) and target signature
  - Illuminator-target-receiver geometry, spatial/angular resolution and Signal-to-Noise Ratio (SNR)

- *Tracking:* Association of individual sensor detections (single- or multi-target tracking) against a hypothesised target set, including modelling of sensor performance and recursive processing

- *Dynamical Models*: Representation of realistic physical dynamics and associated forces acting on space object, e.g.:
  - Gravitational, atmospheric drag, Solar Radiation Pressure (SRP) perturbations, etc.
  - Constant vs. finite-duration vs. impulsive forces

[1] Neils Bohr is attributed with coining the famous phrase: *"Prediction is difficult, especially about the future"*.

- *Orbit Calculation*: Batch estimation of the orbital parameters of a space object derived through processing of associated metric observation data:
  - Long-term target dynamics
  - Force-modelling and propagation

- *Catalogue Maintenance*: Management of a recognised "picture" of the orbital population, including:
  - Correlation to existing entries, update of object orbital state estimates and manoeuvre processing
  - Handling of Uncorrelated Tracks (UCTs); detection of 'new' objects
  - Sensor tasking against cataloguing/orbital uncertainty metrics

- *Characterisation of Objects*: Identification of composition, capability and "intent" of an object in space from observed signatures and pattern-of-life

- *Generation of Resulting Products*: Use of catalogue/orbit data to derive products for a range of users; e.g. satellite overflight warnings, conjunction/collision warnings, re-entry predictions, fragmentation alerts, etc.

2.2 Identification of Emerging Technology Trends of Relevance to "SSA"

To complement the "bottom-up" approach progressed during *Step 1*, the following steps pursue a "top-down" methodology to identify and capture broad trends in spacecraft technologies, before qualitatively mapping the implications of these outcomes onto potential impacts for the SSA functions described in **§2.1**.

Firstly, this involved exploring potential on-orbit technologies and design principles anticipated to reach technical maturity (circa Technology Readiness Level [TRL] 8-9) within the 2045 timeframe expected to be fielded within an RSO population on which an SSA mission is being conducted.

To maintain tractability of the problem, a number of technologies and concept areas were omitted from this initial study; namely those associated with:

- Space tourism and human spaceflight
- Specific future launch capabilities, delivery mechanisms or access to space
- Ground segment architectures and capabilities
- Population-based implications (i.e. related to number[s] of objects)
- SSA "beyond Earth" (i.e. cislunar and higher/heliocentric orbits)

To complement the approach, a survey of space(craft) technologies was conducted by the Dstl Horizon-Scanning team that featured a broad scan of relevant recent literature published within the last 5 years, based on a set of keywords provided by Subject Matter Experts (SMEs). These keywords included specific technologies such as solar cell and antenna technologies, as well as generic terms such as 'Electric Propulsion', 'Active Debris Removal', 'spacecraft subsystems' and 'de-orbit technologies'. Furthermore, a series of workshop exercises were conducted by Dstl space SMEs to characterise a set of primary themes that aim to capture the entirety of future spacecraft systems that have implications on the SSA functions.

Four primary themes emerged from this activity; from which a set of future "hypotheses" were also generated that consolidate these trends into a more tractable set of use cases against which future SSA processes may be examined.. The output from this exercise is summarised in Table 1.

To focus the analysis, these hypotheses were qualitatively ranked by SMEs based on their likelihood of enforcing progressive or disruptive changes to the "generic" SSA functions; this prioritised set forms the basis for a deeper holistic examination (listed in **bold** within Table 1). Those hypotheses which emerged with the highest priority formed the basis for specific case studies against which to test the holistic methodology: these are examined further within this paper to demonstrate the approach.

Table 1. Primary Themes and Future Hypotheses Identified during Initial Scoping Study

Theme	Hypothesised Scenarios ["Use Cases"]
Non-Traditional Orbits and Dynamics	**Increased Utilisation of Highly Non-Keplerian Orbits**
	Usage of Novel (Keplerian) Orbit Regimes
	Increasing "Non-Conservative" or Variable Trajectory Dynamics
Vehicles Operating in Proximity	*Proliferation of Tethered/Interconnected Objects*
	Routine Rendezvous Missions and Associated Activity
	Increased Deployment of Sub-Objects from "Parent" Systems
	Proliferation of Free-Flying and Proximity-Formation Missions
Novel Spacecraft Compositions Affecting Observed Signature(s)	*Increased Implementation of Non-Traditional Form Factors*
	Proliferation of Objects with Variable Form Factors
	Increased Usage of Non-Traditional Spacecraft Materials
	Proliferation of Standardised or Mass-Produced Platforms
Enhanced Spacecraft Operations and Behaviour	*Improvements in Typical Orbit Transfer and Control Capability*
	Proliferation of Small Platforms with Manoeuvre Capability
	Increased Levels of (Onboard) Flight Autonomy
	Novel or Changing Mission/Life Cycles
	Enhanced/Modified Power Generation Capabilities
	Enhanced Use of Signature Control

2.3 Deconstruction of Hypotheses and Identification of Enabling Technologies

In reality, individual SSA architectures (conducting the functions described in in **§2.1**) are designed with specific performance metrics in mind, defined against a tangible set of target characteristics.

To begin to devolve the implications of the different future scenarios identified in Table 1, *Step 4* seeks to identify specific technology areas which could enable (or effect) the realisation of these hypotheses, and to use these to draw out qualitative impact(s) on specific SSA functions. For each scenario, the approach looked to deconstruct each use cases into associated spacecraft technologies/principles which could enable these scenarios, and 'match-make' on-orbit capabilities against them.

For this paper, Table 2 outlines the broad technology areas associated with the subset of use cases marked in **bold** in Table 1, along with the section of the paper in which they are discussed.

2.4 Audit of Technologies and Mapping to "Generic" SSA Functions

Using the derived definitions of enabling capabilities, specific technology audits were then conducted in order to generate a more detailed understanding of the future outlook of specific classes of technologies.

The intention of this step was to capture an understanding and taxonomy of the relevant (realistic) technology classes of interest, to build an initial picture of the associated timescales and likelihoods of adoption of such technologies/features on a substantial proportion of the future population, and to qualitatively analyse identified performance impacts (either positive or negative) on "generic" SSA functions. To facilitate this, a matrix-capture format was designed; shown in Table 3, and populated within interactive workshops using SME judgement.

Table 2. Deconstruction of Exemplar Hypotheses

§	Hypothesis	Description	Associated On-Orbit Capabilities
3	Increased Utilisation of Highly Non-Keplerian Orbits	Periodic, displaced orbits non-compliant with Keplerian dynamics; enabled by (long-term) propulsive force	Long-duration / high-thrust propulsion systems; e.g. Electric Propulsion (EP) and passive propulsive devices Novel orbit design(s) and control
3	Increasing "Non-Conservative" or Variable Trajectory Dynamics	"Open" trajectories non-compliant with Keplerian dynamics over temporary/short durations; e.g. spiral orbit transfers	Long-duration / low-thrust propulsion systems; e.g. EP and passive propulsive devices Novel orbit design(s) and transfers
3	Proliferation of Small Platforms with Manoeuvre Capability	Enhanced ability for small satellites & CubeSats to conduct active orbit transfer or collision-avoidance manoeuvres	Miniaturised primary propulsion systems (all subtypes)
4	Routine Rendezvous Missions and Associated Activity	Routine Rendezvous & Proximity Operation (within ~10 km) and in support of e.g. on-orbit servicing, Active Debris Removal and other missions	Relative navigation technologies Interface/docking mechanisms
4	Proliferation of Satellite Cluster Constellations and "Companion" Missions	Satellites in close proximity (order of 10s-1000s of m) within optimised constellations / formations	Relative navigation technologies "Formation-flying" orbit design and control Inter-satellite communications

Table 3. Matrix Template for Assessment of Technology Areas

Technology Area	Likelihood of Widespread Adoption	Expected SSA "Impact"	Mitigation Challenge
e.g. CubeSat Electric Propulsion	*High / Medium / Low + description*	*High / Medium / Low + description*	*High / Medium / Low + description*

No effort was made to conduct a fully comprehensive audit of all future technologies & concepts, or to exhaustively characterise every possible implication; instead, the efforts have been to construct a representative picture of the future "landscape" of technology and to initiate thinking on exemplar areas as a mechanism to direct future research toward system design. Particular attention was diverted to novel concepts and applications which have the capacity to effect disruptive changes to the "traditional" dynamics of spacecraft. From this, qualitative assessments were pursed in order to extract primary themes which enable further research to be targeted in candidate areas.

2.5 Develop Analysis Approaches to Quantify Impact and Develop Mitigations

To date, the activity has established a qualitative understanding of exemplar areas using the aforementioned *holistic* approach to translate predicted in-space technology trends onto generic SSA functions.

A crucial aspect of future activity lies in quantifying the impact of each hypothetical scenario on specific SSA architectures; that is to aggregate the impact on the generic SSA functions to understand the implication when these are presented with the hypothesised scenarios. Only though tractable analysis can the needs of future SSA architectures be clearly defined and hence solutions developed that are resilient to a range of hypothesised changes to the future space population.

This step is foreseen to include the following activities:

- Develop methods to estimate the likelihood that the hypothesised scenarios will come to fruition, and speculate on how exemplar spacecraft technologies/techniques will mature in time
- Conduct "deep-dives" within candidate technology areas to quantify speculative performances; e.g.
    - Performance(s) of future propulsion systems in terms of thrust magnitudes & durations
    - Feasible spacing/ranging of satellite clusters and rendezvous missions, based on candidate technologies and orbit designs
    - Signature modification associated with non-traditional (or varying) form factor spacecraft
    - Albedo performance of novel bus materials and structures
- Leverage SSA performance models and simulation tools to prototype speculative dynamics and explore architecture resiliency toward hypothesised future RSO dynamics and design aspects
- Testing of alternative (novel) algorithms/methods to quantify benefits/drawbacks against existing methods

To demonstrate the methodology derived so far, two case studies are pursued further within this paper:

1. Enhanced utilisation of non-traditional orbits and dynamics [**§3**]
2. Elevated likelihood of "close-proximity" operations such as Active Debris Removal (ADR), On-Orbit Servicing (OOS), companion missions and satellite clusters [**§4**]

Each chapter is separated into two parts: the first briefly reviews a set exemplar technologies aligned with the topic, whilst the second enters a qualitative discussion on the resulting implications on the "generic" SSA system. Where possible, indicative space-flown demonstrator missions are included as potential signposts of future capability.

3. CASE STUDY A: NON-TRADITIONAL ORBITS AND DYNAMICS

When modelling the dynamics of heavenly bodies (galaxies, planets and/or man-made objects), their motion can principally be governed by Kepler's laws and gravitational potential; following "Keplerian" dynamics. This (two-body) model is fundamentally valid only for point mass targets, but is a reasonable approximation for true dynamics when the ratio of one object to another is very large and/or their relative distances are significant, and when other forces (non-gravitational, and gravity arising from third bodies) can be assumed to be negligible.

As these assumptions diverge, the approximation of purely "Keplerian" orbits to describe the motion of real objects becomes less valid: in the case of man-made objects in orbit around the Earth, this situation occurs when satellites are under action by forces that are significant in comparison to Earth's gravity; e.g. thrust, drag, and Luni-Solar perturbations. Consideration of these additional forces, particularly when they are rapidly-varying (either spatially or temporally), can considerably complicate the Orbit Determination (OD) process with respect to idealised, two-body mechanics.

Whilst, in practice, no object truly follows a truly "Keplerian" orbit, within the SSA community the term "non-Keplerian" is typically reserved only for those which differ significantly this model, and hence from the typical force models used in satellite OD and propagation models. Where, historically, RSOs have occupied largely stable orbits that aim to minimise the effect of orbital perturbations, improvements in satellite propulsion technology will, in future, enable a wider range of complex orbit trajectories to be occupied by spacecraft (including usage of 'new' regimes), as well as improved agility and capacity for moving between them.

Future, high-capability (active and/or passive) propulsion systems could enable more disruptive orbit designs and long-duration orbital transfers. These "non-Keplerian" dynamics are poorly-represented by current techniques used for dynamical modelling and numerical integration within algorithms for orbit determination and catalogue maintenance. In this chapter, we focus on the potential for future propulsion technologies to facilitate orbital dynamics which diverge from the existing assumptions relevant to the SSA functions described in **§2.1**.

Regarding the topics within this theme denoted in Table 1, those which are relevant to this section are:
- Increased Utilisation of Highly Non-Keplerian Orbits
- Increasing "Non-Conservative" or Variable Trajectory Dynamics
- Proliferation of Small Platforms with Manoeuvre Capability

In line with these hypothesised scenarios, the following sub-sections offer perspectives on the breadth of potential methods of long-duration, variable-thrust propulsion, and regarding 'democratisation' of manoeuvre capability onto a greater wider of systems. Within this audit of applicable technologies, a particular focus was made on examining the speculative capabilities of future EP and other, long-duration (constant- or variable-thrust) propulsion methods in enabling new, or radical, orbit sets and novel on-orbit dynamics.

3.1 Exemplar Technologies

3.1.1 Electric Propulsion (EP)

At the time of reporting, most EP systems fielded on orbit are modest, sub-Newton thrust and are used for frequent (but minor) orbit correction changes, or in the context of long-term orbital (or interplanetary) transfers. Existing examples include Hall-effect thrusters and ion/plasma thrusters commonly found on Geostationary Earth Orbit (GEO) spacecraft for station-keeping purposes, long-term Geostationary Transfer Orbits (GTOs) effected by "all-electric" spacecraft such as *Eutelsat-172B*, or interplanetary transfers such as that conducted by *BepiColombo*.

At present, the principal classes of EP systems include:
- *Electrothermal thrusters*: arcjets, resistojets, Variable Specific Impulse Magnetoplasma Rockets, etc.
- *Electrostatic engines*: ion thrusters, Hall-Effect thrusters, colloid thrusters, Field-Emission thrusters, etc.
- *Electromagnetic engines*: Magnetoplasmadynamic thrusters, Pulsed Plasma Thrusters, Helicon Plasma Thrusters, etc.

Evolutionary progression of existing EP performances is already anticipated for these systems, seeking to increase thrust capacity and/or Specific Impulse (I_{SP}), or lifetime/reliability of current classes of system. A recent review of current and future EP technologies for typical "large" spacecraft can be found reported by [1].

Miniaturised EP systems for orbit transfer and attitude control are also foreseen for use on smaller spacecraft (discussed in more depth in **§0**); however, the activity also highlighted a number of future options and concepts for an evolutionary class of "high-power" EP techniques on-board typical mid- to large-size satellites. Whilst subject to a considerable mass penalty and predominantly speculated for interplanetary missions, such systems look to exploit the availability of large power draws (on order of Megawatts, enabled by progresses in photovoltaic and nuclear power systems) to generate a high I_{SP} and long-duration propulsive forces. Whilst it is notable that nuclear-powered EP system have been previously demonstrated on Soviet *PLASMA-A* missions, a 1992 United Nations resolution on the use of nuclear power sources in Earth orbit (along with limitations on technology transfer) has somewhat constrained their widespread use.

As exemplars, the following low-TRL EP examples can be identified:

- 'Atmosphere-Breathing' EP (ABEP) for long-term operation of satellites in very low or elliptical orbits; e.g. the RAM-EP system considered by ESA/Sitael [2]
- Developments in "high-power" [~megawatt] EP driven by nuclear (fission) and/or high solar electric power; e.g. [3][4]
- Geostationary orbit transfers enabled by beamed power generation; e.g. [5]
- Future ion drives and mass driver ("space debris as fuel") concepts; e.g. Pulsed Cathodic Arc Thrusters ["Neumann Drives"]

3.1.2 Passive Devices

To date, the use of passive ("propellantless") devices for orbit transfer and control are most commonly associated with the deployment of 'deorbit' devices for disposal of satellites from the Low-Earth Orbit (LEO) & GEO protected regions at End-of-Life (EOL). This has been motivated by the prospect of a low-cost way of ensuring compliance with Inter-Agency Debris Coordination Committee (IADC) guidelines on satellite disposal without the need for additional propellant to conduct EOL manoeuvres.

Within the LEO regime, a number of technologies are becoming mature for conduct of either direct re-entry or deorbit to a lower altitude; for example, (aerodynamic) drag deorbit sails and electrodynamic tethers. At present, deorbit from the GEO protected region is typically conducted via a direct thruster burn to exit; however there is potential that solar sails (or other techniques) could be applied to this role in the future; as speculated by [6]. Alternative disposal methods are speculated for objects in deep-space regimes; e.g. by exploiting orbital perturbations ("dynamical pathways") to reduce times for re-entry into Earth's atmosphere, as examined within the *ReDSHIFT* project using passive methods [7].

Approaches are also being considered which employ propellantless devices for orbital maintenance and propulsion, as well as for interplanetary transfers. Passive technologies which are capable of perturbing (purely Keplerian) orbital dynamics in Earth orbit through non-conservative forces include:

- Thin-film/membrane and inflatable sail concepts exploiting atmospheric drag ["aerobraking"] or Solar Radiation (photon) Pressure ["solar sailing"] forces; e.g. *CANX-7* and *InflateSail* (drag devices), *IKAROS* and *LightSail 2* (solar sails)
- Electrodynamic tethers (non-conductive, conductive, and/or powered) exploiting Lorentz forcing; e.g. [8]
- Electrostatic ("brake-tether") devices exploiting Coulomb drag from ionospheric plasma; e.g. *Aalto-1*
- Electric-sail and hybrid thruster-sail concepts; e.g. [9]
- Retractable booms for control of ballistic coefficient; e.g. [10]
- Magneto plasma-drag methods; e.g. [11]
- Exploitation of differential drag (through attitude or geometry control) for satellite cluster control; e.g. *AeroCube-4*, the *Flock* constellation
- Stability booms exploiting gravity-gradient forces

3.1.3 Miniaturised Systems

Improvements in the primary propulsion capability of small satellites (particularly CubeSats) are also emerging. Where, historically, small (< 10 kg) satellites have been largely non-manoeuvrable and with limited orbit/attitude control, future systems are expected to have increasing manoeuvre capability for station-keeping or orbital transfer [12].

Small platforms are increasingly a realistic option for performing missions such as Earth Observation, traditionally undertaken by larger systems. Such application necessitates an increased level of orbital control as well as capability to conduct collision-avoidance or formation-keeping manoeuvres. Few CubeSat systems have flown with primary propulsion capability: existing flights have included the *AeroCube-8* spacecraft fitted with ion-electrospray thrusters and the *BRICSat-P* mission, which demonstrated micro-Cathode Arc Thrusters [13]. Recent demonstrations have been made of electrolysis ("water-powered") propulsion via the steam thrusters onboard *AeroCube-7A* and *-7B* within NASA's Optical Communications and Sensor Demonstration, and EP qualification studies are underway for micro- Pulsed Plasma [e.g. ESA/Mars Space] and Field-Effect [e.g. Morpheus Space] thrusters for CubeSats.

More detailed reviews of CubeSat propulsion technologies and trends can be found in [12]-[14], covering chemical, electric and propellantless propulsion methods.

3.2 Discussion: Implications on "Generic" SSA Functions

Impact on Dynamical Models and Orbit Determination

Ultimately, the nomenclature for "Non-Keplerian Orbits" (NKOs) is most commonly reserved for periodic orbits where a long-duration or continual perturbing/propulsive acceleration is applied in addition to modelled, natural forces; however, these conditions are also consistent with other "open" trajectories (albeit over shorter timescales), such as orbital transfers or decays. Typically, such dynamics are enabled by techniques capable of delivering near-constant thrust levels over long periods of time (e.g. EP, or passive devices exploiting atmospheric drag or SRP). Within orbit determination, solving for these forces requires an accurate model of orbital dynamics under a constant perturbing force, however finite-duration propulsive forces may often be considered to be impulsive for simplicity.

Unknowns associated with variable thrust/drag profiles can make it challenging to align variable force dynamics to observation data within orbit models; particularly for passive devices, where additional information regarding environmental conditions and target orientation is required. These factors pose challenges for including dynamical models within "generic" SSA functions, since the dynamics of NKOs differ from the traditional (Keplerian) models used for OD: the prevalence of complex orbital dynamics will necessitate improved modelling of non-impulsive, potentially time-varying forces within the dynamical system (in terms of magnitude, direction and time[s]); the envelope of which may not be known *a priori* unless bespoke arrangements are sought with spacecraft operators.

Application of "high-power" EP or high-thrust passive systems could enable a class of NKOs that have capacity to modify their orbit radically away from typical 'semi-ballistic' trajectories modelled by existing General- or Special-Perturbation techniques, as reported by [15]. These will enable new mission that diverge from orbital regimes traditionally observed by SSA sensors: for instance, the concept of a "pole-sitter" spacecraft situated in deep space at high latitudes is subject to much study to support interplanetary communications. SSA of spacecraft in these new orbital regimes is likely to require the use of new sensors types and locations, as well as alternative sensor strategies which are capable of sensing in these unorthodox regions.

Our review of novel orbit regimes has identified the following concepts that appear to be of highest interest:

- Low-thrust orbital transfers over long durations; e.g. *Eutelsat-172B* (GTO to GEO), *Starlink* (LEO)
- Very Low Earth Orbit (VLEO) platforms counteracting atmospheric drag; e.g. *GOCE*, *SLATS* [*Tsubame*]
- Single-orbit repeat ground-track ("Earth-synchronous") orbits; e.g. [16]
- Periodic orbits about displaced artificial equilibrium points; e.g. for GEO [17]
- "Pole-sitter"-type spacecraft at high latitude; e.g. [18]

Advances in propulsion methods are already enabling changing dynamics throughout a mission lifetime, including long-duration (low-thrust) orbit transfer at spacecraft Beginning- and End-of-Life (BOL/EOL) [e.g. orbit-raising by *Eutelsat-172B* and *Starlink* at BOL, or the deorbit of *CANX-7* and *RemoveDEBRIS* at EOL] or changes to station-keeping manoeuvre cycles enabled by low-thrust orbital maintenance. The increasing miniaturisation of chemical, electric and passive systems capable of primary propulsion is accelerating [e.g. *AeroCube-7*, *BRICSat-P*], and may soon enable even smaller platforms to detectably perturb their dynamics from Keplerian trajectories, or to exhibit extended life cycles of manoeuvrability. Also, through improved capacity to conduct impulsive manoeuvres, it is likely that small systems will increase in capability to effect reasonable orbit transfers, as well as to conduct collision avoidance strategies, which is likely to shift perception on the capability and role of small satellites.

Some approaches towards orbit estimation of continuously-thrusting spacecraft, through use of variable-dimension filters, are discussed by [19], whilst [20] consider methods for mapping of highly non-Keplerian orbits to classical orbital elements.

Impact on Tracking and Cataloguing

For the tracking & cataloguing of uncooperative objects (where manoeuvre plans/operator ephemerides are not readily accessible) which exhibit variable thrust/drag dynamics, there will be a need to develop automated manoeuvre-processing algorithms tuned to these perturbing forces. In order to maintain a suitable fit to observation data, tracking schemes may be required to solve through multiple hypotheses of finite-duration force dynamics in order to identify likely solutions, and to potentially store such hypotheses for adaptive processing through (e.g.) Machine-Learning techniques. From a sensor perspective, increased cadence of observations may enable the ability to maintain custody of such manoeuvring vehicles, also driving towards sensor architectures with persistence of observations.

Through application of near-constant (low) thrust, an increasing number of low-altitude (< 300 km), semi-aerodynamic platforms will become increasingly feasible and which are beneficial for a number of missions; notably Earth observation. Such dynamics were previously witnessed during the *GOCE* mission, which thrusted near-continuously at a low altitude for 4 years and led to challenges for uncooperative tracking as reported by [21]. Sustained VLEOs present greater tracking challenges, since vehicles occupy a lower regime offering fewer opportunities for sensors to observe target motion and, as such, form tracklets that feed into the OD process. In terms of cataloguing, the correlation process will be assisted by the relatively limited VLEO population at present: other objects within these altitudes will primarily consist of transitory events such as launches, de-orbits and re-entries. Performance of closed-loop (radar) tracking methods will be dependent on the internal filters used to schedule the radar, but may be alleviated due to the size of a typical beam even at these lower altitudes.

Other classes of NKOs, such as orbits “displaced” in apparent latitude from GEO present tracking challenges which will be affected by the choice of sensor: for example, traditional optical survey systems which conduct multiple scans of the GEO regime over the course of a night. The increased deviation of such orbits from “natural” trajectories for sustained periods of time, as well as their presence in volumes of space which may only be sparsely-sampled, is likely to cause issues with the track formation processes whereby dynamics are often simplified to enable association of observations from subsequent scans (e.g. through admissible-region approaches). From a cataloguing perspective, there are many other objects that may be observed in the similar regime or the same scene; for instance, debris in graveyard orbit or highly-inclined Geosynchronous objects which are no longer under North-South station-keeping control. This will make the correlation process more difficult to manage, noting that this already presents issues for current systems in cataloguing of the graveyard population; especially high-area-to-mass objects, as reported by [22].

Future, highly-agile (impulsive) propulsion systems utilising improved chemical-based primary propulsion systems, may be capable of delivering significant Δv to enact more radical orbit changes than witnessed at present. Existing satellites do not change their orbital inclination significantly over their lifetime, and this fact is exploited by current algorithms within the tracking function for custody maintenance. However, the ability for larger manoeuvre forces to be applied both in- and out-of-plane will make custody and catalogue maintenance processchallenging with existing track association and manoeuvre processing tools, and necessitate wide surveillance systems to mitigate tracking issues.

In the short-term, such vehicles are likely to require considerable mass and volume to accommodate large propulsion systems; this will make them highly detectable and identifiable. Whilst heavily "science-fiction"-style craft are still somewhat distant; agile spaceplanes and multi-mission "Space Tug" vehicles are already progressing and such capabilities are likely to be fielded within the next 5-10 years. Further increases in on-board autonomy is being developed to enable highly-agile control even during gaps in ground control coverage, and enable increasingly "non-Keplerian" orbits with autonomous trajectory control. So-called "evasive" NKOs will have consequences for tracking and custody maintenance; defined as the purposeful exploitation of perceived flaws in the existing approaches to track association and orbit determination. Reference [23] explicitly discusses the implementation of purposefully evasive NKOs; although the effectiveness of such behaviour may also depend on sensitive knowledge of an adversary's SSA detection & processing systems and how best to mitigate them.

Other Implications

Since most passive techniques for orbital and attitude control (listed in **§3.1.2**) are associated with devices which create an increase in surface area and hard-body radius of the vehicle, deployment of such devices have demonstrated improvement of the detectability of such objects. Signature changes can also be used to confirm successful deployment of such devices, and also to allow tracking by less capable sensors. However, they can also be sensitive to other forces/torques which create secondary (unintended) dynamics, such as pinwheeling and tumbling of drag sail devices, which affect visible signatures when the platform is not under active control.

Technical progresses elsewhere in on-orbit propulsion systems are likely to have "soft" effects on a broad range of SSA topics: for example, greater fuel and thrust efficiency will lead to ability to reduce wet mass and overall spacecraft volumes, or to allow for greater mission lifetimes and hence time on orbit. The prospect of proliferated On-Orbit Servicing (discussed in **§4**) capabilities may also enable spacecraft to be launched with fuel mass significantly below that required for a full lifetime, or to allow greater flexibility for conducting radical manoeuvres on a more frequent basis; for example, for debris avoidance or for mission reconfiguration. Long-duration transfer of a significant number of objects through densely-populated regimes (e.g. the *Starlink* and *OneWeb* constellations at BOL/EOL, or spacecraft undergoing passive deorbit) will also increase burden on conjunction screening function that will drive the need for reductions in orbital uncertainty in order to improve flight safety. Such low-thrust transfer orbits are also indicative of a future class of vehicles which not constrained to a single orbit regime, but which instead employ "open" trajectories across a wide volume of accessible space and which may redefine their nominal, operational orbit with mid-mission (orbital) agility.

Possible Mitigations

Where discussion in this section has examined some of the qualitative implications associated with future propulsion systems, an initial subset of mitigations has been identified which can drive the need(s) for future work in this area:

- Improve access and ability to process manoeuvre information for cooperative spacecraft operators [magnitudes, durations and times of thrust application], perhaps by mandating delivery of this information to licensing authorities
- Conduct detailed study of dynamical modelling and estimation of non-conservative forces on high area-to-mass ratio objects, capturing variabilities associated with atmospheric and solar models
- Conduct improved study of manoeuvre-processing / variable force (thrust/drag) estimation in uncooperative cases, potentially using Machine Learning approaches and other techniques alongside patterns-of-life
- Explore methods to increase observation persistence for custody of both impulsive and finite-duration manoeuvres, including appropriate geographical distribution of sensor architecture(s) and gap reduction
- Examine methods to unambiguously identify objects from characteristic signatures
- Explore enhanced screening / prediction methods for conjunction analysis and re-entry, accounting for predictive hypotheses in a computationally-efficient manner

Future work to: (a) widen the audit to other propulsion types [including chemical systems and methods of impulsive manoeuvre], and (b) to quantify impacts of exemplar propulsion types on specific SSA techniques, will enable an improved assessment of the resiliency of current approaches and how these challenges may be mitigated.

4. CASE STUDY B: OBJECTS IN PROXIMITY

A consistent theme associated with many future spacecraft missions is the desire for multiple objects to be operated cooperatively whilst in close proximity. Within the realm of Rendezvous and Proximity Operations (RPOs), the domain is expected to witness a growing frequency of encounters between spacecraft conducting ADR and OOS missions in the next years, whilst similar proliferation is anticipated in satellite clusters and proximity "formation-flying"/disaggregation concepts being fielded in Earth orbit.

Fundamentally, the primary challenge associated with retaining (space situational) awareness of closely-separated spacecraft lies in observing and resolving individual platforms where the sensing architecture is at some distance; i.e. on the ground or in an alternative orbital regime. These influences predominantly affect discrimination of multiple bodies when their separation is at – or below – the 'spatial resolution' of the sensor system according to Rayleigh-type effects. Depending on the range and angular resolution of a sensor system, signal detections from individual craft may effectively fall within a single resolution cell and hence be declared as an individual body; making it challenging to understand the composition or the head-count of objects contained within it.

There is considerable similarity to the technologies associated with OOS and ADR, since both involve rendezvous of craft towards a target (that may or may not be cooperative) and establish some form of interface; this may be direct [where two bodies come into direct contact] or "non-contact" methods such as inspection or delivery of an effect at distance. On-Orbit Servicing refers to mission concepts which seek to extend the on-orbit lifetimes of active spacecraft via maintenance, refuelling, upgrade of parts and/or retrofit of new hardware of a cooperative in-orbit "client" satellite. Active Debris Removal considers technological solutions – of varying maturity – for the removal of large (typically 500+ kg) payloads in LEO and GEO, primarily focusing on uncooperative interface techniques.

Most ADR or OOS concepts assume direct-interface solutions to rendezvous and dock with their targets (thereby leading to separations of objects which slowly approach from several kilometres and eventually converge), whilst many LEO satellite cluster concepts envisage configurations of free-flying objects which are separated – by novel orbit design and fine orbital control – by distances on the order of 100s to 1000s of metres. Aspects associated with relative navigation, orbital/formation design and onboard autonomy & control are relevant for all mission types, governing the principles of safe operation of multiple objects in proximity. An effective summary of enabling technologies which could be implemented on future proximity missions (with a particular focus on small platforms) is provided by [24].

This activity has examined a variety of enabling technologies that facilitate the operation of unmanned objects in proximity, and the resulting implications for (primarily ground-based) detection and tracking of closely-spaced objects. The following hypotheses were analysed within this section:

- Routine Rendezvous Missions and Associated Activity
- Proliferation of Satellite Cluster Constellations and "Companion" Missions

Illustrative examples of spacecraft technologies which facilitate operation of spacecraft in proximity are discussed in **§4.1**, whilst a discussion on the implications of such operations on "generic" SSA functions, and potential mitigative activities, are qualitatively addressed in **§4.2**.

4.1 Exemplar Technologies

4.1.1 Interface/Capture Technologies

Whilst a subset of rendezvous technologies have been mature for many years within the realm of manned space travel, the technological readiness of a variety of automated interface devices for unmanned systems has been progressing at pace, including technologies towards "standard" fixture devices for OOS. Notional technological solutions to the interfacing and manipulation of large platforms in LEO and GEO are relevant to the fields of both ADR and OOS, and are associated with a number of sub-categories. A comprehensive review of devices can be found published in [31], whilst an audit of servicing and refueling systems is provided in [32].

The identified techniques can be aligned to direct interface concepts (that dock/attach to a target), whilst some are more relevant to non-contact methods as represented by an asterisk (*) in the following list:

- Single- or dual-arm robotic manipulators; e.g. *ETS-VII*, *ASTRO*/*NEXTSat* [DARPA *Orbital Express*] 'Tentacle' systems or grappling wires/shaft latches (either with or without robotic arm)
- Tether-gripper, tether-net or tether-harpoon systems; e.g. *RemoveDEBRIS*
- Docking probe devices with latching mechanisms; e.g. *MEV-1*'s Liquid Apogee Engine probe
- Velcro or adhesive techniques; e.g. [25]-[26], NASA *SPHERES*
- Magnetic systems and ferromagnetic docking plates; *ELSA-d*, Airbus *Cycler* [27]
- Slingshot methods; e.g. *TAMU Space Sweeper* [28]
- * Space-based laser debris sweepers; e.g. literature review by [29]
- * Propulsion plume / ion beam shepherd / ambient gas ion drive techniques; e.g. [30]
- * Electrostatic or gravitational tractors

As systems for RPO of both cooperative and uncooperative capture mature, it is reasonable to assume that the domain will witness an increasing number of rendezvous and docking activities; leading to an increase in frequency of vehicles purposefully approaching one another. This is likely to raise questions within the international community about satellite registry, ownership, liability and civil/military "dual-use" applications; maturation of international law and/or norms of behaviour may affect the evolution of this hypothesised scenario.

4.1.2 Proximity-Class Vehicles

For many ADR and OOS concepts in the open literature, "Space Tug" servicing vehicles are speculated which dock with clients and manoeuvre the combined body to a new orbit regime (including direct atmospheric re-entry); some standardised, application-agnostic concepts (e.g. the Airbus DS *Cycler* system [27]) are even emerging today. These craft typically have a form factor appreciable to that of target satellites (several tons in mass); however, smaller systems which deploy "deorbit" of "servicing" packages aboard sub-payloads are also foreseen. For mission efficiency, concepts commonly examine the use of multi-mission "chaser" spacecraft which rendezvous and dock with numerous clients during a single lifetime, moving from target-to-target with agility and with orbit transfer dynamics mathematically optimised for fuel conservation. "Mothership"-type craft are also anticipated, whereby a 'carrier' vehicle releases deploys a number of smaller payloads; one tangible example is the forthcoming *Mission Robotic Vehicle* (MRV) system put forward by Northrop-Grumman.

Whilst clusters of objects sharing a single GEO station-keeping slot are well-established (e.g. the *Astra* and *Anik* clusters), future satellite clusters are anticipated to emerge in LEO in formations with a spatial extent of fewer than a few kilometres. These LEO missions will build upon experiences from exemplar missions such as *SWARM*, *TerraSAR-X*/*TanDEM-X* and *CANX-4*/*-5*. Within this realm, long-standing concepts for fractionated/disaggregated systems such as the DARPA *System F6* [33] may see resumed interest as spacecraft autonomy, communications and power-delivery technologies mature. Concepts like the Aerospace Corp. *HIVE* system are also redefining modular and proximity spacecraft; being capable of adaptive configurations, multi-changing form factors and resilient architectures.

So-called "companion" satellites, operating in close proximity to high-value payloads for the purpose of self-inspection and/or monitoring are seen as an emerging mission type in their own right. Such platforms are witnessed in both the military and civilian domains for a variety of missions, in numerous orbital regimes: for example, the US Air Force Research Laboratory *ANGELS* (2014) and *Mycroft* (2018) systems fielded in GEO, to small-satellite 'free-flyer' objects in LEO such as the NASA *AERCam Sprint* (1997) through to *Seeker* (2019). The latter, a 3U CubeSat, is expected to conduct inspection-like manoeuvres at a range of 50 m from the *Cygnus NG-11* cargo craft during September-October 2019. These will be enabled by improvement in Guidance, Navigation and Control (GNC) technologies to enable relative motion of the two satellites to be maintained for protracted periods of time.

4.1.3 Relative Navigation

RPO operations have a strong reliance on precise positional knowledge of all nodes in the system, with increasing autonomy anticipated in order to maintain precise geometric formations and orbital dynamics. Ranging systems are essential to rendezvous and docking performance as well as for management of satellite clusters whilst, for OOS and ADR missions, a thorough understanding of the target's rotational and translational dynamics ("pose") is crucial. Such missions also require access to accurate, real-time, 3D images of the target: the *RemoveDEBRIS* mission (2018) is notable for conduct of Visual Based-Navigation (VBN) experiments on deployed 2U CubeSats at ranges circa 200 m, raising the maturity of flash LiDAR to TRL7.

Technology areas associated with relative navigation include:

- Infra-Red sensors for target thermal recognition during far-range rendezvous approach (> ~3 km)
- Position and orientation of object at near-range rendezvous (< ~3 km); e.g. by monocular cameras, scanning LiDAR, star trackers and Inertial Measurement Units
- 3D object image reconstruction; e.g. by stereo cameras or active 3D LiDAR scanning
- Close-approach avionic systems
- Algorithm & learning approaches for inference of target thermal, inertial, optical and kinematic properties

A comprehensive review of pose determination techniques for proximity missions is published in [34]. Reference [35] provides a review of previous formation-flying spacecraft and discuss requirements for various formation-based GNC systems, whilst [36] surveys the state-of-the-art in orbit design and technologies for formation control of small satellites.

Alternative propulsion solutions that enable maintenance of relative dynamics are being explored internationally; such as by exploiting inter-satellite electromagnetic forces ("Coulomb control"; e.g. [37]), or through differential drag techniques (e.g. *AeroCube-4*).

4.2 Discussion: Implications on "Generic" SSA Functions

Impact on Detection and Characterisation

Given current physical limitations of propulsion systems for most proximity missions in LEO, a rendezvous approach will (almost inevitably) occur over the duration of several orbital revolutions. Since orbital plane-changes are extremely expensive to achieve from a fuel-saving and Δv perspective, most current concepts consider co-planar operations as the most efficient way to achieve safe rendezvous, and as currently applied within manned spaceflight. Changes in altitude profile or eccentricity are therefore required to alter the period of one satellite relative to the other to reduce this apparent distance. As such, there is typically an observable distance in true anomaly when the two objects are in the same orbit (with a shift in phase) which, as the objects approach, falls to zero.

From a sensing perspective, this poses several considerations for ground-based sensors:

- In general, Electro-Optical (EO) sensors benefit from good angular resolution as compared to RF systems due to the associated wavelengths of each regime that drives system design. For a system tracking a given target, objects in proximity will appear offset to the primary detection: for wide field-of-view EO sensors, multiple objects in close proximity will present trails in the exposed image that will be close, or even overlap, complicating the image reduction and trail extraction process.
- In contrast, radar systems primarily benefit from good range resolution, and may also potentially capture range-rate information based on Doppler effects. This information could be valuable for observing potentially subtle differences in altitude between objects during the rendezvous phase, when a "chaser" is reducing relative distance to the target. However, radars can have beamwidths of sizes ~0.1 degree and with only modest angular resolution, which can limit the ability to discern objects that are co-orbital depending on techniques employed, such as monopulse processing.

Even if multiple objects in proximity can be resolved by sensors; conducting unambiguous identification of individual objects can still be non-trivial unless the motion dynamics can be persistently-observed to avoid loss of individual custody. As already witnessed with some constellations in GEO (for example, the *Astra* and *Anik* clusters at 19.2°E and 107°W, respectively) mis-tagging of observations can become problematic since sparse observation of relative-motion objects linked with poor association processes (that do not account for station-keeping manoeuvres), can lead to degradation in quality of the orbital solutions for individual objects. Techniques analogous to that presented in [37] may be needed to combine signature identification and positional information into the observation association process to resolve mis-tagging issues. Improvements in signature identification/characterisation may also assist tagging discrimination in cases where objects merge and separate, as in ADR/OOS missions or cluster dynamics where one object occludes others. Not only are such capabilities of utility for regaining custody of discrete objects, but potentially for detecting subtle changes to the status and geometry of any objects following a close approach or docking activity.

Impact on Tracking and Orbit Determination

For future satellite “swarms” and proximity formation-flying missions where the span of a body of free-flying objects can be expected to be on the order of 100s-1000s of metres or less, and individual objects may not necessarily be resolved by the sensor system. It may be necessary to consider new approaches within the orbit determination and cataloguing functions that do not attempt to identify each object discretely, rather treat the constellation as an entity.

For Radio Frequency (RF) systems, the presence of multiple reflecting bodies within a constrained volume of space could lead to simultaneous returns detected at the receiver or multipath effects, leading to new difficulties in tracking multiple objects and determining whether an observed body is a single large object, or a cluster formed of several, discrete objects. At sensor level, instabilities are known to occur when tracking closely space separating objects particularly when the spatial distances are comparable to the modelled sensor resolution (i.e. the tracker cannot distinguish between the returns from two targets and the expected measurement noise from a single target). For satellite clusters in particular, it is likely that the formation will be formed of objects utilising the same bus platform and exhibiting similar signatures, adding complexity to the processing step. Aside from developing architectures capable of persistent observations, implementation of additional measures, such as identification ‘beacons’ on individual craft or head-count discrimination using passive RF signals arising from Telemetry, Tracking, and Command (TT&C) links offer additional opportunities for discrimination.

Cluster-tracking is a technique utilised within some radar domains to manage the resources of the system when faced with targets that are closely-spaced and flying along similar trajectories. Rather than scheduling waveforms to observe each individual scattering centre associated with a resolvable object, the radar can choose to use a coarser mode of operation whereby the radar waveform is degraded from a resolution perspective (e.g. through reduced pulse compression). The benefit of this technique is that, generally, this yields enhanced observability of the overall target cluster by superimposing returns into a single detection bin, at the expense of resolving individual objects. Such approaches may necessitate solutions to managing and conducting handover between tracking sensors of differing fidelity: sensors with exquisite detection performance may observe and track individual objects, but coarser-capability sensors may instead track the whole ‘cluster’ via a centroiding approach.

Impact on Cataloguing and Generation of Products

SSA functions associated with cataloguing and the delivery of SSA products related to regulatory monitoring will be become more complex as ADR, OOS and payload-deployment missions become more customary. Whilst orbital docking is nothing ‘new’ in the realm of human spaceflight, these have typically been infrequent, cooperative and simplified from a cataloguing and service perspective; often handled with a high degree of human-operator intervention.

Maintenance of a public catalogue of space objects will need to account for multiple objects that share a common set of orbital parameters; this may also necessitate the inclusion of target geometry, mass and observed signature as well as recording constituent “parent”, “child”, “docked” / ”undocked” taxonomies over the complete orbital history. The forthcoming servicing of *Intelsat-901* by *MEV-1* in 2020 may trigger discussion on how to represent two objects permanently uniting into a single entity; as well as regarding operation of multi-mission “Space Tug”-type vehicles which are anticipated to rendezvous and dock with multiple objects throughout their orbital lifetime. ‘Mothership’ or “carrier” concepts may pose additional challenges to SSA arising from release and rendezvous of multiple objects across the mission lifetime. It is likely that these missions will have much wider implications on the traditional cataloguing process as well as registration of sub-payloads with the United Nations’ Register of Objects Launched into Outer Space, including questions of liability.

Furthermore, increases in numbers of objects in (controlled) proximity may necessitate changes to automated conjunction analysis processes to avoid generation of false alarms between cooperative objects under operator control, but also to provide effective screening of clustered formations with secondary objects. Aside from inevitable needs to reduce orbital covariance/uncertainty across the entire catalogue, increasing numbers of objects operating in proximity are likely to drive additional demand for publicly-available SSA services; particularly conjunction screening. This may drive a greater emphasis in the sharing of indigenous orbit determination and collision assessment at satellite-operator level; potentially as part of wider consortia (*c.f.* the Space Data Association).

Other Implications

Whilst there have been few wholly successful tether-based missions to date, in future there may be increases in the number of coupled bodies which are interconnected. The most likely uses appear to be tether-capture and tether-deorbit vehicles; however the drivers and feasibility for widespread adoption remain unclear. Whilst the centre-of-mass of a two-body state will follow a largely Keplerian orbit, differential forces will act on the individual objects; especially if the tether/connector is used to generate power or exploit differential drag or gravity-gradient forces.

Finally, beyond purely technical considerations, technologies used for ADR and orbital servicing – particularly those capable of interfacing with or manipulating an existing space object – have regulatory and political implications aligned with the potential for “dual-use” of these techniques for disabling or hijacking an asset without consent. Through greater proliferation of rendezvous and interfacing capabilities, allied SSA systems must be capable of detecting such activity if it is directed against sovereign assets, and to be able to derive attributable evidence should it take place.

Possible Mitigations

Based on the previous discussion a set of topics emerge which could help to mitigate the impact of proximity operations on typical SSA functions:

- Examine sensor architectures, specifically the balance of coarse and fine angular (spatial) resolution capabilities, to manage custody and head-count tracking issues. This should look to leverage strengths of different sensor phenomenologies (e.g. electrical-optical for angular separation, radar for range separation) to deliver a more capable architecture
- Investigate the likely occurrence and impact of multipath effects of RF sensors observing RPO, and explore potential methods to exploit this data
- Pursue advanced methods to process observed signatures to detect changes to status/etc. of multiple objects occupying a single resolution cell, or for unambiguous identification
- Re-appraise the implementation of traditional SSA models for tracking of discrete objects and examine applicability of cluster models to proposed formation designs
- Store additional pattern-of-life information on targets of interest, including detailed genealogy and composition information
- Explore the policy implications of routine RPO and docking on international policy that may affect the widespread adoption of specific mission concepts

Future activity shall seek to develop a simulation environment in which to test the dynamics of representative systems against a range of typical SSA techniques, allowing to quantify architecture performances and to understand how enhancements to detection, tracking, identification and characterisation may mitigate these challenges.

5. SUMMARY AND NEXT STEPS

As described in **§**Error! Reference source not found.**,** and demonstrated in **§3-4**, our activity to date has focussed on the development of a methodology to understand and investigate the qualitative implications of future spacecraft technologies on existing SSA functions. In this paper, we have presented the initial findings of this approach within two case studies to demonstrate the application of this method.

From our initial case studies, we conclude that future propulsion systems that enable long-term, variable-thrust dynamics will have a significant impact on current methods for orbit determination, tracking and dynamical modelling of active space objects. Furthermore, technological progress in enabling routine, closely-space operations of multiple spacecraft will principally affect the detection, tracking and characterisation of individual spacecraft in proximity that will also have wider implications for international policy and service provision.

Within **§3-4**, an indicative technology audit has so far been conducted considering:

- Technologies facilitating enabling potential “non-traditional” orbits and dynamics:
  - Constant-/ dynamic-thrust (typically electric) propulsion systems
  - De-orbit (drag and electrostatic) and solar sail augmentation devices
  - Other long-duration, propellantless propulsion methods
  - Miniaturised propulsion systems

- Technologies facilitating operations of spacecraft in close proximity:
  - Direct/indirect interface devices
  - Relative navigation instrumentation
  - Formation-flying and enabler technologies

Our plan for subsequent work will expand this methodology to a wider set of spacecraft technology areas, and undertake specific quantified analysis of the high priority hypothesised scenarios. Finally, we will undertake *Step 5* for the case studies presented so far, and look to develop specific mitigation strategies.

The following specific recommendations will shape future work in this area:

- Expand methodology to additional on-orbit technology areas (e.g. those denoted in Table 1) and to topics which were excluded from this initial study
- Develop an expanded taxonomy (and associated definitions) of potential orbit families associated with spacecraft exhibiting highly “non-Keplerian” dynamics to help facilitate analysis activities
- Examine taxonomies associated with interacting/docking/interconnected/modular spacecraft from a genealogical perspective
- Conduct community/industry expert workshops to improve understanding of technical maturity & performance, and establish signposts towards technology trends; including identification of external (environment, policy, economy) drivers affecting widespread adoption
- Pursue quantitative studies against exemplar technologies to assess performance of existing, and potential future, SSA techniques in handling the potential dynamics and signatures of future space vehicles from a resiliency perspective

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