Space Capability Matrix: Development and Application toward the Characterisation of Satellite Capabilities

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ABSTRACT

Space Situational Understanding (SSU) beyond Space Situational Awareness (SSA), is necessary due to the increased commercialisation and militarisation of space. To truly understand potential adversary capabilities, mere detection and identification of satellites is insufficient. The first step in threat assessment and towards situational understanding is the characterisation of the capabilities of an observed satellite. The presented study aimed to determine the capabilities of adversary satellites through distinctive (sets of) characteristics. Characteristics comprise physical, situational and behavioural aspects. An relationship information-model is used to map characteristics to capabilities, and characteristic to observation and information processing methods. A concept demonstrator of this model is created and implemented into a tool. Both the model and the tool are named the Space Capability Matrix (SCM). The SCM can identify satellite capabilities, but also to find the characteristics that contributed the most to determination of the capabilities. The model is used to identify an optimal combination of measurements for the characterisation of the capabilities of an observed satellite, and the need for new types of sensor technology and processing that would enhance this process. Use in military application and the potential for research purposes of the Capability Matrix was demonstrated through realistic examples. For the SCM to help in the transition from Space Situational Awareness (SSA) towards Space Situational Understanding (SSU) further development, mainly adding more data and creating a user friendly interface, and testing is needed.

1.0 INTRODUCTION

Space situational awareness (SSA) is concerned with the maintained knowledge and characterisation of the space environment. Due to the rapid evolution of the space domain and it becoming “more congested and contested”, there is a growing demand for capabilities beyond traditional SSA. Space traffic management (STM) among cooperative and capable satellites is a topic of much discussion [1, 2, 3]. Similarly, it is important to identify civil and military applications of space, and the resulting opportunities and threats they enable. Since more parties have access to space, adversary satellites could pose a threat to military operations on Earth, or to space assets. To understand the threat, mere detection and tracking of adversary satellites is insufficient. The next step in the threat assessment and in moving towards Space Situational Understanding (SSU) is the characterisation of the capabilities of observed satellites.

The capabilities of non-cooperative satellites are not always shared or known exactly. Moreover, the capabilities can be obfuscated on purpose or only become visible a long time after its launch. In these cases, it is needed to understand satellite capabilities based on various data sources and own intelligence. The literature and satellite type classification, and more specifically satellite capability determination is limited.

The presented study aimed to generate a framework (information model and tooling), the Space Capability Matrix (SCM), for the purpose of determining the capabilities of an adversary satellite from observed or derived characteristics of the satellite. Because spaceflight is technically demanding and financially expensive, satellites design and operations are primarily functionally driven. As a result, satellite characteristics, including physical (e.g. design), situational (e.g. orbit) and behavioural (e.g. manoeuvres), are highly indicative of their capabilities. To use this, the following research question was posed:

Can the capabilities of a satellite be determined from observable and derived characteristics?

To address this research question, it is first necessary to develop an information model of the related entities. Such a model can subsequently be exploited in a classifier or tool for use. The objectives of the presented research are: develop the information model, determine its feasibility, explore potential applications, and outline a development plan towards operational capabilities.

Section 2 outlines how the research was approached. In section 3, the realised information model and concept demonstration tool are described. Application and use cases are discussed in section 4. Finally, section 5 presents conclusions and the way ahead for the research.

2.0 APPROACH

Development of the information model required grouping and categorisation of information. This was done through brainstorm sessions with experts from within the project and by desk research. In those sessions overall satellite categories were determined and the types of information that could characterise each of those categories. Literature was searched for existing, relevant taxonomies and classifications and used to create our own categorisation. From the general satellite types, often referred to as capabilities, more function-specific, generic capabilities were determined. Furthermore, characteristics were linked to their information source types and distinguishing characteristics were identified were possible.

Because distinguishing capabilities from each other can be difficult, focus should be applied on characteristics that specifically distinguish capabilities. Gathering information of these differentiating characteristics would help to corroborate or exclude the presence of certain capabilities. By relating distinguishing characteristics to information sources such as sensor technology and processing techniques, information sources contributing (the most) to the characterisation of satellite capabilities can be deduced and exploited. Therefore, the developed SCM information model, has a dual use: (1) linking capabilities to identified opponent satellite characteristics to estimate the type of threat they may pose based on their capabilities and (2) linking characteristics to sources of how to identify them to be able to specifically acquire distinguishing characteristics. The later could also inspire to develop new types of sensor technology and processing that would enhance future characterisation of satellites.

To support the development of the information model and to evaluate its intended use a tool was developed. Microsoft Excel was chosen, because it is suitable to facilitate a matrix-type information model, is highly adaptable, and is expected to be relatively easy to use by the anticipated users[1]. Content was added during group sessions and individually. Data was derived from various (open) sources, including the Internet.

3.0 SPACE CAPABILITY MATRIX MODEL

The Space Capability Matrix (SCM) information model, as shown in Figure 3-1, was created reasoning backwards from the threat. The base of the concept is that satellite capabilities (in green, "What it implies"), determine their potential use and, therefore, their potential threat (in red, "SSU"). Because satellites are highly functionally optimised, their form and behaviour, i.e. characteristics (in blue, "What to observe/measure/calculate") are directly related to those capabilities. Linking the characteristics to the way they can be obtained (in orange, "How to observe/measure/calculate"), helps identifying specific retrieval

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options for distinguishing characteristics. The link between capabilities and potential threat is currently not part of the model. Because standard interpretation of information elements was aspired, for further decomposition of the groups existing relevant taxonomies and classifications were evaluated for applicability in addition to developing our own sets.

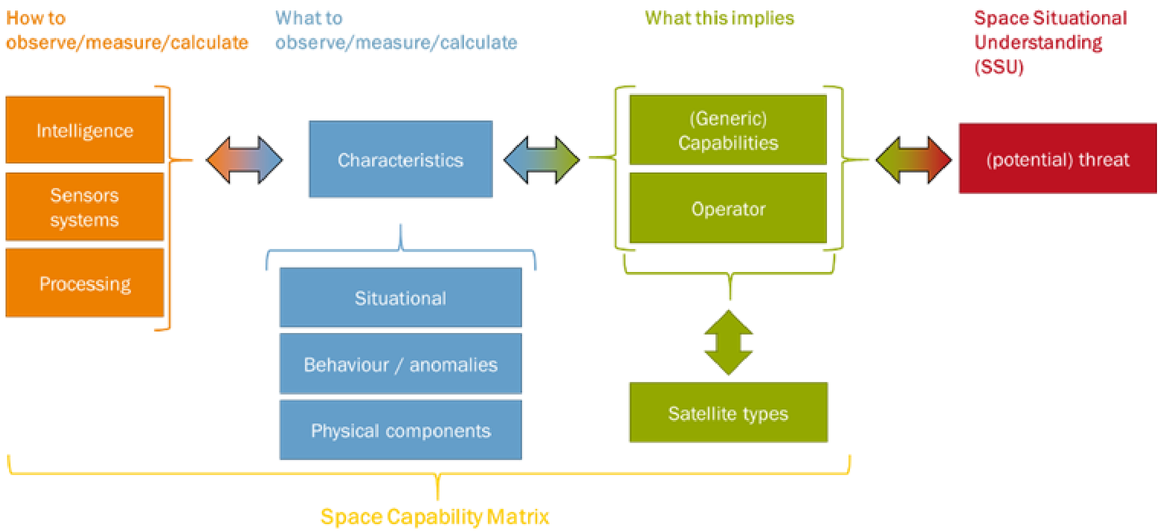

Figure 3-1: Information model of the SCM concept

One of the existing taxonomies that has been used in the development of the information model is the NASA Satellite project life cycle [4], as shown in Table 3-1. Satellites go through a life cycle, partly on Earth and mostly in space, during each of which information can be gathered about the satellite. For the SCM, satellites to be characterised will typically be in phase E of the satellite project life cycle, operation and sustainment. Pre-launch information, i.e. information from all phases before phase E, has additional value, so these characteristics were included in the model, too. Even end-of-life information, i.e. phase F, could potentially deliver valuable information if a threat needs to be evaluated in retrospect.

Table 3-1: A simplified version of the NASA Satellite project life cycle [4]

	Formulation			Implementation			
Project phases	*Pre-phase A*	*Phase A*	*Phase B*	*Phase C*	*Phase D*	*Phase E*	*Phase F*
Project activities	Concept studies	Concept and technology development	Preliminary design and technology completion	Final design and fabrication	System assembly, integration & test, launch & checkout	Operation and sustainment	Closeout
Satellite				Build	Build Launch	Mission	End-of-life (re-entry or graveyard orbit)

Satellite characteristic and their relationship to capabilities are central to the SCM, as shown in Figure 3-1. There is currently a lack in the literature on the description of satellite characteristics and capabilities in the broad scope as discussed in this paper. Therefore, a characteristics taxonomy was specifically developed for this research, which currently has 126 nodes and is up to seven levels deep. Similarly, a break-down of satellite capabilities was developed.

Partial sources and inspiration for these efforts were taken from "Critical Space Infrastructure (CSI)" [5], "A Taxonomy for Military Space Operations" [6] and "Space Mission Analysis and Design" [1]. In the CSI taxonomy, the space systems and their associated infrastructures are grouped in categories. In the taxonomy for military space operations, a similar grouping is used under the category Space Application (SA). Because the focus of the SCM is on the (military) application, the terms for space application were taken and used to categorise satellite types. Orbit information is a characteristic that can often can be obtained for a satellite in operation. In orbit classifications, orbit characteristics are grouped along various perspectives, which was considered useful for SCM. Because the SCM focusses Earth-orbiting satellites, only relevant terms were used from the taxonomy and orbit classifications.

3.1 SCM Capabilities "What It Implies"

As mentioned above, high level classification of capabilities was largely based on the Space Application part of the taxonomy for Military Space Operations [6]. Because the operator of the satellite (intent) in addition to the capability of the satellite may determine if the satellite will be viewed as an opponent satellite, the operator category was added. In the information model, another category was added, the satellite types, which was added to facilitate the inventory of distinguishing characteristics from known satellites. How this was used will be explained in the next section.

3.2 SCM Characteristics "What To Observe/Measure/Calculate"

In the information model, the characteristics are grouped at the highest level along physical, situational and behavioural aspects, where situational aspects describe the space environment (situational) in which the space system is placed, physical aspects describe the physical properties of a satellite (system), and behavioural aspects describe actions that can be taken by a space system. From there further logical groupings were defined up to seven levels deep. The highest levels are shown in Figure 3-2.

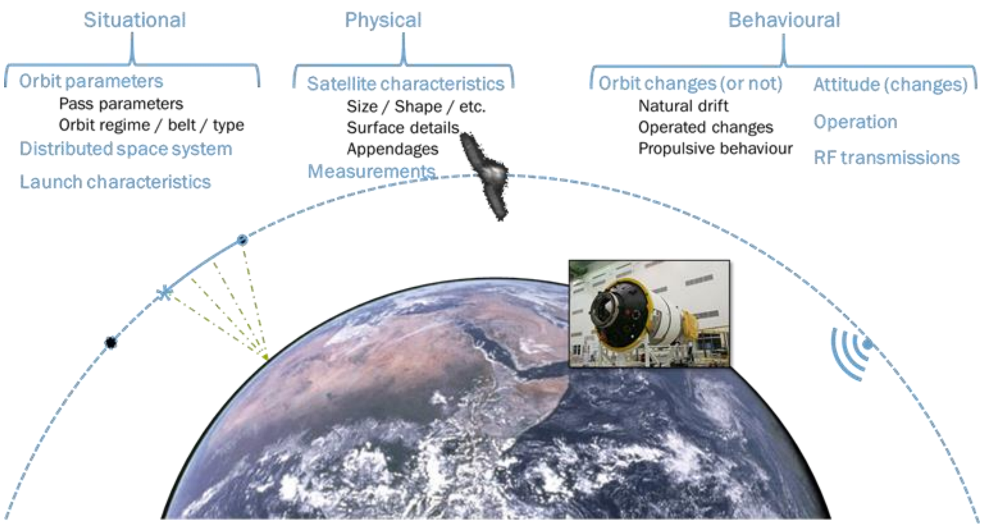

Figure 3.2: Highest classification levels of characteristics used in SCM with visualisation.

3.3 SCM Observation Methods "How To Observe/Measure/Calculate"

Some characteristics can be obtained from a single satellite overpass, either by direct observations or by processing measurements of the overpass. Other characteristics, such as orbital changes, require (or are enhanced by) measurements from several satellite overpasses or from overpasses, either at the same location or at multiple locations. Input could come from various sensor systems, but also from pre-launch intelligence, existing databases, and intelligent data processing, like sensor fusion, quality enrichment or mathematical models. Therefore, the main categories for how characteristics can be obtained were defined as Intelligence, Sensor systems and Processing.

3.4 Implementation

Implementing the model in a tool and filling the tool with data helped to refine the model. Because Microsoft Excel was used for creating the tool, adaptation was quick and easy. The characteristics are what links both other groups, so they were used for the rows, and the other groups as columns. By colouring the cells, the link with the information model is visualised as shown in Figure 3-4. An additional group (in yellow, “Analysis”) was added at the end. This column is used in the operational use of the model. Details about the satellite that needs to be characterised can be filled there.

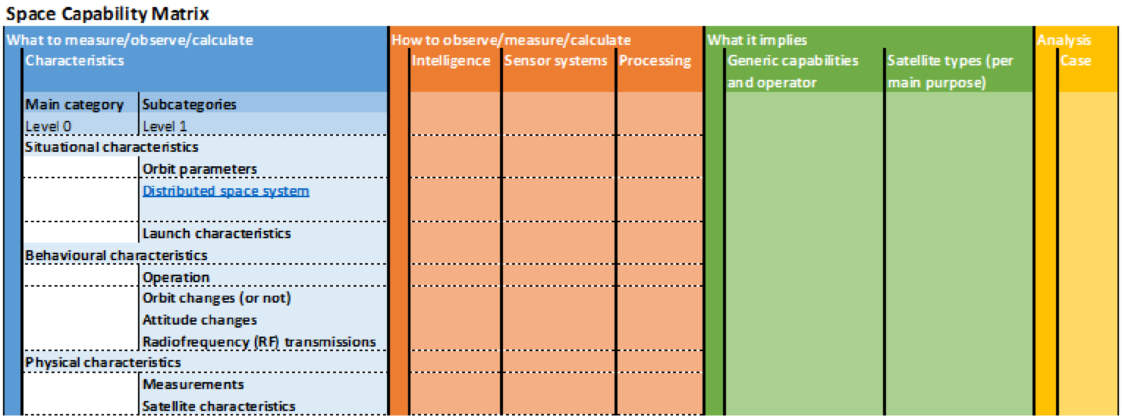

Figure 3-4: A collapsed version of the model sheet.

In order to identify relevant and possibly distinguishing characteristics, details about existing satellites of various types, applications and countries were entered into the model. Satellites were selected to represent the main satellite types (Remote sensing, Communication, Navigation and Servicing). The servicing type is a container category for satellites with varying purposes, ranging from maintenance up to space attack, that do no fall into the other categories. Most satellites used had a non-military application, because their data was more readily available. However, satellites with military application also were included.

Based on this small selection, only a limited set of characteristics could be identified as distinguishing characteristics for capabilities. The main observations showed that mostly a combination of characteristics make them distinguishing:

1. Some characteristics help to distinguish between satellite types (or generic capabilities). For instance, while being part of a constellation and station keeping points toward communication and navigation (and some remote sensing), their type of constellation and their transmission type will further discriminate between the types.
2. Some characteristics show a distinction within a type. For example, within remote sensing satellites a dusk/dawn orbit suggests visible and near-visible optic capability in contrast to SAR capability
3. Some characteristics showed a distinction between commercial use or military use within a satellite type. For instance, when spot mode of sensor transmission is observed, the (remote sensing) satellite more likely has a military application.

What complicates the characterisation is that lack of observing a characteristic does not necessarily mean that the characteristic does not apply. This is especially true for the behavioural characteristics.

4.0 APPLICATION

Many possible applications for a SCM exist. Next to the applications envisioned at the onset of the project, additional applications were discovered in the development. The applications can be broadly distinguished in (1) for operational use (production time), dealing with primary research objective on determining the capabilities of a satellite from observable and derived characteristics, and (2) for planning and development use (design time), which exploits the relationships in the model to gain additional insight into how to *most optimally* perform the operational usage. Below, various uses and an example for each are outlined, separated in two categories.

1. Operational application:

- *Determine capabilities of unfamiliar space systems*: Based on the observed and calculated characteristics, what possible capabilities does the subject space system possess?
- *Determine optimal sensor assignment tasking for capability refinement*: Which sensor system will bring distinctive and conclusive enough information and additional characteristics to rule out or confirm suspect satellite capabilities?

2. Planning and development application:

- *Determine a characteristics gap*: Which characteristics are not covered by existing observation capabilities?
- *Determine required data and information processing capabilities*: Which sensor systems and processing methods are able to bridge the characteristics gap?
- *Qualitative comparison of various observation and processing capabilities and input for larger trade studies*: Which SSA sensor systems cover which characteristic?
- *Requirements on the development of observation and processing capabilities*: How does a sensor system need to be developed to cover (additional) characteristics?

In the following section an example use case of operational application is presented.

4.1 Example operational use case

The main intended operational use of SCM is to support in in characterisation of an unidentified, potential hostile satellite. In such a scenario, the steps that need to be performed are:

- *Step 1. Initiation*: The trigger will typically be the observation of an unidentified satellite, either by change or based on a cue. The satellite may be newly launched, may have made a manoeuvre to a new orbit, or may have been deployed from another satellite.
- *Step 2. Characterisation*: Initial characterisation is done in a few sub-steps.
    - *Sub-step 2.a. Gathering information and process data*: To first attempt a characterisation, all available data is gathered and analysed. If the satellite is active, one or more observations from one or more locations could be used. Further processing of the information could reveal additional characteristics.
    - *Sub-step 2.b. Entering data into the SCM*: The available information is entered in the Analysis part (yellow section, column “Unknown satellite”) of the SCM for the listed characteristics (blue

section, rows). The cells in the yellow column could be filled with either the value that was obtained for that characteristic, or with an indication of presence or absence of the characteristic. Undetermined characteristics should stay blank.

  - *Sub-step 2.c. Determining (generic) capabilities*: The entered values (yellow section, columns) are per row compared with the values within the 'Generic capabilities and operation' part (green section, columns) of the SCM, especially the cells that have been marked as distinguishing characteristic. Because some characteristics are optional for certain capabilities, this was indicated in addition to indications of present and absent.

- *Step 3. Follow-on research*: Using an initial set of information, characterisation may not be conclusive. Therefore, additional steps may be required.
  - *Sub-step 3.a. Identifying data gaps of opportunity*: For the capabilities that are most likely applicable (or that can easily be excluded) additional data can be gathered. For this, first, from the most likely capabilities for the observed satellite the missing characteristics have to be determined (blue-greyish cells in the yellow column), and, secondly, in the "How to observe/measure/calculate" section (orange columns) of the SCM, techniques can be identified that may deliver meaningful information.
  - *Sub-step 3.b. Gathering additional data*: Specific measurements and/or data processing techniques can be applied to retrieve more relevant data. Furthermore, other sources could be found. Open sources may provide information about the original launch site, etc.
  - *Sub-step 3.c. Refining capabilities*: Again, add the new data to the SCM and look for matches with the generic capabilities. In addition comparison can also be made with specific satellites for reference (section 'Satellite types (per main purpose)').

Steps of refinement can be repeated with data from more sources until a certain confidence is reached about the capabilities of the satellite. It is out of scope of the SCM to determine how to proceed with the findings about the satellite. In a proof of concept, the steps have been successfully executed using a hypothetical use case (not described here).

5.0 CONCLUSIONS AND FURTHER RESEARCH

This study aimed to generate a model for the characterisation of satellite capabilities and to demonstrate the concept in a tool. The proof of concept experience with the Space Capability Matrix (SCM) using a hypothetical use case provided sufficient encouragement to continue with the current approach for operational use. The case demonstrated (1) identification of the capabilities of the satellite under investigation by registering its characteristics, and (2) determination of information sources that could confirm or exclude distinguishing characteristics for further narrowing down potential capabilities. Using the model for planning and development application is still in its early stages. To be able to provide guidance on which sources to develop or exploit that make more distinguishing characteristics available, more existing satellite data has to be analysed on determine those distinguishing characteristics.

In order to evaluate the SCM more formally, especially for operational use, the next step is applying the tool in a simulated setting as part of a workshop or a training exercise, preferably followed by a real-life application. Future SCM development, building upon the results from the formal evaluations, could proceed with further concept development and with operationalising the tool.

For this demonstrator set-up of the SCM the focus is primarily on the structure of the model, and only a limited amount of data is used within the model: sufficient to get an idea of its usefulness. However, if the concept is developed further, more data in the tool is a must. Several approaches have been identified to achieve this, for instance:

1. Automated mining and combination of data from existing registries, databases, and websites.
2. AI-models may be used to process registry data in bulk to determine distinguishing characteristics between the satellites and map it to specific capabilities.
3. Students could perform data entry into the model of selected existing satellites.

Microsoft Excel was found to be the right platform for the current purpose of the tool. For development into an operational product (TRL-9), it is recommended to build a more user-friendly interface where the users are guided through the process on top of a database system. Additional features may also be added, such as providing recommendations for matches and follow-on data gathering. Identifying and involving potential users would be the best way forward on this path.

6.0 REFERENCES

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